PRESSURE TRANSDUCER HANDBOOK
1983

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Preface

Here is your new 1983 catalog and handbook of integrated circuit pressure transducers from Sensym.* It contains:

- — General information about IC pressure transducers
- — Up-to-date product information and specifications
- — Descriptions of typical pressure transducer applications.

Integrated circuit pressure transducers are being used in a wide variety of applications. Furthermore, the scope of IC pressure transducer applications is growing rapidly with the availability of low-cost microprocessors and microcomputers for automation and control. We hope that this book provides the necessary insight into understanding and using Sensym's pressure transducers.

For information on devices introduced after the date of this printing, or for more information on listed devices or applications, please contact your Sensym representative or Sensym directly.

This edition supercedes all previous catalogs, specifications, and application notes.

*Formerly the Transducer Group, National Semiconductor Corporation.

European Representative for SenSym

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

WARNING
DO NOT USE IN LIFE SUPPORT

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Sensym Custom Products

In addition to the standard product line, Sensym manufactures a variety of custom products. These custom products all feature IC pressure sensor elements which are signal-conditioned and packaged to meet a variety of applications beyond those served by the standard product line. In regard to using custom products, Sensym will design and develop products to meet a specific application's requirements.

Typical Custom Products

Sensym's custom products range from relatively simple modifications to our standard part, such as different scaling of an output voltage, to a variety of products in different pressure ranges, mechanical housings and electrical specifications. Typical custom products consist of various combinations of the following features:

- Output Scaling
- Tighter Tolerances on Offset and Span
- Special Parametric Selections
- Special Output Features
- Special Pressure Ranges
- Special Mechanical Housings

Custom Product Policies

All custom products require interface with the factory. Development charges, product prices, and lead times can vary significantly and each custom product is evaluated on an individual basis.

All custom products are assigned special part numbers, typically SZ#XXXX. Once this number is established, parts can be ordered through standard distribution channels.

Typically, the following policies will apply for custom products:

- Minimum Order Quantity of 100 Pieces (Non-cancellable)
- Factory Interface Required for Initial Order
- Pricing and Lead Time Established on an Individual Basis

For further information on custom products, please consult your local Sensym representative or the factory directly.

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TRANSDUCER SELECTION GUIDE

MARCH 1983

MONOLITHIC DEVICES

Reference Temperature = 25°C; $V_E = 7.5V_{DC}$; Operating Temperature Range = −40°C to 85°C; Reference Pressure = Minimum Operating Pressure.

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/ps (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis ± % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output mV (Typical)

Absolute Pressure Devices

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/ps (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis ± % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output mV (Typical)
LX0503A	0 to 30 psia	100 psia	0 ± 100	2 to 8	1.0	0.1	2.0	0.5	150
LX0520A	0 to 100 psia	200 psia	0 ± 50	0.2 to 0.8	1.0	0.4	0.67	0.5	50
LX0420A, LX0520AO	0 to 100 psia	200 psia	0 ± 50	0.2 to 0.8	1.0	0.4	0.67	0.5	50
LX0440A, LX0540AO	0 to 1000 psia	2000 psia	0 ± 50	0.1 to 0.3	1.5	0.4	0.07	0.5	200
LX0460A, LX0560AO	0 to 3000 psia	5000 psia	0 ± 50	0.05 to 0.15	2.0	0.4	0.02	0.5	300
LX0470A, LX0570AO	0 to 5000 psia	7000 psia	0 ± 50	0.02 to 0.06	2.0	0.4	0.01	0.5	200

Gage Pressure Devices

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/ps (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis ± % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output mV (Typical)
LX0603GB	0 to +30 psig	45 psig	0 ± 100	2 to 8	1.0	0.5	2.0	0.5	150
LX0620GB	0 to +100 psig	150 psig	0 ± 50	0.2 to 0.8	1.0	0.5	0.67	0.5	50

Differential Pressure Devices

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/ps (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis ± % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output mV (Typical)
LX0603D	0 to ±30 psid	±45 psid	0 ± 100	2 to 8	1.0	0.5	2	0.5	50
LX0620D	0 to ±100 psid	±150 psid	0 ± 50	0.2 to 0.8	2.0	0.5	0.67	0.5	50

TEMPERATURE COMPENSATED MONOLITHIC DEVICES

Reference Supply Voltage = 10.00V; Reference Temperature = 25°C.

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/psi (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output Calibration mV (Typical)

Absolute Pressure Devices

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/psi (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output Calibration mV (Typical)
LX06015A	0 to 15 psia	60 psia	0 ± 2	−6.67	1.0	0.10	2	1.5	−100
LX06L15A	0 to 15 psia	60 psia	0 ± 2	−2.67	0.25	0.10	2	1.5	−40
LX06030A	0 to 30 psia	60 psia	0 ± 2	−2.63	0.50	0.50	2	1.5	−79

Gage Pressure Devices

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/psi (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output Calibration mV (Typical)
LX06001G	0 to ±1 psig	20 psig	0 ± 2	27.7	1.5	0.10	2	1.5	28
LX06002G	0 to ±2 psig	20 psig	0 ± 1	20.0	1.5	0.10	2	1.5	40
LX06005G	0 to ±5 psig	20 psig	0 ± 1	10.0	1.5	0.10	2	1.5	50
LX06015G	0 to ±15 psig	60 psig	0 ± 1	6.67	1.0	0.10	2	1.5	100
LX06L15G	0 to ±15 psig	60 psig	0 ± 1	2.67	0.25	0.10	2	1.5	40
LX06030G	0 to 30 psig	60 psig	0 ± 1	2.63	0.50	0.10	2	1.5	79
LX06100G	0 to 100 psig	200 psig	0 ± 1	1.4	0.50	0.10	2	1.5	140

Differential Pressure Devices

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration mV	Sensitivity mV/psi (Typical)	Linearity (Note 1) ± % FS (Typical)	Repeatability and Hysteresis % FS (Typical)	Offset Shift w/Temperature (0°C to 50°C) ± mV (Typical)	Sensitivity Shift w/Temperature (0°C to 50°C) ± % FS (Typical)	Full-Scale Output Calibration mV (Typical)
LX06001D	±1 psid	20 psid	0 ± 2	27.7	1.5	0.10	2	1.5	28
LX06002D	±2 psid	20 psid	0 ± 2	20.0	1.5	0.10	2	1.5	40
LX06005D	±5 psid	20 psid	0 ± 1	10.0	1.5	0.10	2	1.5	50
LX06015D	±15 psid	60 psid	0 ± 1	6.67	1.0	0.10	2	1.5	100
LX06L15D	±15 psid	60 psid	0 ± 1	2.67	0.25	0.10	2	1.5	40
LX06030D	±30 psid	60 psid	0 ± 1	2.63	0.50	0.10	2	1.5	79

**Manufacturer of
Semiconductor Sensors
and Sensor Based
Systems**

TRANSDUCER SELECTION GUIDE

SIGNAL CONDITIONED DEVICES

Reference Temperature = 25°C; $V_E = 15V_{DC}$; Operating Temperature Range = 0 to 85°C;
Reference Pressure = Minimum Operating Pressure.

Absolute Pressure Devices

		Offset Characteristics					Span Characteristics			
Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration V	Shift w/ Temp. (0°C to 80°C) ±%FS	Repeatability ±%FS	Stability ±%FS	Span Volts	Shift w/ Temp. (0°C to 80°C) ±%FS	Linearity Hysteresis Repeatability ±%FS	Stability ±%FS
LX1420A(E,F,S)	0 to 100 psia	150 psia	2.5 ± 0.25	2.2	0.4	1.2	10 ± 0.20	2.75	0.67	0.3
LX1430(E,F,S)	0 to 300 psia	450 psia	2.5 ± 0.25	1.65	0.4	1.0	10 ± 0.20	2.75	0.67	0.3
LX1440A(E,F,S)	0 to 1000 psia	1500 psia	2.5 ± 0.25	1.65	0.4	1.0	10 ± 0.20	2.75	1.0	0.4
LX1450A(E,F,S)	0 to 2000 psia	3000 psia	2.5 ± 0.25	1.65	0.4	1.0	10 ± 0.20	2.75	1.5	0.4
LX1460A(E,F,S)	0 to 3000 psia	4500	2.5 ± 0.25	1.65	0.4	1.0	10 ± 0.20	2.75	2.0	0.4
LX1470A(E,F,S)	0 to 5000 psia	5000 psia	2.5 ± 0.25	1.65	0.4	1.0	10 ± 0.20	2.75	3.0	0.4
LX1601A LX1801A(N,Z)	10 to 20 psia	100 psia	2.5 ± 0.70	3.3	0.5	5.0	10 ± 0.20	2.75	0.67	1.0
LX1602A LX1802(N,Z)	0 to 15 psia	100 psia	2.5 ± 0.50	2.75	0.4	3.3	10 ± 0.20	2.75	0.67	0.7
LX1603A LX1803A(N,Z)	0 to 30 psia	100 psia	2.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1610A LX1810A(N,Z)	0 to 60 psia	125 psia	2.5 ± 0.30	1.65	0.4	1.5	10 ± 0.20	1.65	0.67	0.3
LX1620A LX1820A(N,Z)	0 to 100 psia	200 psia	2.5 ± 0.30	1.10	0.4	1.2	10 ± 0.20	1.10	0.67	0.3
LX1830A(N,Z)	0 to 300 psia	350 psia	2.5 ± 0.30	1.10	0.4	1.0	10 ± 0.20	1.10	0.67	0.3

Differential Pressure Devices

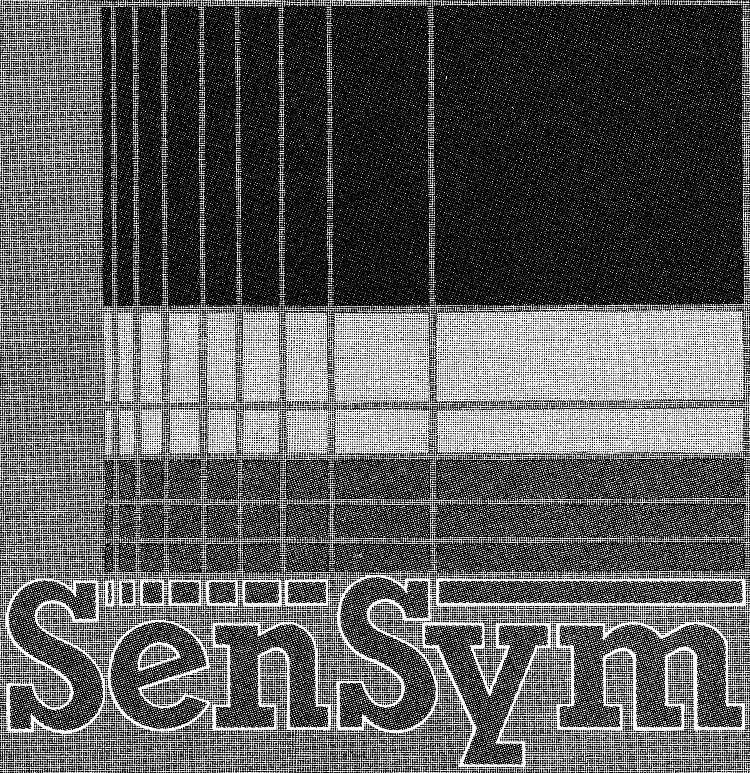
LX1601D LX1801DZ	0 to ± 5 psid	45 psid	7.5 ± 0.70	3.3	0.5	5.0	10 ± 0.20	2.75	0.67	1.0
LX1602D LX1802DZ	0 to 15 psid	45 psid	2.5 ± 0.50	2.75	0.4	3.3	10 ± 0.20	2.75	0.67	0.7
LX1603D LX1803DZ	0 to 30 psid	45 psid	2.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1604D LX1804DZ	0 to ±15 psid	45 psid	7.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1610D LX1810DZ	0 to 60 psid	100 psid	2.5 ± 0.30	1.65	0.4	1.5	10 ± 0.20	1.65	0.67	0.3
LX1620D LX1820DZ	0 to 100 psid	150 psid	2.5 ± 0.30	1.10	0.4	1.2	10 ± 0.20	1.10	0.67	0.3
LX1830DZ	0 to 300 psid	350 psid	2.5 ± 0.30	1.10	0.4	1.0	10 ± 0.20	1.10	0.67	0.3

Gage Pressure Devices

LX1601G LX1801G(N,Z)	0 to ±5 psig	100 psig	7.5 ± 0.70	3.3	0.5	5.0	10 ± 0.20	2.75	0.67	1.0
LX1602G LX1802G(N,Z)	0 to 15 psig	100 psig	2.5 ± 0.50	2.75	0.4	3.3	10 ± 0.20	2.75	0.67	0.7
LX1603G LX1803G(N,Z)	0 to 30 psig	100 psig	2.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1604G LX1804G(N,Z)	0 to ±15 psig	100 psig	7.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1610G LX1810G(N,Z)	0 to 60 psig	125 psig	2.5 ± 0.30	1.65	0.4	1.5	10 ± 0.20	1.65	0.67	0.3
LX1620G LX1820G(N,Z)	0 to 100 psig	200 psig	2.5 ± 0.30	1.10	0.4	1.2	10 ± 0.20	1.10	0.67	0.3
LX1830G(N,Z)	0 to 300 psig	350 psig	2.5 ± 0.30	1.10	0.4	1.0	10 ± 0.20	1.10	0.67	0.3
LX1601GB LX1801GB(N,Z)	0 to ±5 psig	45 psig	7.5 ± 0.70	3.3	0.4	5.0	10 ± 0.20	2.75	0.67	1.0
LX1602GB LX1802GB(N,Z)	0 to 15 psig	45 psig	2.5 ± 0.50	2.75	0.4	3.3	10 ± 0.20	2.75	0.67	0.7
LX1603GB LX1803GB(N,Z)	0 to 30 psig	45 psig	2.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1604GB LX1804GB(N,Z)	0 to ±15 psig	45 psig	7.5 ± 0.35	1.65	0.4	1.7	10 ± 0.20	1.65	0.67	0.3
LX1610GB LX1810GB(N,Z)	0 to 60 psig	100 psig	2.5 ± 0.30	1.65	0.4	1.5	10 ± 0.20	1.65	0.67	0.3
LX1620GB LX1820GB(N,Z)	0 to 100 psig	150 psig	2.5 ± 0.30	1.10	0.4	1.2	10 ± 0.20	1.10	0.67	0.3
LX1830GB(N,Z)	0 to 300 psig	350 psig	2.5 ± 0.30	1.10	0.4	1.0	10 ± 0.20	1.10	0.67	0.3

Section 1

Low- and Mid-Pressure Range Monolithic Pressure Transducers



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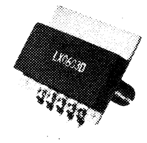


LX05XXA and LX06XX Series Low and Mid-Pressure Range Monolithic Pressure Transducers

General Description

The monolithic pressure transducers are piezoresistive integrated circuits which provide an output voltage proportional to applied pressure. The devices are provided in compact packages with pressure ports, suitable for PC board mounting and attachment of flexible tubing.

The LX05XXA is an absolute pressure transducer with a single pressure inlet tube axially aligned with its TO-5 package, suitable for use with non-ionic working fluids.

The LX06XXGB is a gage transducer with a single tube and an ambient inlet. It is well suited for use with package-compatible working fluids, including water.

The LX06XXD is a differential pressure transducer with two pressure ports, suitable for use with non-ionic working fluids in either pressure port, and package-compatible working fluids in the positive pressure port.

See Application Guide — Media Compatibility

Advantages of Monolithic

The monolithic transducers include only the basic monolithic pressure IC chip used in Sensym's signal-conditioned pressure transducer products. This greatly reduces unit cost and allows the electronic designer greater freedom in implementing transducer circuits. The monolithic transducer is temperature compensated with respect to sensitivity and features low offset temperature coefficient. High sensitivity and low noise allow easy amplification. These devices are especially useful in applications requiring battery power, circuit flexibility, or compatibility with microprocessors.

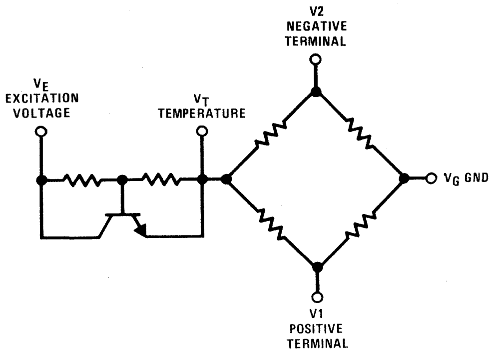
Features

- Low cost
- Interface circuit flexibility
- Temperature compensation of span
- Compact, PC board compatible
- Low noise
- High natural frequency
- Low volumetric displacement
- Separate temperature-sensitive output
- Silguard coating for low-pressure devices and all GB devices is available

Applications

- Automated equipment
- Residential, commercial and industrial controls
- Medical diagnostics
- Automotive diagnostics and controls
- Machine tool controls
- Barometry

Schematic Diagram



Electrical Connections

Symbol	LX05XX	LX06XX
V_E	3	5
V_T	7	1
V1	6	3
V2	5	4
V_G	8	2

Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage, V_E	12V
Operating Temperature Range	−40°C to +105°C
Pressure Range	
LX0503A	100 psia
LX0603D	±45 psid
LX0603GB	45 psig
Common Mode Line Pressure, LX0603D	200 psig
Bridge Voltage, V_T	$\leqslant V_E$
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 1)

Excitation Voltage, V_E	7.5V
Reference Temperature	25°C
Reference Temperature Range	0°C to 50°C
Offset Reference Pressure (Note 5)	
LX0503A	0 psia
LX0603D	0 psid
LX0603GB	0 psig
Common Mode Line Pressure, LX0603D	0 psig

Performance Characteristics

		Guaranteed Specifications			Typical Specifications						
Device Type	Operating Pressure Range	Offset Calibration	Linearity, Hysteresis and Repeatability (Note 2)		Offset Repeatability (Note 3)		Offset Stability (Note 4)		Span Sensitivity Calibration	Span Stability (Note 4)	
		mV	±%FS	±psi	±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX0503A	0 to 30 psia	0 ± 100	1.00	0.3	0.4	0.12	1.7	0.5	2 to 8	0.3	0.09
LX0603D	0 to ±30 psid	0 ± 100	1.00	0.6	0.4	0.24	0.8	0.5	2 to 8	0.3	0.18
LX0603GB	0 to +30 psig	0 ± 100	1.00	0.45	0.4	0.18	1.1	0.5	2 to 8	0.3	0.14

		Typical Characteristics					
Device Type	Operating Pressure Range	Offset Shift w/Temperature (0°C to 50°C) (Note 6)	Sensitivity w/Temperature (0°C to 50°C) (Note 7)	Bias Current	Bridge Resistance	Diaphragm Natural Frequency	Compensation Circuit Temperature Coefficient (Note 8)
		±mV	± %FS	mA	kΩ	kHz	mV/°C
LX0503A	0 to 30 psia	2	0.5	2.0	1.8	50	−10.0
LX0603D	0 to ±30 psid	2	0.5	2.0	1.8	50	−8.0
LX0603GB	0 to +30 psig	2	0.5	2.0	1.8	50	−8.0

Specification Notes:

Note 1: Conditions at which "Performance Characteristics" are specified.

Note 2: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\ \text{FS error} = \frac{V_{\frac{1}{2}\ \text{full scale}} - \left\{\left(\dfrac{(V_{\text{full scale}} - V_{\text{offset}})}{\text{full scale pressure}}\right) \times \left(\tfrac{1}{2}\ \text{full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 3: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 4: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 5: Offset Reference Pressure — the lowest pressure in the operating pressure range.

Note 6: Temperature error is measured into an infinite impediance without offset adjusted.

Note 7: Voltage applied at V_E, with no offset nor sensitivity adjust.

Note 8: Compensation Circuit Temperature Coefficient $\Delta V_{ET}/\Delta T$ — the change in voltage across the compensation circuit, $V_{ET} = V_E - V_T$, as the temperature changes within the permitted operating range.

Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage, V_E	12V
Operating Temperature Range	−40°C to +105°C
Pressure Range	
LX0520A	200 psia
LX0620D	±150 psid
LX0620GB	150 psig
Common Mode Line Pressure, LX0620D	200 psig
Bridge Voltage, V_T	$\leqslant V_E$
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 1)

Excitation Voltage, V_E	7.5V
Reference Temperature	25°C
Reference Temperature Range	0°C to 50°C
Offset Reference Pressure (Note 5)	
LX0520A	0 psia
LX0620D	0 psid
LX0620GB	0 psig
Common Mode Line Pressure, LX0620D	0 psig

Performance Characteristics

Device Type	Operating Pressure Range	Guaranteed Specifications			Typical Specifications						
		Offset Calibration	Linearity, Hysteresis and Repeatability (Note 2)		Offset Repeatability (Note 3)		Offset Stability (Note 4)		Span Sensitivity Calibration	Span Stability (Note 4)	
		mV	±%FS	±psi	±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX0520A	0 to 30 psia	0 ± 50	1.00	1.00	0.4	0.40	1.2	1.2	0.2 to 0.8	0.3	0.30
LX0620D	0 to ±100 psid	0 ± 80	1.00	2.00	0.4	0.80	0.6	1.2	0.2 to 0.8	0.3	0.60
LX0620GB	0 to +100 psig	0 ± 50	1.00	1.15	0.4	0.46	1.0	1.2	0.2 to 0.8	0.3	0.35

Device Type	Operating Pressure Range	Typical Characteristics					
		Offset Shift w/Temperature (0°C to 50°C) (Note 6)	Sensitivity Shift w/Temperature (0°C to 50°C) (Note 7)	Bias Current	Bridge Resistance	Diaphragm Natural Frequency	Compensation Circuit Temperature Coefficient (Note 8)
		±mV	±%FS	mA	kΩ	kHz	mV/°C
LX0520A	0 to 100 psia	0.67	0.5	2.0	1.8	100	−10.0
LX0620D	0 to ±100 psid	0.67	0.5	2.0	1.8	100	−8.0
LX0620GB	0 to +100 psig	0.67	0.5	2.0	1.8	100	−8.0

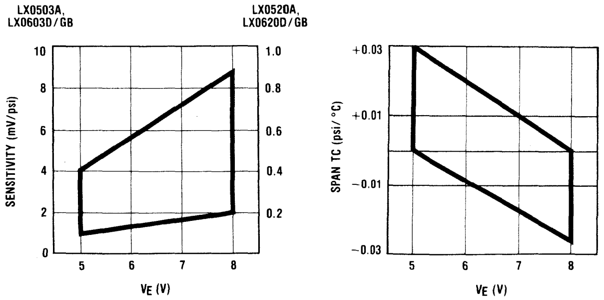


Figure 1. Typical Ranges of Sensitivity and Span TC vs. Applied Voltage V_E for LX05XXA and LX06XXD, GB Pressure Transducers

Application Guide

Accuracy Specifications — Auto-Referencing

Error parameters are specified separately for offset and span. These errors are independent which allows easy computation of error bands, recalibration, and use of auto-referencing, a technique of automatic recalibration. For a detailed discussion of accuracy specifications and auto-referencing, see Section 6.

Using the Handbook

Please consult Sections 6, 7, and 8 of this handbook for comprehensive information on auto-referencing, precautions for installing pressure transducers and applications information. You should keep in mind that the information contained in Sections 5, 6, and 7 use signal-conditioned devices as examples. Hence, in using this information relative to monolithic pressure transducers, which are not fully signal-conditioned, additional circuitry is required for the applications described.

Signal Conditioning

Effective application of the monolithic device will require external circuits to perform signal conditioning. The included Application Hints provide guidance in designing such circuits. The three Example Circuits illustrate designs for low cost, high sensitivity, and digital interface applications.

Media Compatibility — Humidity

The heart of the transducer is a monolithic silicon chip with a cavity etched out to form a diaphragm. The top side of the diaphragm contains the transducer pressure sensing circuitry.

As shown in *Figure 3a*, the LX05XXA has a single pressure inlet that allows the working fluid to make contact with the circuit side of the diaphragm. This area is covered with a thin, compliant materal. This material does not protect against water and other aqueous and ionic fluids. Therefore, these must be kept out of the pressure inlet to avoid electrical failure.

As shown in *Figure 3b*, the LX06XX series transducers have two pressure inlets which differ in susceptibility to moisture and other fluids. The ambient pressure port (or negative pressure port for differential devices) allows the working fluid to make contact with the circuit side of the diaphragm and thus requires the same precautions discussed relative to the LX05XXA above. The working fluid port (or positive pressure port, for differentials) makes contact with the cavity side of the diaphragm, which is insensitive to water and ionic fluids. The main criterion for fluid in this port is package compatibility. That is, the fluid must not be highly corrosive to brass or silicon.

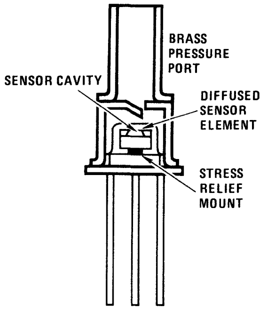


Figure 3a. LX05XXA Pressure Transducer Structure

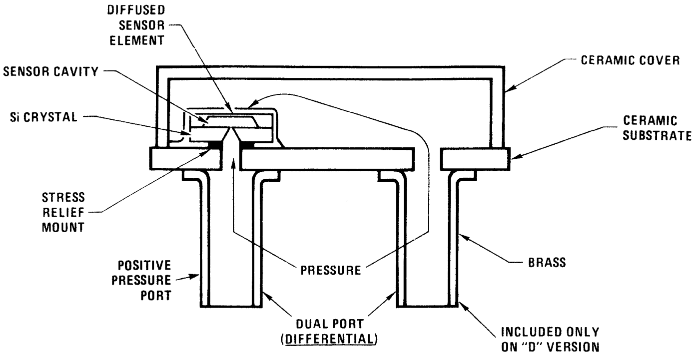


Figure 3b. LX06XX Pressure Transducer Structure

Hence, the LX06XXGB can operate with aqueous working fluids but water must be kept out of the ambient inlet during operation. Similarly, the LX06XXD can operate with aqueous working fluids in the negative pressure port, but must be protected from aqueous fluids in the positive port. Both devices can be adversely affected by very high humidity ambient conditions.

For high humidity environment applications, low pressure devices and all "GB" devices are available with silguard coating. Please consult the "−1" Option Applications Note shown at the end of this section.

Leak Rate

PX5 and PX6 packages are not hermetic. Sensym's pressure transducers are guaranteed to have an effective leak area less than 10^{-7} cm^2 as defined in Section 9. Each transducer is leak tested at room temperature with 45psig compressed air.

However, the user should be aware that the leak rate can depend on the type, viscosity, pressure, and temperature of the working fluid and can increase with fatigue resulting from pressure cycling. This is especially important in static systems where a fluid under pressure is to be maintained for an extended period in an enclosure without replenishment. In such cases, it may be necessary to enclose the LX05XXA in a pressure vessel and bring the leads out via a hermetic feedthrough connector installed in the enclosure wall.

"Dead-Ending" Feature

If the pressure applied to the LX05XXA greatly exceeds *proof pressure* (maximum specified operating pressure), the silicon diaphragm could rupture. But, unlike gage transducers, the absolute devices are "dead-ended" so that diaphragm rupture does not necessarily result in fluid leakage.

Application Hints

Hint 1. Input/Output Polarity

The LX05XXA transducer output signals, pins 6 and 5, are taken directly from a Wheatstone bridge. Pin 6 is the positive signal output. It goes positive when the absolute pressure increases. Pin 5, the negative signal output, goes negative (less positive) when the absolute pressure increases. *Figure 4* shows a bottom view of the TO-5 pinout.

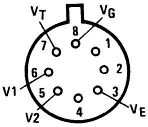


Figure 4. LX05XXA Pinout, Bottom View

The LX06XX series transducer output signals, pins 3 and 4, are taken directly from a Wheatstone bridge. Pin 3 is the positive signal output. It goes positive when pressure is increased at the left-most port as viewed from the bottom of the device (*Figure 5*). Pin 4 is the negative signal output. It goes negative (less positive) when the pressure is increased at the left-most port. The left-most port is the *positive port* for the LX06XXD and the *gage pressure port* for the LX06XXGB.

Hint 2. Bridge Buffering

Interfacing with the piezoresistive Wheatstone bridge is the most critical step in signal conditioning. If designed and fabricated properly, the interface/buffer circuit will provide high gain and minimum interaction of temperature coefficients. This greatly simplifies subsequent signal conditioning and processing.

The bridge has a resistance of approximately 1800Ω at room temperature. Severe bridge loading by external resistors (i.e., low value resistors with temperature coefficients very different from that of the bridge) cause distortion of transducer characteristics and temperature coefficients. The most effective bridge buffering circuits use very high impedance, well-matched, carefully installed resistors. High quality instrumentation amplifiers can also be used (see Example Circuits, *Figure 7*).

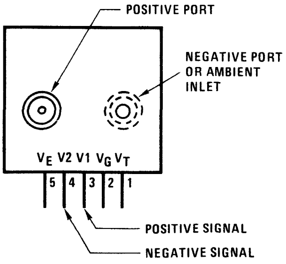


Figure 5. LX06XX Pinout, Portside View

Hint 3. Calibration and Scaling

The principal problem encountered in calibration and scaling of a transducer is the interaction of offset (common-mode) and span (normal-mode) parameters and their temperature coefficients. Since most signal conditioning circuits have this problem, it is important to make span-offset independence a prime criterion. The rewards are easy calibration, simple scaling, and a natural interface with auto-referencing. (See Section 6.) The simplest technique for effective reduction of span-offset interaction requires the use of two amplifier stages. Step-by-step procedure is given in the individual circuit discussions.

Hint 4. Temperature Compensation

The span temperature compensation circuit built into the monolithic device is adequate for most users. It requires V_E to be regulated at 7.5V and repeatable with temperature. As shown in *Figure 1,* improved span temperature compensation can be achieved simply by tailoring V_E to the specific device. To select the best excitation voltage, vary temperature slowly while switching pressure between high and low operating levels. Vary V_E until the difference in output at high and low pressure (span voltage) remains constant with temperature.

For improved offset temperature compensation, a signal conditioning circuit can be used. To adjust the temperature compensation circuit, vary the temperature slowly while trimming the appropriate resistor to minimize the output voltage rate of change. The method requiring the lowest parts count uses a low temperature coefficient, high value resistor (see *Figure 6,* R5). A more effective method is to use the temperature sensitive output, V_T, to feed a compensating signal to the summing junction of the output stage (see *Figure 7,* R6). With either of these methods, auto-referencing can provide further improvement.

Hint 5. Uses of V_T Pin

As discussed in Hint 4, V_T can be used for offset temperature compensation if the voltage applied to V_E is well regulated and repeatable with temperature. It can also be characterized as a temperature sensor, if desired. In either case, the V_T pin cannot be allowed to source or sink more than 25μA in this circuit configuration. The preferred method of buffering is shown in the High Sensitivity Circuit.

For applications that do not require span temperature compensation, such as those having a limited temperature range within their duty cycles, the excitation voltage can be applied to pin V_T instead of to V_E. This bypasses the internal span temperature coefficient compensation circuit and provides the following potential advantages:

1. Sensitivity is greater with the same excitation voltage applied directly to the bridge.
2. Applied voltage can be other than 7.5V. For example, 5V can be used for compatibility with logic systems.
3. The bridge is inherently ratiometric in the absence of the span temperature compensation circuit (see Hint 6).

These advantages can be realized along with span temperature compensation if a temperature sensitive supply (1500 ppm/°C to 2000 ppm/°C) is applied to V_T.

IMPORTANT: V_T must never be more positive than V_E. To prevent this when applying excitation to V_T, connect V_T to V_E.

Hint 6. Supply Voltage Sensitivity — Regulation

As illustrated in *Figure 1,* the change in sensitivity of the transducer with supply voltage is governed by the equation:

$$S_p \cong k(V_E - V_{ET})$$

where S_p is the sensitivity in mV/psi, V_E is applied voltage, k is a device dependent constant relating sensitivity to the supply voltage in mV/psi/V, and voltage, V_{ET}, is a constant of the temperature compensation circuit, nominally 3V for the LX06XX and 4V for the LX05XX devices.

To determine k for a device, set V_E to some nominal value, say 7.5V. Measure S_p and V_{ET}. If S_p is found to be 4.5 mV/psi and V_{ET} is 3V, for example, then $k = 1$ mV/psi/V.

True ratiometricity ($S_p = k V_E$) is realized at the expense of internal temperature compensation by applying excitation voltage to V_T instead of V_E as discussed in Hint 5.

Hint 7. Noise Suppression — Mech/Elec

Noise in a pressure transducer arises from both mechanical and electrical sources. Careful attention to both is required to ensure high accuracy and trouble-free performance.

The most prevalent source of common-mode noise is the input pressure line. The monolithic pressure transducer will accurately sense all mechanical and thermomechanical effects, including those in the acoustic domain. Where acoustics are parasitic, snubbing (i.e., constricting the input pressure orifice to slow the signal) is recommended. Hydro-thermal effects can be minimized by understanding and avoiding creation of a "hot-bulb thermometer" in the plumbing.

Electrical noise can also be minimized by certain standard practices. These include: keeping resistor leads to summing junctions short; using low noise amplifiers (such as the LH0044); and decoupling the supply by capacitive bypass. With the monolithic transducer, it is also possible to decouple V_T to ground and filter the first amplifier stage. A low noise regulator (such as the LM329) should also be used in the supply circuit.

WARNING

When soldering or cleaning transducers, the pressure inlet ports (including the ambient port) must be protected from harmful contaminants, such as flux and acidic fumes.

Example Circuits

All Example Circuits accommodate independent span and offset adjustability, and allow the use of auto-referencing and the preceding application hints.

Low Cost Circuit—*Figure 6*

Dual supply, zener reference, and two-stage amplification provide a temperature compensated zero-based output characteristic.

Step No. 1—Offset Temperature Compensation: Monitor the output while slowly varying temperature. Select R5 value and connection to minimize the change in output with a change in temperature.

Step No. 2—Offset Adjust: Monitor the output. Select R6 value and connection to achieve 0V output.

Step No. 3—Span Adjust: Monitor output while applying full-scale pressure. Select R10 value to achieve desired full-scale voltage.

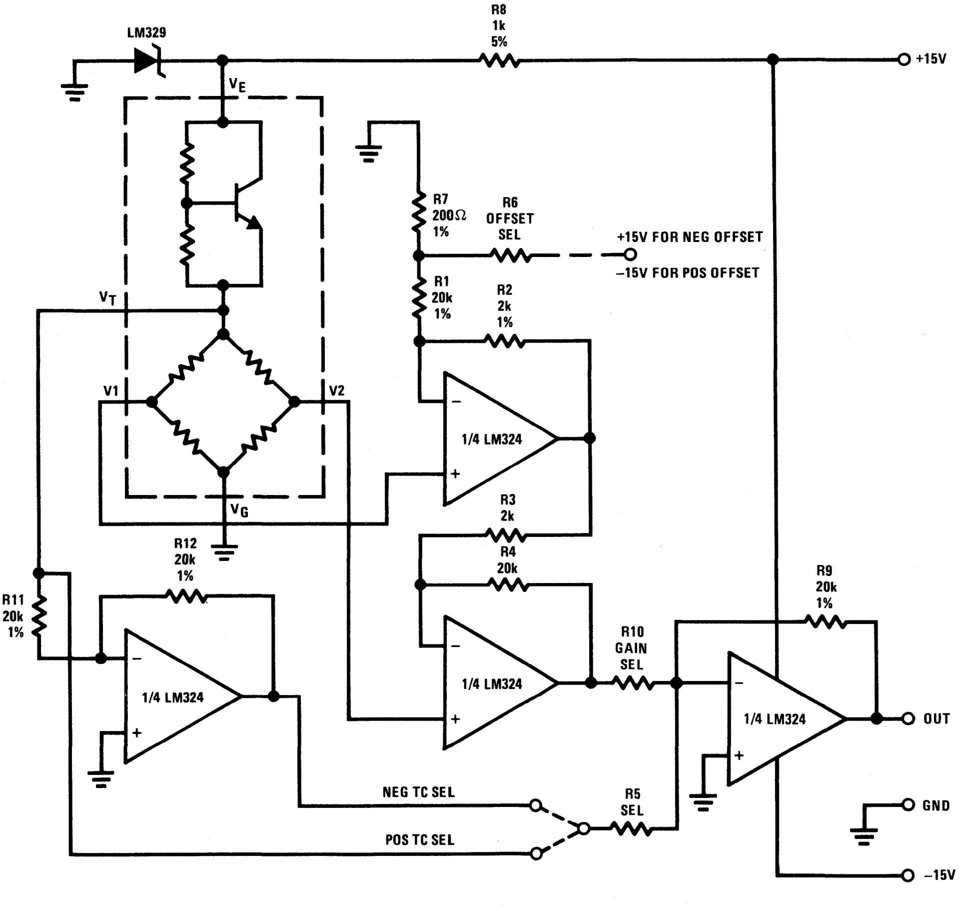


Figure 6. Low Cost/Zero Based

Example Circuits (Continued)

High Sensitivity Circuit—*Figure 7*

This circuit has dual supply, buffered zener reference, low noise first stage amplification, isolated offset temperature coefficient compensation, two-stage amplification, and provides a fully temperature compensated, high sensitivity, zero-based output characteristic.

Step No. 1—Span Temperature Compensation: Vary temperature slowly while switching input pressure between high and low operating levels. Vary R1. When the difference in output voltage at high and low pressures remains constant with temperature, R1 is optimum.

Step No. 2—Initial Offset Adjust: Monitor the voltage at point D, the first stage amplifier output. Select R12 value and connection to achieve 0V at point D.

Step No. 3—Second Offset Adjust: Monitor the voltage at point E. Select R7 value to achieve 0V at point E.

Step No. 4—Span Adjust: Monitor the output while applying full-scale pressure. Select R16 value to achieve desired full-scale voltage.

Step No. 5—Offset Temperature Compensation: Monitor the output while slowly varying temperature. Select the value and connection of R6 to minimize change in output with change in temperature. Alternatively, the value of R6 can be chosen analytically. Measure the change in output voltage (ΔV) resulting from a known change in temperature (ΔT). The compensation resistor value can then be chosen in accordance with the equation: $R6 \cong 1600\ \Delta T/\Delta V$; where R6 is in ohms, ΔT is in degrees Centigrade, and ΔV is in volts.

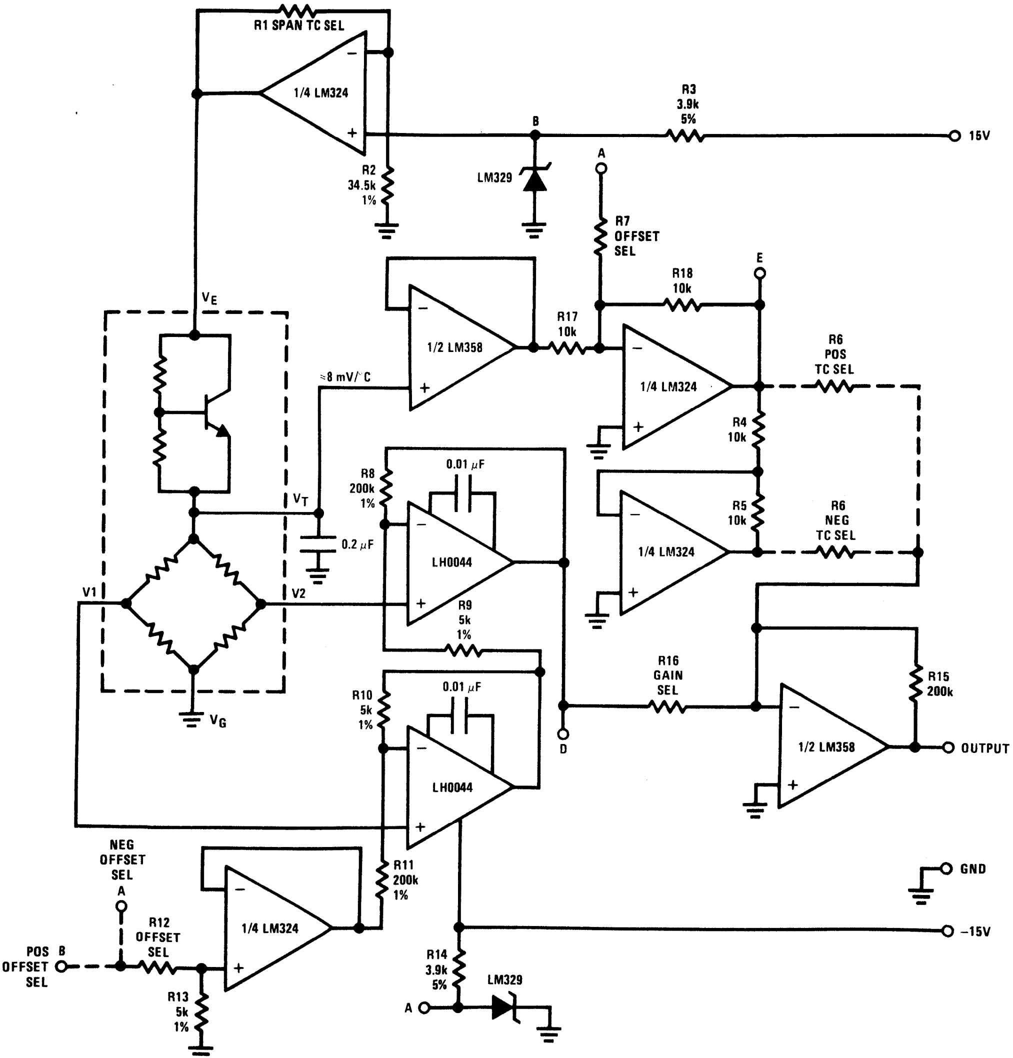


Figure 7. High Sensitivity Circuit

Example Circuits (Continued)

FM Output Circuit—*Figure 8*

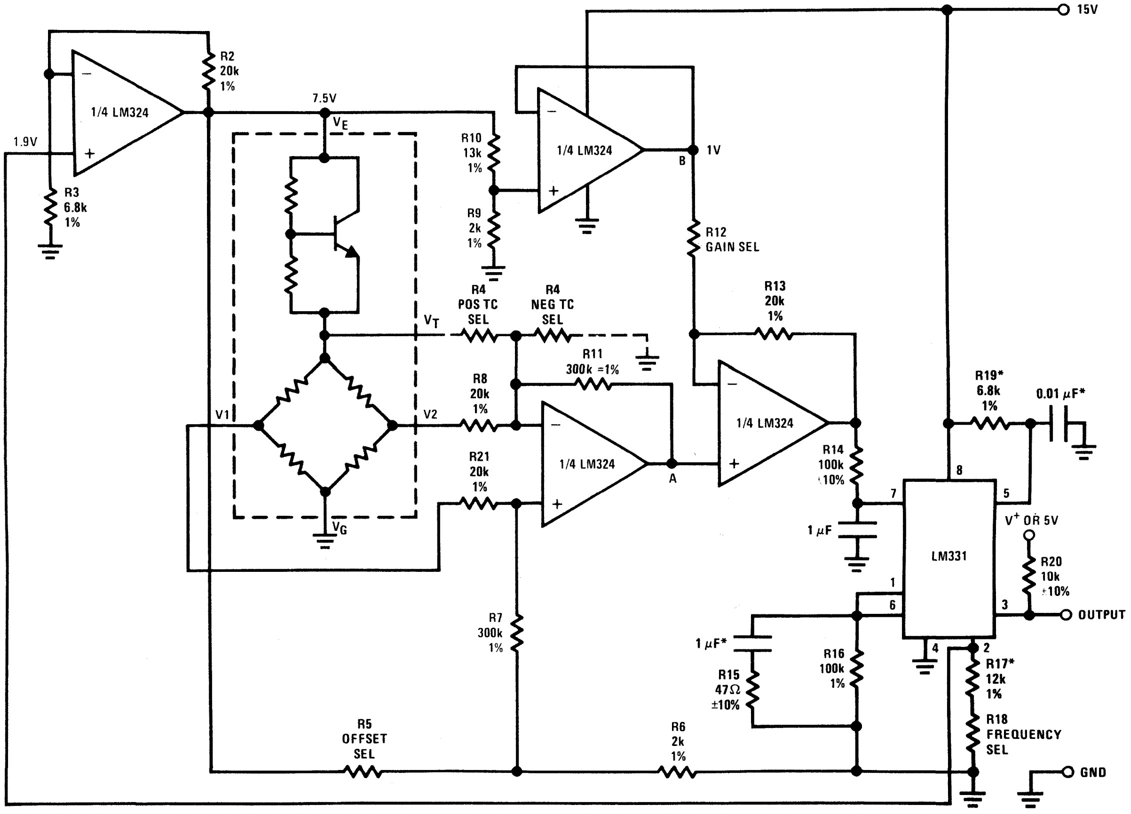
A single supply, zener reference, two-stage amplification, and voltage to frequency converter provide a frequency output compatible with analog-to-digital converter or microprocessor input.

Step No. 1—Offset Temperature Compensation: Monitor point A while slowly varying temperature. Select R4 value and connection to minimize change in temperature.

Step No. 2—DC Offset Adjust: Monitor point A and point B. Select R5 value to achieve zero difference voltage between points A and B.

Step No. 3—Frequency Offset Adjust: Monitor frequency output. Select R18 value to achieve desired frequency offset (1 kHz for circuit values shown).

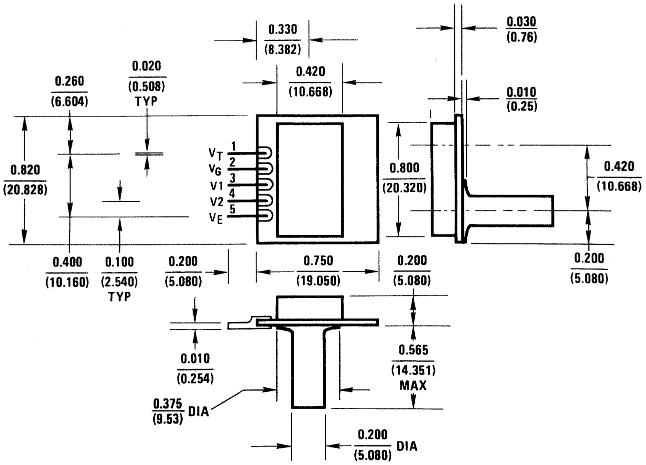
Step No. 4—Frequency Span Adjust: Monitor frequency output while applying full-scale pressure. Select R12 value to achieve desired full-scale frequency (maximum output frequency is 10 kHz for circuit values shown, see LM331 data sheet).



* Use stable components with low TC. See LM331 data sheet.

Figure 8. Frequency Output

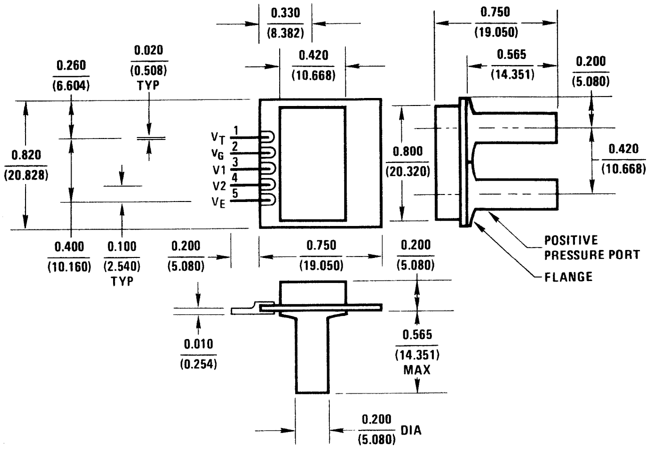
Typical Physical Dimensions inches (millimeters)



PX6B

Package for LX06XXGB Series Pressure Transducers

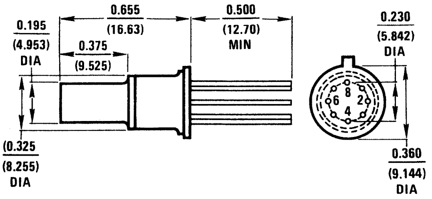
Weight: 5 grams



PX6D

Package for LX06XXD Series Pressure Transducers

Weight: 5 grams



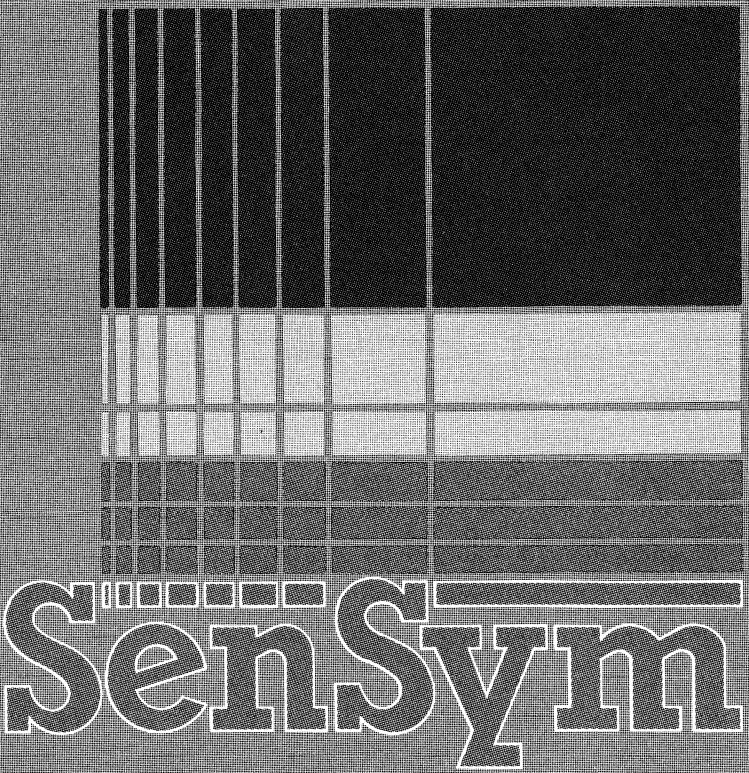
PX5A

Package for LX05XXA Series Absolute Pressure Transducers

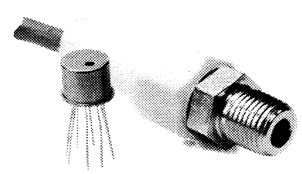
Weight: 1.5 grams

Section 2

Mid- and High-Pressure Range Monolithic Absolute Pressure Transducers



SenSym



LX04XXA, LX04XXAB, and LX05XXAO Series Mid- and High-Pressure Range Monolithic Absolute Pressure Transducers

General Description

The monolithic pressure transducers are piezoresistive integrated circuits which provide an output voltage proportional to applied pressure. They are designed for very high cycle life and have thus been termed the "ABUSABLES". They are provided in two different package types.

The LX04XXA is a ruggedly packaged device, featuring the compact concentric stainless steel housing; LX04XXAB is available in a similar brass housing. It is easily installed with a crescent wrench and has 10-inch flying leads for easy soldering and secure electrical connection. The leads are epoxy-sealed to provide protection against hostile exterior environments. The device is suitable for use with non-ionic and non-corrosive working fluids.

The LX05XXAO is a gold plated, Kovar TO-5 header (PX5AO), with a nickel cap. It is suitable for PC board mounting. The pressure port is located in the top of the cap. The device is suitable for use with non-ionic and non-corrosive working fluids.

Advantages of Monolithic

The monolithic transducers include only the basic monolithic pressure IC chip used in Sensym's signal-conditioned pressure transducer products. This greatly reduces unit cost and allows the electronic designer greater freedom in implementing transducer circuits. The monolithic transducer is temperature compensated with respect to sensitivity and features low offset temperature coefficient. High sensitivity and low noise allow easy amplification. These devices are especially useful in applications requiring battery power, circuit flexibility, or compatibility with microprocessors. The units are designed to provide high accuracy and excellent stability.

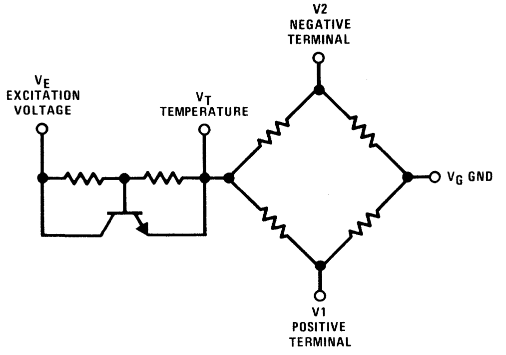
Features

- Very high cycle life
- Low cost
- Interface circuit flexibility
- Temperature compensation of sensitivity
- Compact, PC board compatible or rugged concentric housing with flying leads
- Low noise
- High natural frequency
- Low volumetric displacement
- Separate temperature-sensitive output
- High accuracy and stability
- Available through local stocking distributors

Applications

- Engine diagnostics
- Machine tools
- Hydraulics
- Off-road vehicles
- Pneumatics
- Pressurized tanks and lines
- Deep well pumps
- Oceanography
- Welding machines

Schematic Diagram



Electrical Connections

Symbol	LX04XXA Lead Color	LX05XXAO Pin No.
V_E	Red	3
V_T	Brown	7
V1	Green	6
V2	White	5
V_G	Black	8

Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage, V_E	12V
Operating Temperature Range	
LX04XXA	−40°C to +85°C
LX05XXAO	−40°C to +105°C
Pressure Range	
LX0420A, LX0520AO	200psia
LX0440A, LX0540AO	2000psia
LX0460A, LX0560AO	5000psia
LX0470A, LX0570AO	7000psia
Bridge Voltage, V_T	$\leqslant V_E$
Lead Temperature (Soldering, 10 seconds)	
LX05XXAO	260°C

Reference Conditions (Note 1)

Excitation Voltage, V_E	7.5V
Reference Temperature	25°C
Reference Temperature Range	−0°C to 50°C
Offset Reference Pressure (Note 5)	0psia
Typical Full Pressure Cycle Life	>1 million cycles

Performance Characteristics

Device Type	Operating Pressure Range	Guaranteed Specifications			Typical Specifications						
		Offset Calibration	Linearity, Hysteresis and Repeatability (Note 2)		Offset Repeatability (Note 3)		Offset Stability (Note 4)		Span Sensitivity Calibration	Span Stability (Note 4)	
		mV	±%FS	±psi	±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX0420A(B), LX0520AO	0 to 100 psia	0 ± 50	1.0	1.0	0.4	0.4	1.2	1.2	0.2 to 0.8	0.3	0.3
LX0440A(B), LX0540AO	0 to 1000 psia	0 ± 50	1.5	15	0.4	4	1.2	12	0.1 to 0.3	0.3	3
LX0460A(B), LX0560AO	0 to 3000psia	0 ± 50	2.0	60	0.4	12	1.2	36	0.05 to 0.15	0.3	9
LX0470A(B), LX0570AO	0 to 5000psia	0 ± 50	2.0	75	0.4	15	1.2	40	0.02 to 0.06	0.3	12

Device Type	Typical Characteristics					
	Offset Shift w/Temperature (0°C to 50°C) (Note 6)	Sensitivity Shift w/Temperature (0°C to 50°C) (Note 7)	Bias Current	Bridge Resistance	Diaphragm Natural Frequency	Compensation Circuit Temperature Coefficient (Note 8)
	±mV	±%FS	mA	kΩ	kHz	mV/°C
LX0420A(B), LX0520AO	0.67	0.5	2.0	1.8	100	−10
LX0440A(B), LX0540AO	0.07	0.5	2.0	1.8	300	−10
LX0460A(B), LX0570AO	0.02	0.5	2.0	1.8	500	−10
LX0470A(B), LX0570AO	0.01	0.5	2.0	1.8	500	−10

Specification Notes:

Note 1: Conditions at which "Performance Characteristics" are specified.

Note 2: Linearity—the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\text{ FS error} = \frac{V_{\frac{1}{2}\text{ full scale}} - \left\{\left(\frac{(V_{\text{full scale}} - V_{\text{offset}})}{\text{full scale pressure}}\right)\times\left(\tfrac{1}{2}\text{ full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 3: Offset Repeatability—the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 4: Stability—the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 5: Offset Reference Pressure—the lowest pressure in the operating pressure range.

Note 6: Temperature error is measured into an infinite impediance without offset adjusted.

Note 7: Voltage applied at V_E, with no offset nor sensitivity adjust.

Note 8: Compensation Circuit Temperature Coefficient $\Delta V_{ET}/\Delta T$—the change in voltage across the compensation circuit, $V_{ET} = V_E - V_T$, as the temperature changes within the permitted operating range.

Typical Characteristics

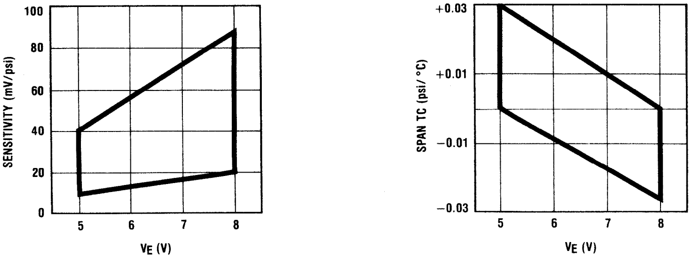


Figure 1. Typical Ranges of Sensitivity and Span TC vs. Applied Voltage V_E for LX04XXA(B) and LX05XXAO Pressure Transducers

Application Guide

Many applications require special consideration of device characteristics. The following application hints are supplementary to Section 7 of this handbook. In consulting this handbook relative to monolithic pressure transducers, it is important to note that monolithic devices are not fully signal-conditioned and require additional circuitry for the applications described.

Effective application of the monolithic device will require external circuits to perform signal conditioning. The included Application Hints provide guidance in designing such circuits. The three Example Circuits illustrate designs for low cost, high sensitivity, and digital interface applications.

1. Accuracy Specifications — Auto-Referencing

Error parameters are specified separately for offset and span. These errors are independent, which allows easy computation of error bands, recalibration, and use of auto-referencing, a technique of automatic recalibration. For a detailed discussion of accuracy specifications and auto-referencing, see Section 6.

2. Use of Absolute as Gage — Altitude Effect

The LX04XXA, LX04XXAB, and LX05XXAO devices are *absolute* pressure transducers with a vacuum enclosed in the silicon chip for reference. The measured pressure is therefore equal to gage pressure plus the local barometric pressure. This appears as an offset in output signal and can vary from 15 psia near sea level to about 10 psia at 10,000 ft. altitude. The local variations in barometric pressure (≤0.5 psia) are normally insignificant, even for the 100 psia device (the LX0420A(B) or LX0520AO); but a change from sea level to 1000 ft. would reduce the apparent gage pressure by 5 psi. If not "zeroed out," this variation could appear as a significant gage error for the LX0420A(B) or LX0520AO transducers. To measure gage pressure in these ranges, other Sensym transducers such as the LX0620GB, may be used. However, in going to transducers with high pressure ranges, the barometric offset and variations become less significant, which allows these devices, LX0440A(B) or LX0540AO, LX0460A(B) or LX0560AO and LX0470A(B) or LX0570AO to be easily used as "pseudo" gage transducers.

Application Guide (Continued)

3. "Dead-Ending" Feature

If the pressure applied to the transducer greatly exceeds proof pressure (maximum specified operating pressure), the silicon diaphragm could rupture. But, unlike gage transducers, the LX04XXA(B) and LX05XXAO devices are "dead-ended" so that diaphragm rupture does not influence fluid leakage. However, excessive overpressure can cause deformation of the inner seal which would allow a slow lead of working fluid through the body of the transducer (see *Figure 2*).

4. Leak Rate — Static Systems

The PX4A(B) and PX5AO series packages are not hermetic. Sensym's pressure transducers are guaranteed to have an effective leak area less than 10^{-7}cm^2 as defined in Section 9. Each transducer is leak tested at room temperature with 100 psig compressed air.

However, the user should be aware that the leak rate can depend on the type, viscosity, pressure, and the temperature of the working fluid and can increase with fatigue resulting from pressure cycling. This is especially important in static systems where a fluid under pressure is to be maintained for an extended period in an enclosure without replenishment. In such cases, it may be necessary to enclose the transducer in a pressure vessel and bring the leads out via a hermetic feedthrough connector installed in the enclosure wall.

5. Pressure Spikes — Importance of Snubbing

In many cyclic pressure systems, large pressure spikes can occur as a result of pumping action, valve closure, or mechanical resonance. Such spikes can damage the transducer as well as other components in the pressure system. In addition to limiting valve closure rate and avoiding undesirable mechanical resonance, it is good design practice to protect critical components, including the transducer, with adequate snubbing or other damping methods. This can greatly improve reliability by reducing fatigue and avoiding catastrophic failure of the transducer.

6. Fast Response — Measuring Transients

The snubbing problem is also complicated by the fact that older, mechanical-type transducers and manometers do not have fast enough response to measure the magnitude of pressure spikes; hence the spikes could go undetected. The LX04XXA(B) and LX05XXAO series can accurately measure and characterize sub-millisecond pressure transients, if system plumbing does not limit the response time (as is the case in most systems). This fast response capability can be used in measuring and evaluating pressure transients as well as for closed-loop operation in fast pneumatic and hydraulic systems.

7. Media Compatibility — Humidity

Since the basic integrated circuit pressure transducer element is coated with a thin, compliant material, the LX04XXA(B) and LX05XXAO series are compatible with many non-aqueous fuels, oils, refrigerants, hydraulic fluids, and non-corrosive gases. But moisture condensate or other ionic, acidic, or corrosive fluids can cause erroneous readings followed by electrical failure. (Contact factory with media compatibility questions.)

8. Submersibility

Although the LX04XXA(B) housing is not fully "hermetic," it is externally submersible as long as ambient pressure doesn't significantly exceed working fluid pressure. For example, it can be used in equipment that must be steam cleaned, or mounted out-of-doors in rain or snow, as long as the working fluid port is properly sealed.

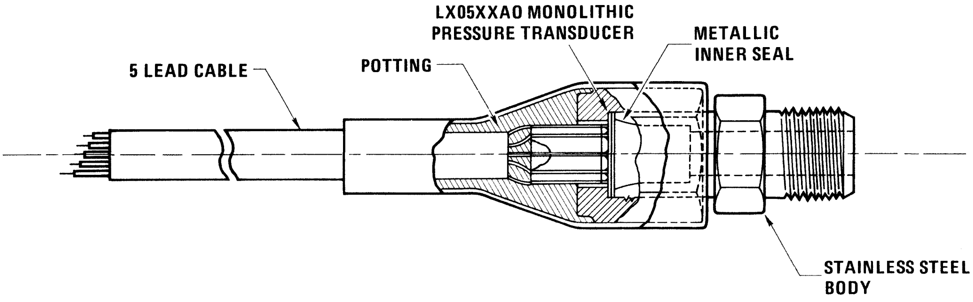


Figure 2. LX04XXA Series Transducer Structure

Application Hints

Hint 1. Input/Output Polarity

The LX04XXA(B) and LX05XXAO transducer output signals are taken directly from a Wheatstone bridge. The green lead (LX04XXA(B)) or pin 6 (LX05XXAO) is the positive signal output. It goes positive when the absolute pressure increases. The white lead or pin 5, the negative signal output, goes negative (less positive) when the absolute pressure increases. *Figure 3* shows a bottom view of the TO-5 (LX05XXAO) pinout.

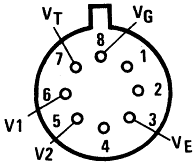


Figure 3. LX05XXAO Pinout, Bottom View

Hint 2. Bridge Buffering

Interfacing with the piezoresistive Wheatstone bridge is the most critical step in signal conditioning. If designed and fabricated properly, the interface/buffer circuit will provide high gain and minimum interaction of temperature coefficients. This greatly simplifies subsequent signal conditioning and processing.

The bridge has a resistance of approximately 1800Ω at room temperature. Severe bridge loading by external resistors (i.e., low value resistors with temperature coefficients very different from that of the bridge) cause distortion of transducer characteristics and temperature coefficients. The most effective bridge buffering circuits use very high impedance, well-matched, carefully installed resistors. High quality instrumentation amplifiers can also be used (see *Figure 5*).

Hint 3. Calibration and Scaling

The principle problem encountered in calibration and scaling of a transducer is the interaction of offset (common-mode) and span (normal-mode) parameters and their temperature coefficients. Since most signal conditioning circuits have this problem, it is important to make span-offset independence a prime criterion. The rewards are easy calibration, simple scaling, and a natural interface with auto-referencing. (See Section 6 for auto-reference discussions.) The simplest technique for effective reduction of span-offset interaction requires the use of two amplifier stages. Step-by-step procedure is given in the individual circuit discussions.

Hint 4. Temperature Compensation

The span temperature compensation circuit built into the monolithic device is adequate for most users. It requires V_E to be regulated at 7.5V and repeatable with temperature. As shown in *Figure 1*, improved span temperature compensation can be achieved simply by tailoring V_E to the specific device. To select the best excitation voltage, vary temperature slowly while switching pressure between high and low operating levels. Vary V_E until the difference in output at high and low pressures (span voltage) remains constant with temperature.

For improved offset temperature compensation, a signal conditioning circuit can be used. To adjust the temperature compensation circuit, vary the temperature slowly while trimming the appropriate resistor to minimize the output voltage rate of change. The method requiring the lowest parts count uses a low temperature coefficient, high value resistor (see *Figure 4*, R5). A more effective method is to use the temperature sensitive output, V_T, to feed a compensating signal to the summing junction of the output stage (see *Figure 5*, R6). With either of these methods, auto-referencing can provide further improvement.

Hint 5. Uses of V_T Pin

As discussed in Hint 4, V_T can be used for offset temperature compensation if the voltage applied to V_E is well regulated and repeatable with temperature. It can also be characterized as a temperature sensor, if desired. In either case, the V_T pin cannot be allowed to source or sink more than 25 μA in this circuit configuration. The preferred method of buffering is shown in the High Sensitivity Circuit.

For applications that do not require span temperature compensation, such as those having a limited temperature range within their duty cycles, the excitation voltage can be applied to pin V_T instead of to V_E. This bypasses the internal span temperature coefficient compensation circuit and provides the following potential advantages:

1. Sensitivity is greater with the same excitation voltage applied directly to the bridge.
2. Applied voltage can be other than 7.5V. For example, 5V can be used for compatibility with logic systems.
3. The bridge is inherently ratiometric in the absence of the span temperature compensation circuit (see Hint 6).

These advantages can be realized along with span temperature compensation if a temperature sensitive supply (1500 ppm/°C to 2000 ppm/°C) is applied to V_T.

IMPORTANT: V_T must never be more positive than V_E. To prevent this when applying excitation to V_T, connect V_T to V_E.

Hint 6. Supply Voltage Sensitivity — Regulation

As illustrated in *Figure 1*, the change in sensitivity of the transducer with supply voltage is governed by the equation:

$$S_p \cong k(V_E - V_{ET})$$

where S_p is the sensitivity in mV/psi, V_E is applied voltage, k is a device dependent constant relating sensitivity to the supply voltage in mV/psi/V, and the voltage, V_{ET}, is a constant of the temperature compensation circuit, nominally 4V.

To determine k for a device, set V_E to some nominal value, say 7.5V. Measure S_p and V_{ET}. If S_p is found to be 3.5 mV/psi and V_{ET} is 4V, for example, then $k = 1$ mV/psi/V.

True ratiometricity ($S_p = k\,V_E$) is realized at the expense of internal temperature compensation by applying excitation voltage to V_T instead of V_E as discussed in Hint 5.

Hint 7. Noise Suppression — Mechanical/Electrical

Noise in a pressure transducer arises from both mechanical and electrical sources. Careful attention to both is required to ensure high accuracy and trouble-free performance.

Application Hints (Continued)

The most prevalent source of common-mode noise is the input pressure line. The monolithic pressure transducer will accurately sense all mechanical and thermomechanical effects, including those in the acoustic domain. Where acoustics are parasitic, snubbing (i.e., constricting the input pressure orifice to slow the signal) is recommended. Hydro-thermal effects can be minimized by understanding and avoiding creation of a "hot-bulb thermometer" in the plumbing (see Sections 7 and 8).

Electrical noise can also be minimized by certain standard practices. These include: keeping resistor leads to summing junctions short; using low noise amplifiers (such as the LH0044); and decoupling the supply by capacitive bypass. With the monolithic transducer, it is also possible to decouple V_T to ground and filter the first amplifier stage. A low noise regulator (such as the NSC LM329) should also be used in the supply circuit.

WARNING

When soldering or cleaning transducers, the pressure inlet ports (including the ambient port) must be protected from harmful contaminants, such as flux and acidic fumes.

Example Circuits

All Example Circuits accommodate independent span and offset adjustability, and allow the use of auto-referencing and the preceding application hints.

Low Cost Circuit—*Figure 4*

Dual supply, zener reference, and two-stage amplification provide a temperature compensated zero-based output characteristic.

Step No. 1 — Offset Temperature Compensation: Monitor the output while slowly varying temperature. Select R5 value and connection to minimize the change in output with a change in temperature.

Step No. 2 — Offset Adjust: Monitor the output. Select R6 value and connection to achieve 0V output.

Step No. 3 — Span Adjust: Monitor output while applying full-scale pressure. Select R10 value to achieve desired full-scale voltage.

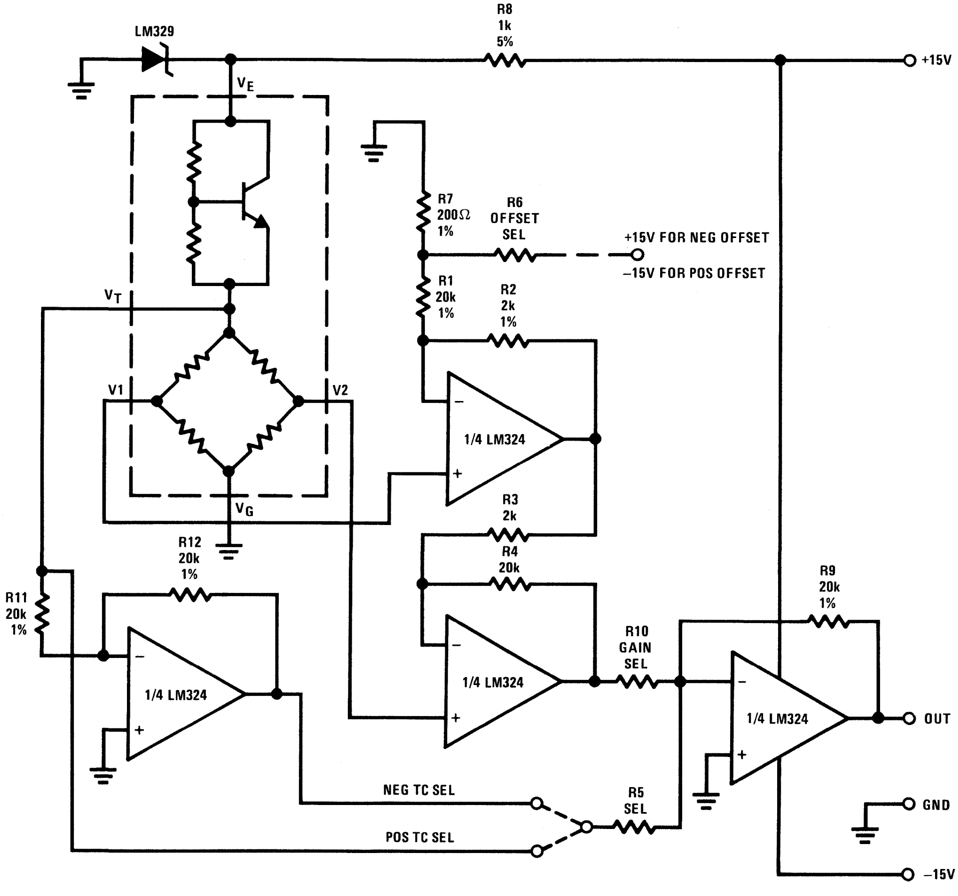


Figure 4. Low Cost/Zero Based

Example Circuits (Continued)

High Sensitivity Circuit—*Figure 5*

This circuit has a dual supply, buffered zener reference, low noise first stage amplification, isolated offset temperature coefficient compensation, two-stage amplification, and provides a fully temperature compensated, high sensitivity, zero-based output characteristic.

Step No. 1 — Span Temperature Compensation: Vary temperature slowly while switching input pressure between high and low operating levels. Vary R1. When the difference in output voltage at high and low pressures remains constant with temperature, R1 is optimum.

Step No. 2 — Initial Offset Adjust: Monitor the voltage at point D, the first stage amplifier output. Select R12 value and connection to achieve 0V at point D.

Step No. 3 — Second Offset Adjust: Monitor the voltage at point E. Select R7 value to achieve 0V at point E.

Step No. 4 — Span Adjust: Monitor the output while applying full-scale pressure. Select R16 value to achieve desired full-scale voltage.

Step No. 5 — Offset Temperature Compensation: Monitor the output while slowly varying temperature. Select the value and connection of R6 to minimize change in output with change in temperature. Alternatively, the value of R6 can be chosen analytically. Measure the change in output voltage (ΔV) resulting from a known change in temperature (ΔT). The compensation resistor value can then be chosen in accordance with the equation: $R6 \cong 1600\ \Delta T/\Delta V$; where R6 is in ohms, ΔT is in degrees Centigrade, and ΔV is in volts.

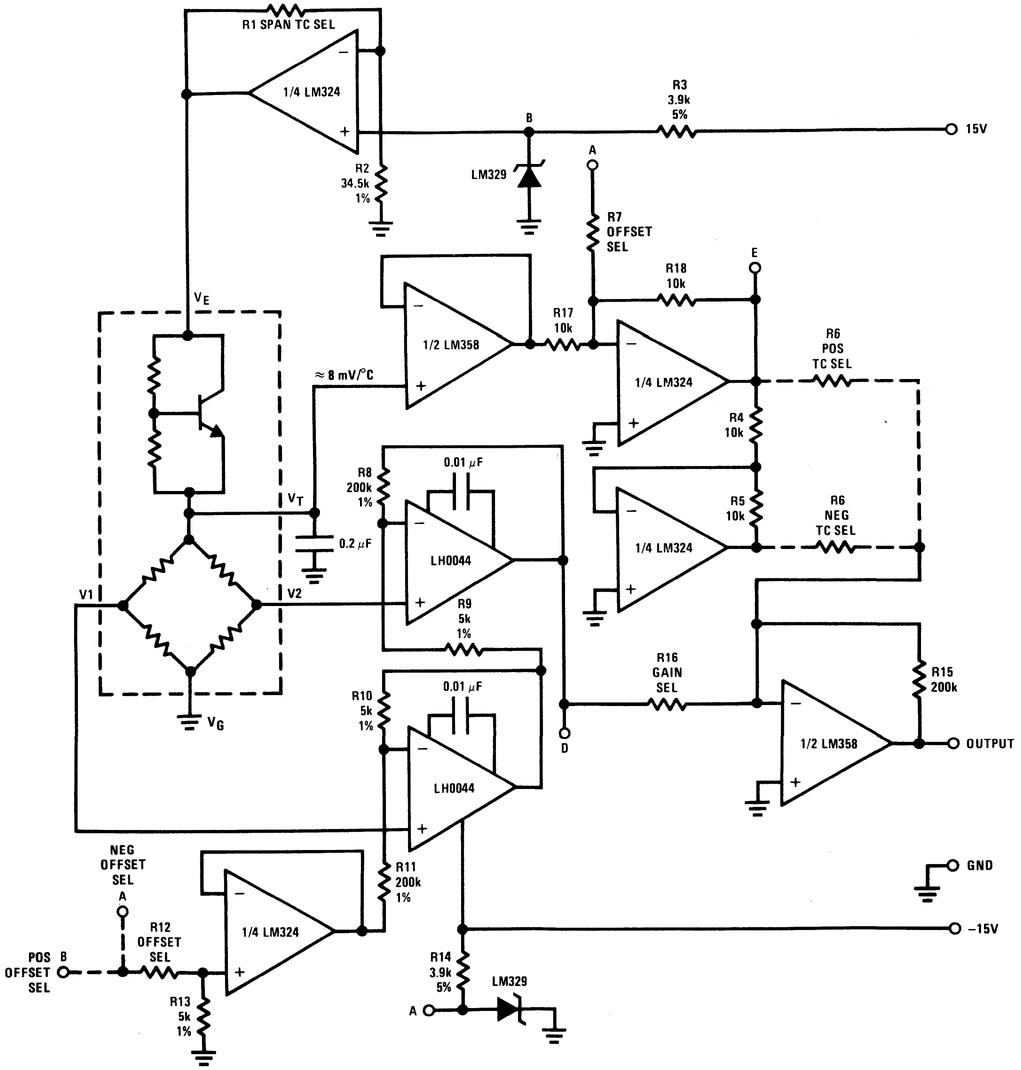


Figure 5. High Sensitivity Circuit

Example Circuits (Continued)

FM Output Circuit—*Figure 6*

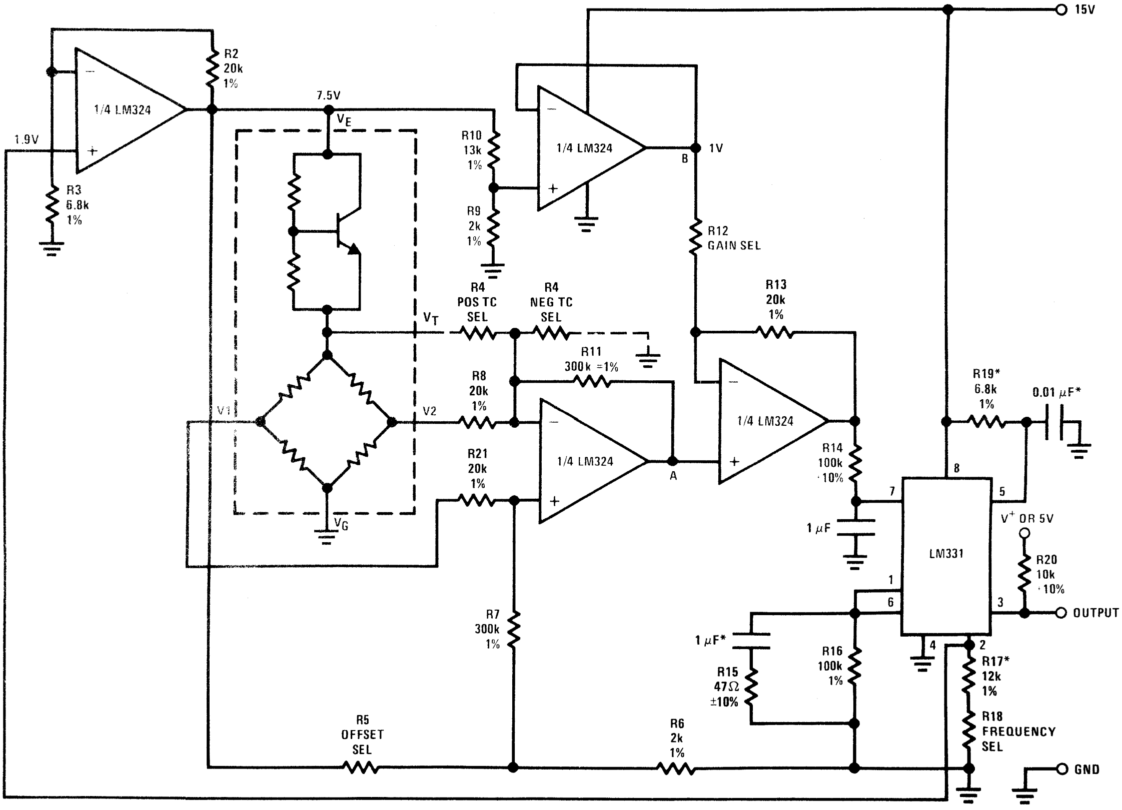
A single supply, zener reference, two-stage amplification, and voltage-to-frequency converter provide a frequency output compatible with analog-to-digital converter or microprocessor input.

Step No. 1 — Offset Temperature Compensation: Monitor point A while slowly varying temperature. Select R4 value and connection to minimize change in temperature.

Step No. 2 — DC Offset Adjust: Monitor point A and point B. Select R5 value to achieve zero voltage difference between points A and B.

Step No. 3 — Frequency Offset Adjust: Monitor frequency output. Select R18 value to achieve desired frequency offset (1 kHz for circuit values shown).

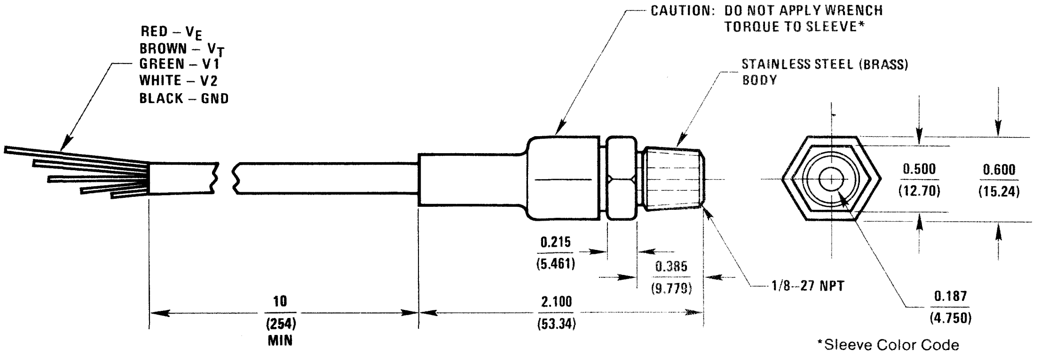
Step No. 4 — Frequency Span Adjust: Monitor frequency output while applying full-scale pressure. Select R12 value to achieve desired full-scale frequency (maximum output frequency is 10kHz for circuit values shown, See NSC LM331 data sheet).



*Use stable components with low TC. See NSC LM331 data sheet.

Figure 6. Frequency Output

Typical Physical Dimensions inches (millimeters)



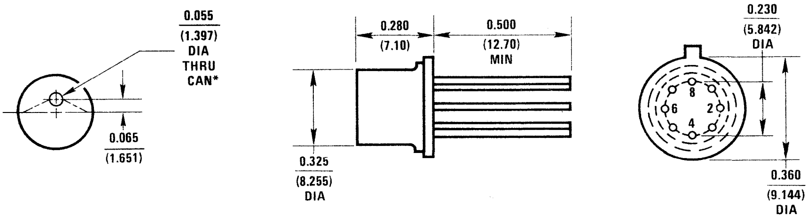
*Sleeve Color Code

Stainless Steel	Brass
White—LX0420A	LX0420AB
Yellow—LX0440A	LX0440AB
Red—LX0460A	LX0460AB
Blue—LX0470A	LX0470AB

PX4A(B)

Package for LX04XXA(B) Series Pressure Transducers

Weight: 35 Grams



* alignment of hole in can relative to pin 8 tab is arbitrary.

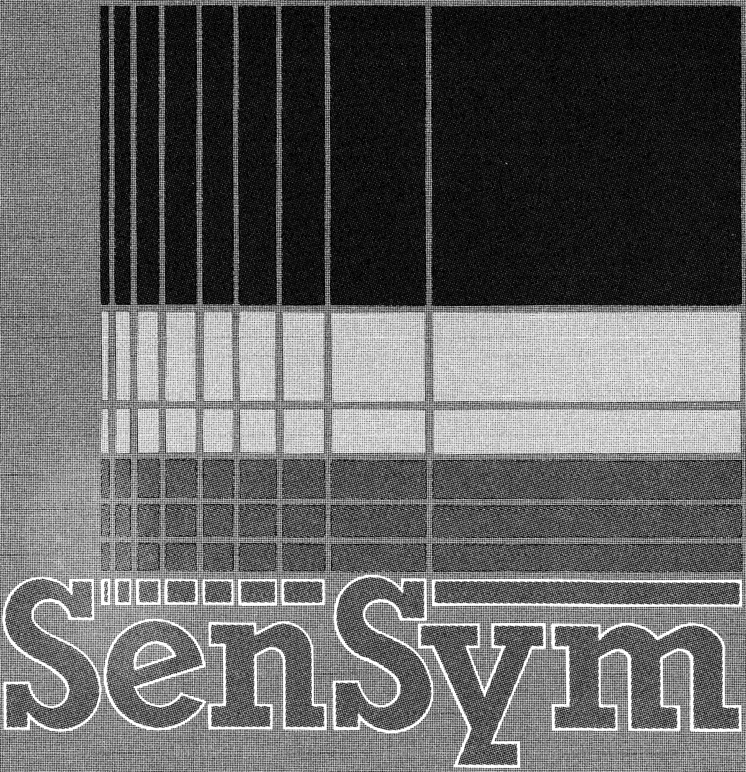
PX5AO

Package for LX05XXAO Series Pressure Transducers

Weight: 1.5 Grams

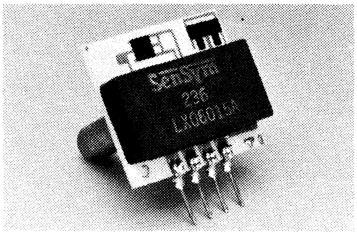
Section 3

Temperature Compensated Monolithic Pressure Transducer—Low-Mid-Pressure Range



SenSym

LX06XXXG, LX06XXXD, and LX06XXXA Series Temperature Compensated Monolithic Pressure Transducers



General Description

The monolithic pressure transducers are piezoresistive integrated circuits which provide an output voltage proportional to applied pressure. The devices are provided in compact packages with pressure ports, suitable for PC board mounting and attachment of flexible tubing.

The LX06XXXG is a gage transducer with a single tube and an ambient inlet. It is well suited for use with package-compatible working fluids, including water.

The LX06XXXD is a differential pressure transducer with 2 pressure ports, suitable for use with non-ionic working fluids in either pressure port, and package-compatible working fluids in the positive pressure port.

The LX06XXXA is an absolute pressure transducer with a single tube pressure port, suitable for use with non-ionic working fluids.

See Application Guide—Media Compatibility.

ADVANTAGES OF MONOLITHIC

The monolithic transducers include only the basic monolithic pressure IC chip used in Sensym's signal-conditioned pressure transducer products. This greatly reduces unit cost and allows the electronic designer greater freedom in implementing transducer circuits.

Calibrated sensitivity, a calibrated offset and low noise allow easy amplification. These devices are especially useful in applications requiring battery power, circuit flexibility, or compatibility with microprocessors.

TEMPERATURE COMPENSATION

All LX06XXX series transducers have thick film thermistor temperature compensation external to the sensor element. This compensation is equally distributed above and below the bridge so as to maintain a consistent common-mode voltage across the bridge, thereby decreasing common-mode signal errors. The temperature compensated is linearized and matched to each sensor using advanced laser trimming techniques.

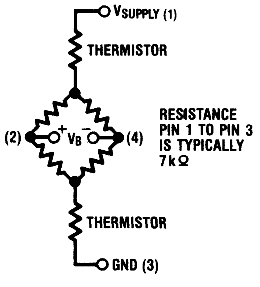
Features

- Low cost
- Low noise
- Temperature compensated
- Wide operating temperature range
- Small size and light weight
- High natural frequency
- Low volumetric displacement
- Alternate source available
- Vibration and shock insensitive
- Ratiometric output voltage
- Offset and sensitivity calibrated
- Compact package suitable for PC board mounting

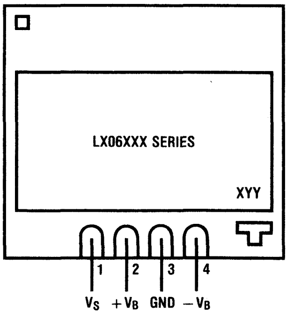
Applications

- Medical diagnostics
- Automotive diagnostics and controls
- Barometry
- Computer peripherals, control and diagnostics

Schematic Diagram



Electrical Connection



Pressure Transducer Characteristics

Maximum Ratings

Supply Voltage, V_S	16V
Temperature Range	
Operating	−40°C to +125°C
Storage	−65°C to +150°C
Common-Mode Line Pressure, LX06XXXD	100 psid
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 1)

Supply Voltage, V_S	10V
Reference Temperature	25°C
Common-Mode Line Pressure, LX06XXXD	0 psid

Performance Characteristics

Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration			Sensitivity	Linearity (Note 2)	Repeatability and Hysteresis	Offset Shift with Temperature (0 to 50°C)	Sensitivity Shift with Temperature (0 to 50°C)	Full Scale Output Calibration		
			mV			mV/psi	%FS	%FS	mV	%FS	mV		
			Min.	Typ.	Max.	Typ.	Typ.	Typ.	Typ.	Typ.	Min.	Typ.	Max.
LX06001G	0 to ±1 psig	20 psig	−2	0	+2	27.7	±1.5	0.10	±2	±1.5	25.5	28	30.5
LX06001D	±1 psid	20 psid	−2	0	+2	27.7	±1.5	0.10	±2	±1.5	25.5	28	30.5
LX06002G	0 to ±2 psig	20 psig	−1	0	+1	20.0	±1.5	0.10	±2	±1.5	38.5	40	41.5
LX06002D	±2 psid	20 psid	−1	0	+1	20.0	±1.5	0.10	±2	±1.5	38.5	40	41.5
LX06005G	0 to ±5 psig	20 psig	−1	0	+1	10.0	±1.5	0.10	±2	±1.5	48.5	50	51.5
LX06005D	±5 psid	20 psid	−1	0	+1	10.0	±1.5	0.10	±2	±1.5	48.5	50	51.5
LX06015A	0 to 15 psia	60 psia	−2	0	+2	−6.67	±1.0	0.10	±2	±1.5	−97.5	−100	−102.5
LX06015G	0 to ±15 psig	60 psig	−1	0	+1	6.67	±1.0	0.10	±2	±1.5	98.5	100	101.5
LX06015D	±15 psid	60 psid	−1	0	+1	6.67	±1.0	0.10	±2	±1.5	98.5	100	101.5
LX06L15A	0 to 15 psia	60 psia	−2	0	+2	−2.67	±0.25	0.10	±2	±1.5	−37.5	−40	−42.5
LX06L15G	0 to ±15 psig	60 psig	−1	0	+1	2.67	±0.25	0.10	±2	±1.5	38.5	40	41.5
LX06L15D	±15 psid	60 psid	−1	0	+1	2.67	±0.25	0.10	±2	±1.5	38.5	40	41.5
LX06030A	0 to 30 psia	60 psia	−2	0	+2	−2.63	±0.50	0.10	±2	±1.5	−74	−79	−84
LX06030G	0 to 30 psig	60 psig	−1	0	+1	2.63	±0.50	0.10	±2	±1.5	75	79	83
LX06030D	±30 psid	60 psid	−1	0	+1	2.63	±0.50	0.10	±2	±1.5	75	79	83
LX06100G	0 to 100 psig	200 psig	−1	0	+1	1.4	±0.50	0.10	±2	±1.5	136	140	144

Specification Notes:

Note 1: Conditions at which device "Performance Characteristics" apply.

Note 2: Linearity—the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\text{ FS error} = \frac{V_{\text{½ full scale}} - \left\{ \left(\frac{V_{\text{full scale}} - V_{\text{offset}}}{\text{full scale pressure}} \right) \times \left(\text{½ full scale pressure} \right) + V_{\text{offset}} \right\}}{2} \times 100\%$$

(V = measured value for each device)

TESTING

All guaranteed parameters are tested on multiple occasions in production and are assured in conformance to specification by outgoing quality assurance inspection. A Mensor pressure reference is used as a calibrated pressure reference source. All voltage readings are verified by a 4½-digit calibrated voltmeter. Non-guaranteed parameters are characterized during initial product characterization and reflect the performance of the product at that time. To guarantee any of these parameters requires a request for special product. Consult your Sensym distributor or representative for details.

Application Guide

MEDIA COMPATIBILITY—HUMIDITY

The heart of the transducer is a monolithic silicon chip with a cavity etched out to form a diaphragm. The top side of the diaphragm contains the transducer pressure sensing circuitry.

Absolute pressure devices (LX06XXXA) have a brass tube on the negative pressure inlet port only. The sensor cavity is a vacuum reference and the positive pressure port is sealed closed. A silicone gel material covers the sensor and provides immunity to high humidity environments. However, this material does not provide long term protection against water, other aqueous fluids, nor ionic fluids.

Gage pressure devices (LX06XXXG) have a brass tube on the positive pressure inlet port only. Ambient pressure is the reference pressure and is applied through a vent hole in the ceramic substrate. A silicone gel material covers the sensor and provides immunity to high humidity environments. The working fluid is applied through the positive pressure port and must be compatible with brass, ceramic, silicon, and polyimide. Silicon is at the same voltage potential as the supply voltage. Therefore the fluid must be electrically non-conductive or electrically isolated from the supply voltage.

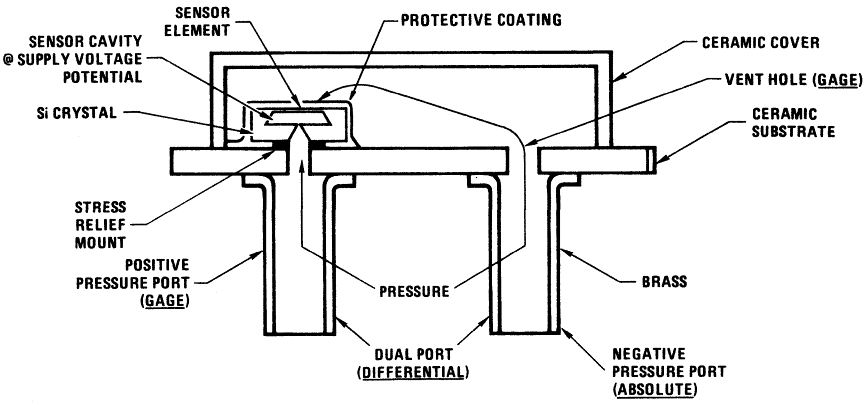
Differential pressure devices (LX06XXXD) have two brass tubes, one on each pressure port. Fluids applied to the negative pressure port must conform to conditions specified for absolute pressure devices. Fluids applied to the positive pressure port must conform to conditions specified for gage pressure devices.

LEAK RATE

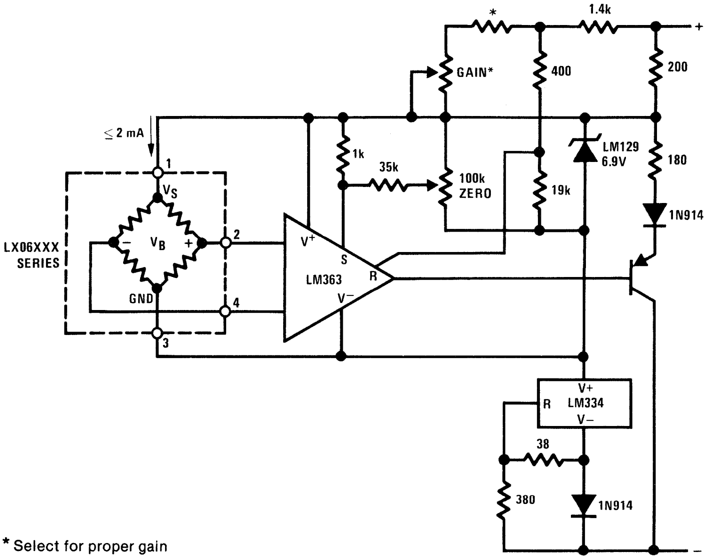
The PX6 package is not hermetic. Sensym's pressure transducers are guaranteed to have an effective leak area less than 10^{-7} cm^2 as defined in Section 9. Each transducer is leak tested at room temperature with 45 psig compressed air. However, the user should be aware that the leak rate can depend on the type, viscosity, pressure, and temperature of the working fluid and can increase with fatigue resulting from pressure cycling. This is especially important in static systems where a fluid under pressure is to be maintained for an extended period in an enclosure without replenishment.

SIGNAL AMPLIFICATION

Figures 1 and *2* show the LX06XXX series in use with NSC's LM163 instrumentation amplifier. (For additional technical information, consult the NSC LM163 data sheet.)



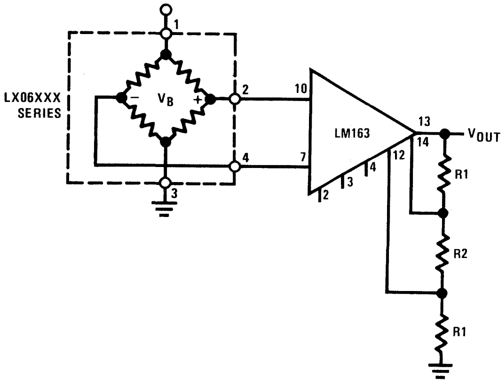
LX06XXX Pressure Transducer Structure



* Select for proper gain

Current regulation is near perfect because the NSC LM163 operates off the Zener reference. Circuitry is simplified by being able to drive the reference pin outside the power supply voltage. Gain and offset adjustments are non-interactive. 2mA is available to drive the bridge.

FIGURE 1. 4 mA-20 mA Transmitter



R1 and R2 should be as low as possible to avoid errors due to 50 kΩ input impedance of reference and sense pins. Total resistance (R2 + 2R1) should be above 4 kΩ, however, to prevent excessive load on the LM163 output. The exact formula for calculating gain (G) is:

$$G = G_O \left(1 + \frac{2R1}{R2} + \frac{R1}{50k}\right)$$

G_O = preset gain

The last term may be ignored in applications where gain accuracy is not critical. The table below gives suggested values for R1 and R2 along with the calculated error due to "closest value" standard 1% resistors.

Gain Increase	1.5	2	2.5	3	4	5	6	7	8	9	10
R1	1.2k	1.2k	2k	2k	1.78k	2k	2.49k	2.94k	3.48k	4.02k	4.53k
R2	5k	2.5k	2.74k	2.05k	1.2k	1k	1k	1k	1k	1k	1k
Error	+0.6%	−0.8%	0	−0.3%	+0.06%	+0.8%	+0.5%	−0.9%	+0.4%	−0.9%	−0.7%

FIGURE 2. Single-Chip Amplifier Circuit
(Consult National's LM163 data sheet for additional information)

SINGLE SUPPLY, RATIOMETRIC, RAIL-TO-RAIL SIGNAL CONDITIONING CIRCUIT

Typically this circuit is employed in single supply 5V systems in conjunction with a ratiometric analog-to-digital converter (ADC0801 series). It could just as easily be incorporated into any fixed voltage system.

Circuit Description

In *Figure 3*, a sensor is used with one NSC LM324 and one NSC LM10. The NSC LM10 reference is used to minimize common-mode voltage error across the first stage differential input. The voltage at V2 is set to one-half the supply voltage. This is the same voltage as pins 2 and 4 of the sensor with an unstrained bridge.

$$V2 = V_R + V_R \frac{R10}{R9}.$$

With R1 equal to R4 and R3 equal to R2 and a change in voltage of ΔV_B across the bridge results in

$$V1 = \Delta V_B \left(1 + \frac{R1}{R2}\right) + V2.$$

R8 and R7 are used to set the offset voltage. At offset conditions, these resistors are adjusted for the desired offset voltage. For zero output voltage, typically R7 = 40Ω and R8 = 400Ω and are adjusted so that the NSC LM10 is on the threshold of saturation at offset conditions.

i.e., for $V_S = 5V$ and $R5 = 4k$,

$R6 = 40k$ (output stage gain of 10) at offset

$V2 = 2.5V$, set $V_O = 0V$

$$V3 = 2.5 - \frac{2.5}{10} = 2.27V$$

The gain of this amplifier is equal to the gain of the first stage times the output stage gain

$$V_O = -(V1 - V3)\frac{R6}{R5} + V3.$$

For LX06015G and 0V to 5V operation, this requires a total gain of 50.

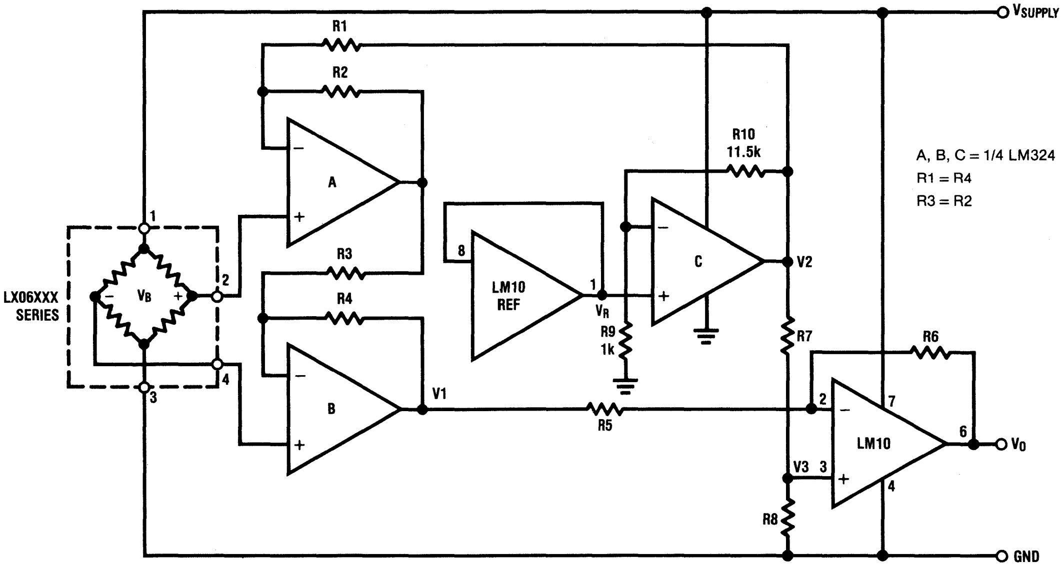


FIGURE 3. Single Supply, Ratiometric, Rail-to-Rail Signal Conditioning Circuit (for absolute devices pins 2 and 4 are reversed)

LOW COST 15V SUPPLY SIGNAL CONDITIONING CIRCUIT *(Figure 4)*

The LH0070 is a precision 10.00V reference. All aspects of this circuit follow the details as described for the single supply, ratiometric, rail-to-rail signal conditioning circuit previously.

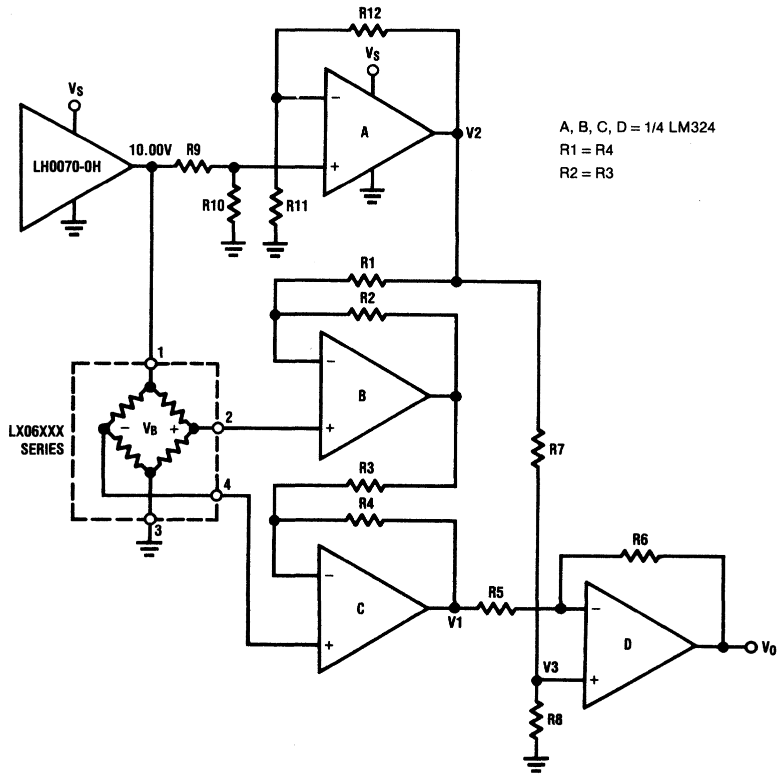


FIGURE 4. Low Cost 15V Supply Signal Conditioning Circuit

Application Guide (Continued)

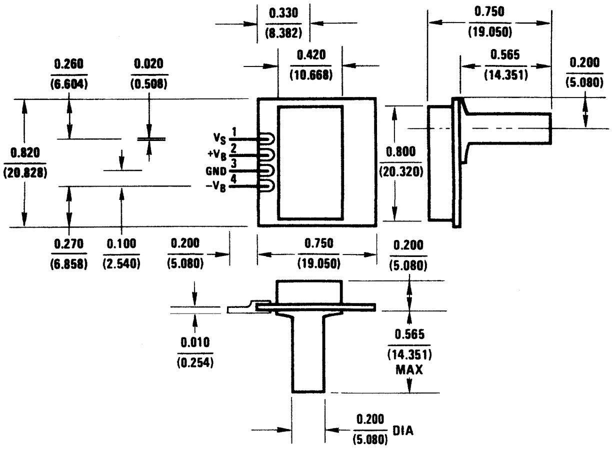
CROSS REFERENCE

These parts are pin-for-pin equivalent to Honeywell microswitch series 126 pressure transducers. There is one difference in the two products. The common-mode voltage upon which the output voltage changes is typically one-half the supply voltage for Sensym's products; for Honeywell devices this is typically one-third the supply voltage. For Sensym's products this allows full use of the pressure rating symmetrically around this voltage. See Typical Physical Dimensions section for pressure port locations.

Sensym Part #	Honeywell Part #	Sensitivity @10V (mV/psi)	Maximum Calibrated Pressure
LX06001G		27.7	1psig
LX06001D		27.7	1psid
LX06002G		20	2psig
LX06002D		20	2psid
LX06005G	126PC05G1, 136PC05G1	10	5psig
LX06005D	126PC05D1	10	5psid
LX06015A	126PC15A1, 136PC15A1	−6.67	15psia
LX06015G	126PC15G1	6.67	15psig
LX0615D	126PC15D1	6.67	15psid
LX06L15A*	126PC15A1L, 136PC15A1L	−2.67	15psia
LX06L15G*	126PC15G1L, 136PC15G1L	2.67	15psig
LX06L15D*	126PC15D1L	2.67	15psid
LX06030A	126PC30A1, 136PC30A1	−2.63	30psia
LX06030G	126PC30G1, 136PC30G1	2.63	30psig
LX06030D	126PC30D1	2.63	30psid
LX06100G		1.4	100psig

*Linearity is typically 0.25% full-scale.

Typical Physical Dimensions inches (millimeters) for reference only

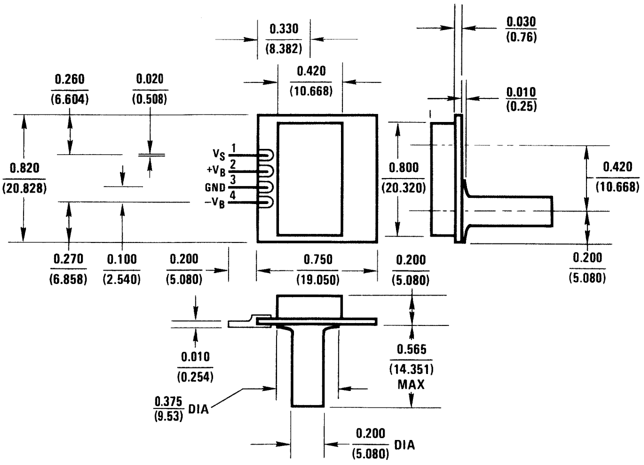


PX6A

Package for LX06XXXA Series Pressure Transducers

Weight: 5 grams

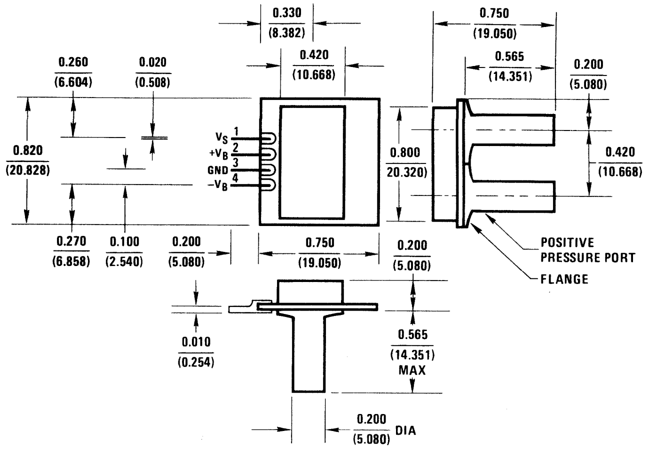
Typical Physical Dimensions (Continued) inches (millimeters) for reference only



PX6B

Package for LX06XXXG Series Pressure Transducers

Weight: 5 grams



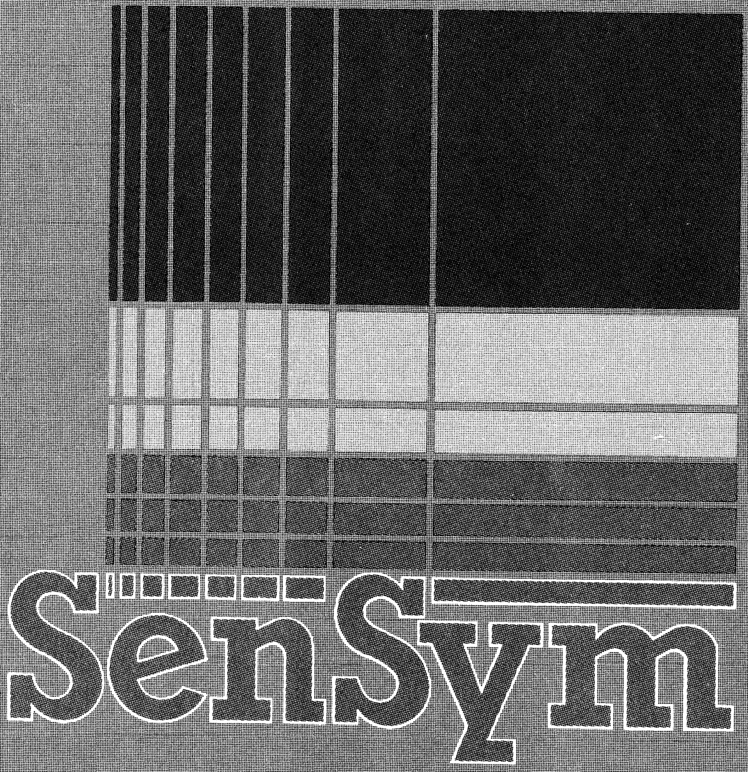
PX6D

Package for LX06XXXD Series Pressure Transducers

Weight: 5 grams

Section 4

Low- and Mid-Pressure Range Hybrid Pressure Transducers



SenSym

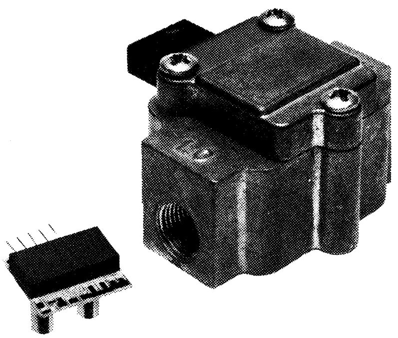
LX16XX and LX18XX Series Low and Mid-Pressure Range Signal Conditioned Pressure Transducers—10 Volt Output

General Description

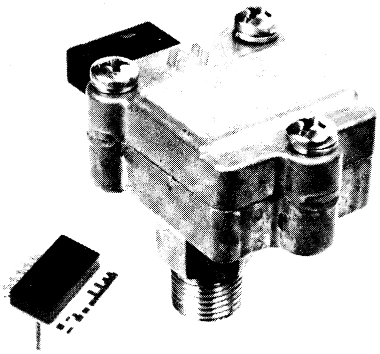
These are fully signal-conditioned pressure transducers with temperature compensation and high level output voltage. The LX16XX series transducers are provided in compact ceramic packages for easy PC board mounting. The LX18XX series transducers are provided in die cast zinc or molded nylon housings with 1/8″ NPT fittings, and a 3-pin Molex connector for easy, low cost electrical interface.

Features

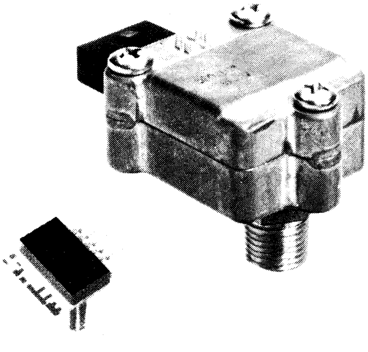
- ±5psi to 0–300psi
- High level output voltage, 2.5V to 12.5V
- Temperature compensated
- PC board mountable versions, LX16XX series
- Rugged zinc or nylon housings, LX18XX series
- Backward gage version for aqueous working fluids
- Silguard option on low-pressure and all GB devices
- Field interchangeability
- Available from local stocking distributors



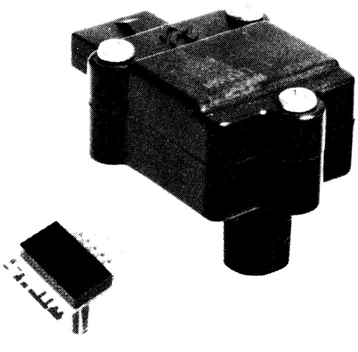
DIFFERENTIAL PRESSURE TRANSDUCERS:
LO Port Compatible with Aqueous
Working Fluids. Ceramic or High
Common-Mode Zinc Housing.



BACKWARD GAGE PRESSURE TRANSDUCERS:
Working Fluid Port Compatible with Aqueous
Fluids. Ceramic, Zinc or Nylon
Housings.



GAGE PRESSURE TRANSDUCERS:
Reference Port Compatible
with Aqueous Fluids. Ceramic,
Zinc or Nylon Housings.



ABSOLUTE PRESSURE TRANSDUCER:
Enclosed Vacuum Reference
Ceramic, Zinc or Nylon Housings.

Absolute Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage (Note 1)	30V
Output Current	
Source	20mA
Sink	10mA
Transducer Bias Current	20mA
Operating Temperature Range (Note 2)	−40°C to +105°C
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 3)

Excitation Voltage, V_E (Note 1)	15V
Reference Temperature	25°C
Reference Temperature Range	0 to 80°C
Reference Offset Pressure	(Note 4)

Typical Characteristics

Output Voltage Change to Excitation Voltage Change	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leqslant f \leqslant 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	>50kHz
Transducer Bias Current	11 – 15mA
Full-Scale Pressure Cycles (Note 9)	tbd
Leak Area (Air Media)	$<10^{-7}$cm^2

Performance Characteristics

			Guaranteed Specifications				
			Offset Characteristics		Span Characteristics		
Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration V (Note 4)	Shift w/Temperature 0°C to 80°C (Note 5)	Shift w/ Temperature 0°C to 80°C	Linearity Hysteresis Repeatability (Note 6)	
				±%FS	±%FS	%FS	±psi
LX1601A LX1801A (N,Z)	10 to 20 psia	100 psia	2.5 ± 0.70	3.3	2.75	0.67	0.067
LX1602A LX1802A (N,Z)	0 to 15 psia	100 psia	2.5 ± 0.50	2.75	2.75	0.67	0.10
LX1603A LX1803A (N,Z)	0 to 30 psia	100 psia	2.5 ± 0.35	1.65	1.65	0.67	0.20
LX1610A LX1810A (N,Z)	0 to 60 psia	125 psia	2.5 ± 0.30	1.65	1.65	0.67	0.40
LX1620A LX1820A (N,Z)	0 to 100 psia	200 psia	2.5 ± 0.30	1.10	1.10	0.67	0.67
LX1830A (N,Z)	0 to 300 psia	350 psia	2.5 ± 0.30	1.10	1.10	0.67	2.0

			Typical Specifications						
			Offset Characteristics				Span Characteristics		
Device Type	Operating Pressure Range	Maximum Over Pressure	Repeatability (Note 7)		Stability (Note 8)		Sensitivity Calibration	Stability (Note 8)	
			±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX1601A LX1801A (N,Z)	10 to 20 psia	100 psia	0.5	0.05	5.0	0.5	1000 ± 20	1.0	0.1
LX1602A LX1802A (N,Z)	0 to 15 psia	100 psia	0.4	0.06	3.3	0.5	670 ± 13	0.7	0.1
LX1603A LX1803A (N,Z)	0 to 30 psia	100 psia	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1610A LX1810A (N,Z)	0 to 60 psia	125 psia	0.4	0.24	1.5	0.9	167 ± 3.3	0.3	0.2
LX1620A LX1820A (N,Z)	0 to 100 psia	200 psia	0.4	0.40	1.2	1.2	100 ± 2	0.3	0.3
LX1830A (N,Z)	0 to 300 psia	350 psia	0.4	1.2	1.0	3.0	33.3 ± 0.67	0.3	0.9

Specification Notes:

Note 1: The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Note 2: Device performance characteristics apply 0 to +85°C, device is functional from −40°C to 0°C and 85°C to +105°C and all the temperature dependent errors are typically doubled over the additional temperature range.

Note 3: Conditions at which device performance characteristics apply.

Note 4: Offset Reference Pressure — for gage and differential devices offset pressure is ambient pressure, for absolute devices offset pressure is the lowest pressure in the pressure range.

Note 5: Temperature tested at 80°C relative to 25°C.

Note 6: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\ \text{FS error} = \frac{V_{\text{½ full scale}} - \left\{ \left(\dfrac{V_{\text{full scale}} - V_{\text{offset}}}{\text{full scale pressure}} \right) \times \left(\text{½ full scale pressure} \right) + V_{\text{offset}} \right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 7: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 8: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 9: Pressure cycle fatigue is a package related parameter. For LX18XX devices the maximum cycle life is limited by pressure magnitude and package O-ring. LX16XX devices are not limited by O-ring.

Differential Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage (Note 1)	30V
Output Current	
Source	20mA
Sink	10mA
Transducer Bias Current	20mA
Operating Temperature Range (Note 2)	−40°C to +105°C
Lead Temperature (Soldering, 10 seconds)	200°C
Pressure at Any Port LX16XXD LX18XXDZ	350psig

Reference Conditions (Note 3)

Excitation Voltage, V_E (Note 1)	15V
Reference Temperature	25°C
Reference Temperature Range	0 to 80°C
Reference Offset Pressure	(Note 4)
Common-Mode Line Pressure LX16XXD LX18XXDZ	0psig

Typical Characteristics

Output Voltage Change to Excitation Voltage Change	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent (0 ≤ f ≤ 1kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	>50kHz
Transducer Bias Current	11 – 15mA
Full-Scale Pressure Cycles (Note 9)	tbd
Offset Shift vs. Common-Mode Pressure	tbd
Leak Area (Air Media)	$<10^{-7}$cm^2

Performance Characteristics

			Guaranteed Specifications				
			Offset Characteristics		Span Characteristics		
Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration V (Note 4)	Shift w/Temperature 0°C to 80°C (Note 5)	Shift w/ Temperature 0°C to 80°C	Linearity Hysteresis Repeatability (Note 6)	
				±%FS	±%FS	%FS	±psi
LX1601D LX1801DZ	0 to ±5psid	45psid	7.5 ± 0.70	3.3	2.75	0.67	0.067
LX1602D LX1802DZ	0 to 15psid	45psid	2.5 ± 0.50	2.75	2.75	0.67	0.10
LX1603D LX1803DZ	0 to 30psid	45psid	2.5 ± 0.35	1.65	1.65	0.67	0.20
LX1604D LX1804DZ	0 to ±15psid	45psid	7.5 ± 0.35	1.65	1.65	0.67	0.20
LX1610D LX1810DZ	0 to 60psid	100psid	2.5 ± 0.30	1.65	1.65	0.67	0.40
LX1620D LX1820DZ	0 to 100psid	150psid	2.5 ± 0.30	1.10	1.10	0.67	0.67
LX1830DZ	0 to 300psid	350psid	2.5 ± 0.30	1.10	1.10	0.67	2.0

			Typical Specifications						
			Offset Characteristics				Span Characteristics		
Device Type	Operating Pressure Range	Maximum Over Pressure	Repeatability (Note 7)		Stability (Note 8)		Sensitivity Calibration	Stability (Note 8)	
			±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX1601D LX1801DZ	0 to ±5psid	45psid	0.5	0.05	5.0	0.5	1000 ± 20	1.0	0.1
LX1602D LX1802DZ	0 to 15psid	45psid	0.4	0.06	3.3	0.5	670 ± 13	0.7	0.1
LX1603D LX1803DZ	0 to 30psid	45psid	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1604D LX1804DZ	0 to ±15psid	45psid	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1610D LX1810DZ	0 to 60psid	100psid	0.4	0.24	1.5	0.9	167 ± 3.3	0.3	0.2
LX1620D LX1820DZ	0 to 100psid	150psid	0.4	0.40	1.2	1.2	100 ± 2	0.3	0.3
LX1830DZ	0 to 300psid	350psid	0.4	1.2	1.0	3.0	33.3 ± 0.67	0.3	0.9

Specification Notes:

Note 1: The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Note 2: Device performance characteristics apply 0 to +85°C, device is functional from −40°C to 0°C and 85°C to +105°C and all the temperature dependent errors are typically doubled over the additional temperature range.

Note 3: Conditions at which device performance characteristics apply.

Note 4: Offset Reference Pressure — for gage and differential devices offset pressure is ambient pressure, for absolute devices offset pressure is the lowest pressure in the pressure range.

Note 5. Temperature tested at 80°C relative to 25°C.

Note 6: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\ \text{FS error} = \frac{V_{\frac{1}{2}\ \text{full scale}} - \left\{\left(\frac{(V_{\text{full scale}} - V_{\text{offset}})}{\text{full scale pressure}}\right) \times \left(\tfrac{1}{2}\ \text{full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 7: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 8: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 9: Pressure cycle fatigue is a package related parameter. For LX18XX devices the maximum cycle life is limited by pressure magnitude and package O-ring. LX16XX devices are not limited by O-ring.

Backward Gage Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage (Note 1)	30 V
Output Current	
Source	20 mA
Sink	10 mA
Transducer Bias Current	20 mA
Operating Temperature Range (Note 2)	−40°C to +105°C
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 3)

Excitation Voltage, V_E (Note 1)	15 V
Reference Temperature	25°C
Reference Temperature Range	0 to 80°C
Reference Offset Pressure	(Note 4)

Typical Characteristics

Output Voltage Change to Excitation Voltage Change	0.5%
Output Impedance	$<50\Omega$
Electrical Noise Equivalent ($0 \leqslant f \leqslant 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	>50 kHz
Transducer Bias Current	11 – 15 mA
Full-Scale Pressure Cycles (Note 9)	tbd
Leak Area (Air Media)	$<10^{-7}$ cm^2

Performance Characteristics

Device Type	Operating Pressure Range	Maximum Over Pressure	Guaranteed Specifications				
			Offset Characteristics		Span Characteristics		
			Offset Calibration V (Note 4)	Shift w/Temperature 0°C to 80°C (Note 5)	Shift w/ Temperature 0°C to 80°C	Linearity Hysteresis Repeatability (Note 6)	
				±%FS	±%FS	%FS	±psi
LX1601GB LX1801GB (N,Z)	0 to ±5 psig	45 psig	7.5 ± 0.70	3.3	2.75	0.67	0.067
LX1602GB LX1802GB (N,Z)	0 to 15 psig	45 psig	2.5 ± 0.50	2.75	2.75	0.67	0.10
LX1603GB LX1803GB (N,Z)	0 to 30 psig	45 psig	2.5 ± 0.35	1.65	1.65	0.67	0.20
LX1604GB LX1804GB (N,Z)	0 to ±15 psig	45 psig	7.5 ± 0.35	1.65	1.65	0.67	0.20
LX1610GB LX1810GB (N,Z)	0 to 60 psig	100 psig	2.5 ± 0.30	1.65	1.65	0.67	0.40
LX1620GB LX1820GB (N,Z)	0 to 100 psig	150 psig	2.5 ± 0.30	1.10	1.10	0.67	0.67
LX1830GB (N,Z)	0 to 300 psig	350 psig	2.5 ± 0.30	1.10	1.10	0.67	2.0

Device Type	Operating Pressure Range	Maximum Over Pressure	Typical Specifications						
			Offset Characteristics				Span Characteristics		
			Repeatability (Note 7)		Stability (Note 8)		Sensitivity Calibration	Stability (Note 8)	
			±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX1601GB LX1801GB (N,Z)	0 to ±5 psig	45 psig	0.5	0.05	5.0	0.5	1000 ± 20	1.0	0.1
LX1602GB LX1802GB (N,Z)	0 to 15 psig	100 psig	0.4	0.06	3.3	0.5	670 ± 13	0.7	0.1
LX1603GB LX1803GB (N,Z)	0 to 30 psig	45 psig	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1604GB LX1804GB (N,Z)	0 to ±15 psig	45 psig	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1610GB LX1810GB (N,Z)	0 to 60 psig	100 psig	0.4	0.24	1.5	0.9	167 ± 3.3	0.3	0.2
LX1620GB LX1820GB (N,Z)	0 to 100 psig	150 psig	0.4	0.40	1.2	1.2	100 ± 2	0.3	0.3
LX1830GB (N,Z)	0 to 300 psig	350 psig	0.4	1.2	1.0	3.0	33.3 ± 0.67	0.3	0.9

Specification Notes:

Note 1: The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Note 2: Device performance characteristics apply 0 to +85°C, device is functional from −40°C to 0°C and 85°C to +105°C and all the temperature dependent errors are typically doubled over the additional temperature range.

Note 3: Conditions at which device performance characteristics apply.

Note 4: Offset Reference Pressure — for gage and differential devices offset pressure is ambient pressure, for absolute devices offset pressure is the lowest pressure in the pressure range.

Note 5. Temperature tested at 80°C relative to 25°C.

Note 6: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\ \text{FS error} = \frac{V_{\frac{1}{2}\ \text{full scale}} - \left\{\left(\dfrac{V_{\text{full scale}} - V_{\text{offset}}}{\text{full scale pressure}}\right) \times \left(\tfrac{1}{2}\ \text{full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 7: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 8: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 9: Pressure cycle fatigue is a package related parameter. For LX18XX devices the maximum cycle life is limited by pressure magnitude and package O-ring. LX16XX devices are not limited by O-ring.

Gage Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage (Note 1)	30V
Output Current	
Source	20mA
Sink	10mA
Transducer Bias Current	20mA
Operating Temperature Range (Note 2)	−40°C to +105°C
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 3)

Excitation Voltage, V_E (Note 1)	15V
Reference Temperature	25°C
Reference Temperature Range	0 to 80°C
Reference Offset Pressure	(Note 4)

Typical Characteristics

Output Voltage Change to Excitation Voltage Change	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leqslant f \leqslant 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	>50kHz
Transducer Bias Current	11 – 15mA
Full-Scale Pressure Cycles (Note 9)	tbd
Leak Area (Air Media)	$<10^{-7}$cm^2

Performance Characteristics

Device Type	Operating Pressure Range	Maximum Over Pressure	Guaranteed Specifications				
			Offset Characteristics		Span Characteristics		
			Offset Calibration V (Note 4)	Shift w/Temperature 0°C to 80°C (Note 5)	Shift w/ Temperature 0°C to 80°C	Linearity Hysteresis Repeatability (Note 6)	
				±%FS	±%FS	%FS	±psi
LX1601G LX1801G (N,Z)	0 to ±5psig	100psig	7.5 ± 0.70	3.3	2.75	0.67	0.067
LX1602G LX1802G (N,Z)	0 to 15psig	100psig	2.5 ± 0.50	2.75	2.75	0.67	0.10
LX1603G LX1803G (N,Z)	0 to 30psig	100psig	2.5 ± 0.35	1.65	1.65	0.67	0.20
LX1604G LX1804G (N,Z)	0 to ±15psig	100psig	7.5 ± 0.35	1.65	1.65	0.67	0.20
LX1610G LX1810G (N,Z)	0 to 60psig	125psig	2.5 ± 0.30	1.65	1.65	0.67	0.40
LX1620G LX1820G (N,Z)	0 to 100psig	150psig	2.5 ± 0.30	1.10	1.10	0.67	0.67
LX1830G (N,Z)	0 to 300psig	350psig	2.5 ± 0.30	1.10	1.10	0.67	2.0

Device Type	Operating Pressure Range	Maximum Over Pressure	Typical Specifications						
			Offset Characteristics				Span Characteristics		
			Repeatability (Note 7)		Stability (Note 8)		Sensitivity Calibration	Stability (Note 8)	
			±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX1601G LX1801G (N,Z)	0 to ±5psig	100psig	0.5	0.05	5.0	0.5	1000 ± 20	1.0	0.1
LX1602G LX1802G (N,Z)	0 to 15psig	100psig	0.4	0.06	3.3	0.5	670 ± 13	0.7	0.1
LX1603G LX1803G (N,Z)	0 to 30psig	100psig	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1604G LX1804G (N,Z)	0 to ±15psig	100psig	0.4	0.12	1.7	0.5	333 ± 6.7	0.3	0.1
LX1610G LX1810G (N,Z)	0 to 60psig	125psig	0.4	0.24	1.5	0.9	167 ± 3.3	0.3	0.2
LX1620G LX1820G (N,Z)	0 to 100psig	200psig	0.4	0.40	1.2	1.2	100 ± 2	0.3	0.3
LX1830G (N,Z)	0 to 300psig	350psig	0.4	1.2	1.0	3.0	33.3 ± 0.67	0.3	0.9

Specification Notes:

Note 1: The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Note 2: Device performance characteristics apply 0 to +85°C, device is functional from −40°C to 0°C and 85°C to +105°C and all the temperature dependent errors are typically doubled over the additional temperature range.

Note 3: Conditions at which device performance characteristics apply.

Note 4: Offset Reference Pressure — for gage and differential devices offset pressure is ambient pressure, for absolute devices offset pressure is the lowest pressure in the pressure range.

Note 5. Temperature tested at 80°C relative to 25°C.

Note 6: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\ \text{FS error} = \frac{V_{\frac{1}{2}\ \text{full scale}} - \left\{\left(\frac{V_{\text{full scale}} - V_{\text{offset}}}{\text{full scale pressure}}\right) \times \left(\tfrac{1}{2}\ \text{full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

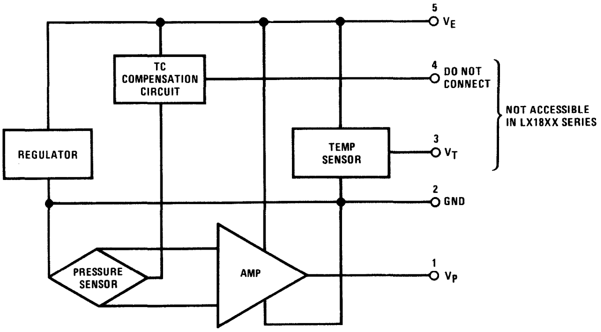
(V = measured value for each device)

Note 7: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 8: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 9: Pressure cycle fatigue is a package related parameter. For LX18XX devices the maximum cycle life is limited by pressure magnitude and package O-ring. LX16XX devices are not limited by O-ring.

Schematic Diagram



Application Guide

ACCURACY SPECIFICATIONS — AUTO-REFERENCING

Error parameters are specified separately for offset and span. These errors are independent which allows easy computation of error bands, reclibration, and use of auto-referencing, a techniqe of automatic recalibration. For a detailed discussion of accuracy specifications and auto-referencing, see Sections 6 and 7.

Consulting the Handbook

It is recommended that Sections 6, 7, 8, and 9 be consulted before using any Sensym pressure transducer, These sections contain comprehensive information on auto-referencing, pressure transducer installation and many applications. The following supplements those sections for the LX16XX and LX18XX families of pressure transducers.

Signal Conditioning — Hybrid vs. Monolithic

The LX16XX and LX18XX series transducers are fully signal-conditioned pressure transducers with temperature compensation, single-ended 10V output span, and internal voltage regulation to allow operation with a 15V to 30V supply. They offer easy electrical interface and high accuracy over a wide temperature range. If the user has the capability of developing temperature compensation circuits (or if the temperature compensation is not required), the LX05XX or LX06XX series monolithic sensors may offer a viable, low-cost alternative (see Section 2).

LX16XX vs LX18XX

As shown in *Figure 2*, the LX16XX series transducers are provided in a ceramic SIP (single-in-line package) for each PC board mounting, with pressure ports suitable for attachment of flexible tubing. The sensor chip is attached with a stress-relieving mount to minimize stress transfer; but to achieve high accuracy, the user must avoid stressing the ceramic package in installation (Section 7). The advantages of using the LX16XX series are low-cost and high-density packaging. They are available with operating pressure ranges up to 100psi.

The LX18XX series devices are LX16XX devices enclosed in rugged zinc or nylon housings, with internal, Buna-N O-ring seals, and 1/8″ NPT fittings. They mate with standard connectors and offer protection against rough handling and stress from the pressure system. The stress protection feature is enhanced in the LX18XXDZ high common-mode differential versions which can measure small pressure differentials on a line pressurized up to 350psig. The LX18XX is available with operating pressure ranges up to 300psi.

Application Guide (Continued)

MEDIA COMPATIBILITY — HUMIDITY

As shown in *Figure 1*, the basic hybrid transducer structure allows for two pressure inlets which differ in susceptibility to moisture and other fluids, depending on whether the fluid is applied to the top side (circuit side) or to the back side (cavity side) of the diaphragm. The top side is coated with a thin compliant layer of protective coating. The circuit side is compatible with many non-aqueous fluids while the back side of the diaphragm is compatible with aqueous fluids. This is summarized below for each pressure transducer type.

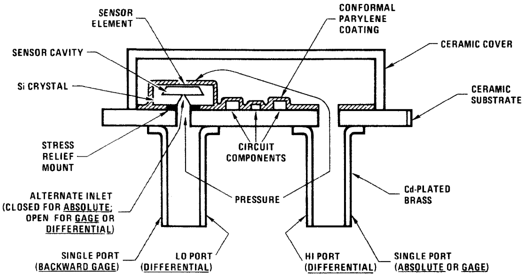


FIGURE 1. Basic LX16XX Series IC Pressure Transducer Structure

The circuit-side inlet is the working fluid port for absolute and gage transducers and the HI port for differential transducers. It is the reference port for backward gage transducers. It can be used with most fuels, oils, refrigerants, hydraulic fluids, and non-corrosive gases (for refrigerants, see LX18XXGBR Data Sheet). But moisture condensate or other ionic, acidic or corrosive fluids can cause erroneous readings and electrical failure. For these applications, the A–1 option is required (see –1 Option).

The cavity-side inlet is the working fluid port for backward gage transducers and the LO port for differential transducers. It is the reference port for gage transducers. It can be used with aqueous fluids but cannot be used with acids and other fluids corrosive to device construction material (brass, zinc, nylon, solder, alumina, silicon and Buna-N).

Hence, the *backward gage* version can be used with many aqueous working fluids but requires a dry ambient. The *differential* version can tolerate aqueous fluids in the LO port but not in the HI port. The *absolute* and *gage* versions both require dry working fluids, but the ambient can be humid.

–1 Option

All low pressure devices and GB devices are available with coating for protections against high humidity environments. Please consult the "–1" option application note shown at the end of this section.

LEAK RATE

The PX6 (LX16XX) and PX8 (LX18XX) packages are not hermetic. Sensym's pressure transducers are guaranteed to have an effective leak area less than 10^{-7}cm^2 as defined in Section 9. Each transducer is leak tested at room temperature with 45psig compressed air.

However, the user should be aware that the leak rate can depend on the type, viscosity, pressure, and temperature of the working fluid and can increase with fatigue resulting from pressure cycling.

"Dead-Ending" Feature

If the pressure applied to the LX16XXA or LX18XXA (N, Z) exceeds proof pressure (maximum specified operating pressure), the silicon diaphragm could rupture. But, unlike gage transducers, the absolute devices are "dead-ended" so that diaphragm rupture does not necessarily result in fluid leakage.

INPUT/OUTPUT POLARITY

The output signal is at pin 1 for all LX16XX series signal-conditioned transducers. *Figure 2* shows the pinout for these transducers, with pressure ports extending out of the drawing.

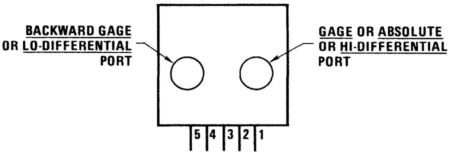


FIGURE 2. LX16XX Pinout, Portside View

The output signal of absolute and gage transducers is positive-going for increasing pressure applied to the absolute or gage port.

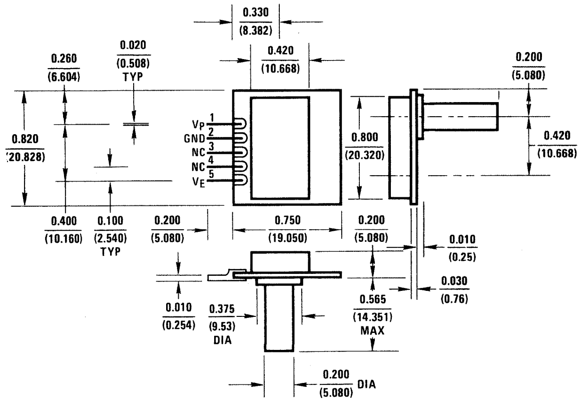
The output signal of backward gage transducers is positive-going for increasing pressure applied to the backward gage port.

The output signal of differential transducers is positive going for increasing pressure applied to the HI port relative to the LO port.

WARNING

The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

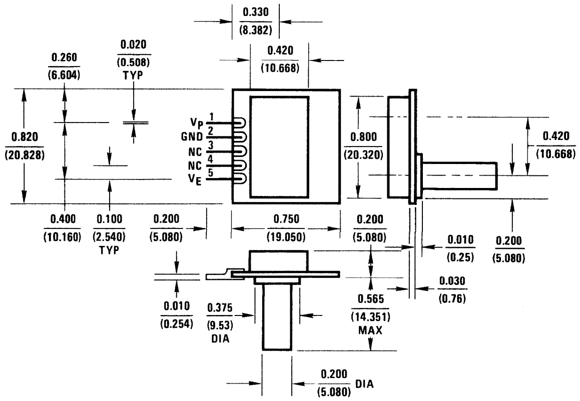
Typical Physical Dimensions inches (millimeters)



PX6

Package for LX16XX Series Pressure Transducers

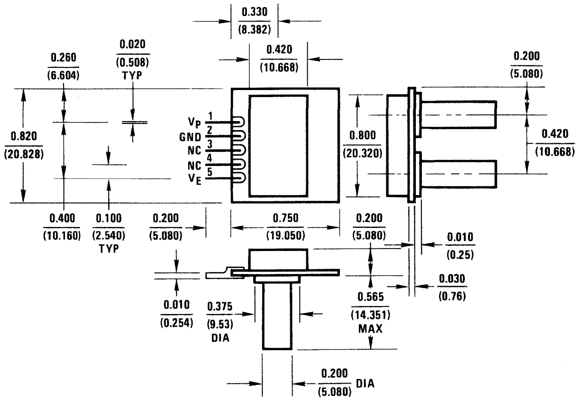
Weight: 5 Grams



PX6B

Package for LX16XXGB Series Pressure Transducers

Weight: 5 Grams

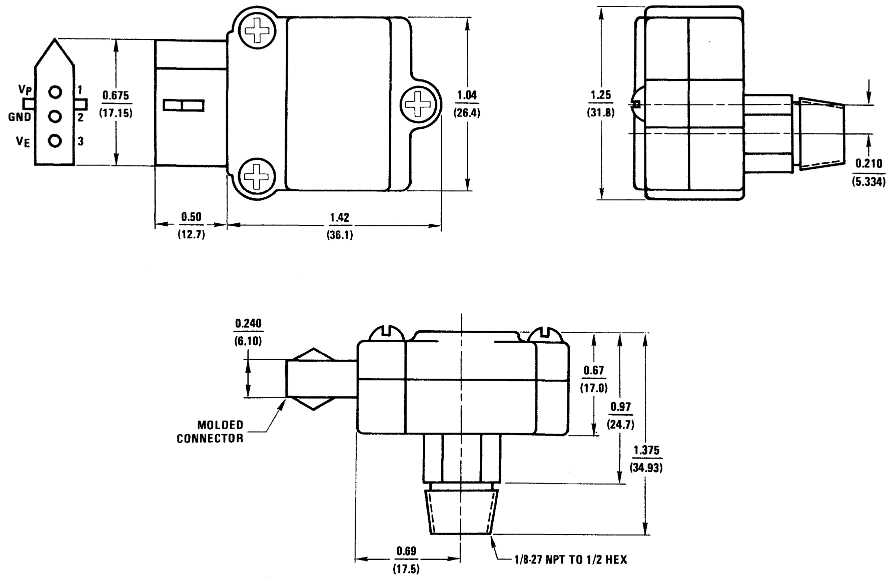


PX6D

Package for LX16XXD Series Pressure Transducers

Weight: 5 Grams

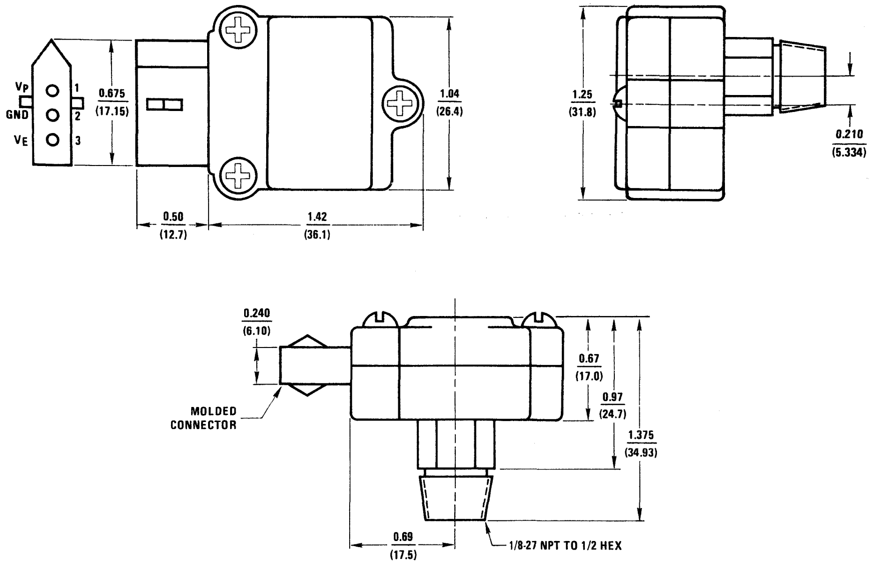
Typical Physical Dimensions (Continued) inches (millimeters)



PX8B (N, Z)

Package for LX18XXGB (N, Z) Series Pressure Transducers

Weight: 100 Grams in Zinc (Z), 50 Grams in Nylon (N)

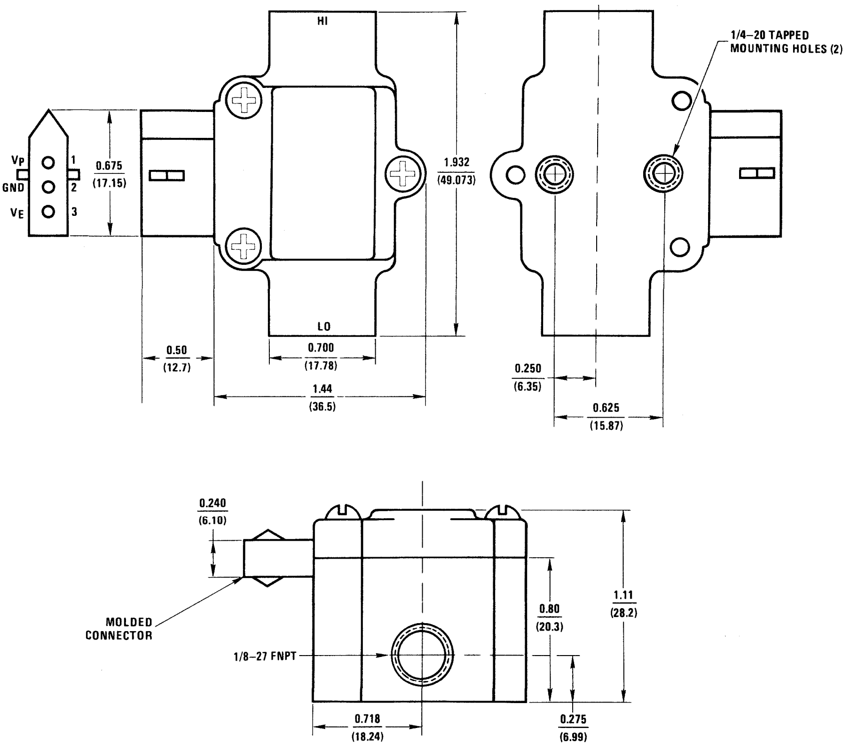


PX8 (N, Z)

Package for LX18XXA, G (N, Z) Series Pressure Transducers

Weight: 100 Grams in Zinc (Z), 50 Grams in Nylon (N)

Typical Physical Dimensions (Continued) inches (millimeters)



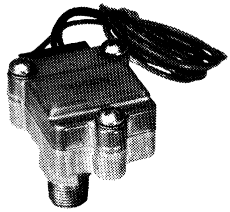
PX8DZ

Package for LX18XXDZ Series Zinc Cast Pressure Transducers

Weight: 170 Grams

LX18XX (PX8) Mating Connector

Vendor	Connector No.	Male Pin No.
Litton-Winchester Win-Com Series	59-03P1000	159-1018P
Waldon/Molex	03-09-2031	02-09-2103
Molex—without mounting ears	03-09-2032	



LX18XXGBR Series Refrigerant Compatible Signal-Conditioned Pressure Transducers

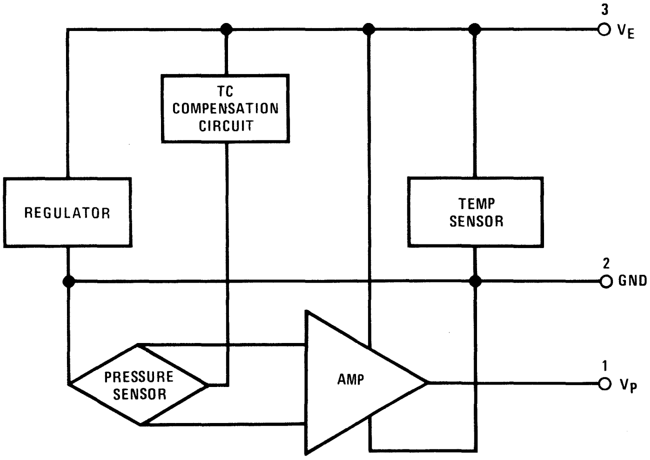
General Description

These are fully signal conditioned pressure transducers with temperature compensation and high level output voltage. The LX18XXGBR series transducers are provided in die cast zinc housings with 1/8″ NPT fittings. They utilize special O-rings to provide freon compatibility[1] and special coatings and connectors to provide resistance to moisture. Except for media compatibility, the LX18XXGBR series devices are functionally equivalent to the LX18XXGB series.

Features

- 0–100 psig and 0–300 psig
- High level output voltage, 2.5V to 12.5V
- Temperature compensated
- Freon compatibility
- Rugged zinc housings
- Field interchangeability
- Available from local stocking distributors

Schematic Diagram



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[1] —See Media Compatibility Section

Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage (Note 1)	30V
Output Current	
Source	20mA
Sink	10mA
Transducer Bias Current	20mA
Operating Temperature Range (Note 2)	−40°C to +105°C
Lead Temperature (Soldering, 10 seconds)	200°C

Reference Conditions (Note 3)

Excitation Voltage, V_E (Note 1)	15V
Reference Temperature	25°C
Reference Temperature Range	0 to 80°C
Reference Offset Pressure	(Note 4)

Typical Characteristics

Output Voltage Change to Excitation Voltage Change	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leqslant f \leqslant 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	>50kHz
Transducer Bias Current	11 – 15mA
Full-Scale Pressure Cycles (Note 9)	tbd
Leak Area (Air Media)	$<10^{-7}$cm^2

Performance Characteristics

Device Type	Operating Pressure Range	Maximum Over Pressure	Guaranteed Specifications				
			Offset Characteristics		Span Characteristics		
			Offset Calibration V (Note 4)	Shift w/ Temperature 0°C to 80°C (Note 5)	Shift w/ Temperature 0°C to 80°C	Linearity Hysteresis Repeatability (Note 6)	
				±%FS	±%FS	±%FS	±psi
LX1820GBR	0 to 100psig	150psig	2.5 ± 0.30	1.10	1.10	0.67	0.67
LX1830GBR	0 to 300psig	350psig	2.5 ± 0.30	1.10	1.10	0.67	2.0

Device Type	Operating Pressure Range	Maximum Over Pressure	Typical Specifications						
			Offset Characteristics				Span Characteristics		
			Repeatability (Note 7)		Stability (Note 8)		Sensitivity Calibration	Stability (Note 8)	
			±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX1820GBR	0 to 100psig	150psig	0.4	0.40	1.2	1.2	100 ± 20	0.3	03
LX1830GBR	0 to 300psig	350psig	0.4	1.2	1.0	3.0	33.3 ± 0.67	0.3	0.9

Specification Notes:

Note 1: The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Note 2: Device performance characteristics apply 0 to +85°C, device is functional from −40°C to 0°C and 85°C to +105°C and all the temperature dependent errors are typically doubled over the additional temperature range.

Note 3: Conditions at which device performance characteristics apply.

Note 4: Offset Reference Pressure — for gage and differential devices offset pressure is ambient pressure, for absolute devices offset pressure is the lowest pressure in the pressure range.

Note 5. Temperature tested at 80°C relative to 25°C.

Note 6: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\text{ FS error} = \frac{V_{1/2\text{ full scale}} - \left\{\left(\frac{(V_{\text{full scale}} - V_{\text{offset}})}{\text{full scale pressure}}\right) \times \left(1/2\text{ full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 7: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 8: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 9: Pressure cycle fatigue is a package related parameter. For LX18XX devices the maximum cycle life is limited by pressure magnitude and package O-ring. LX16XX devices are not limited by O-ring.

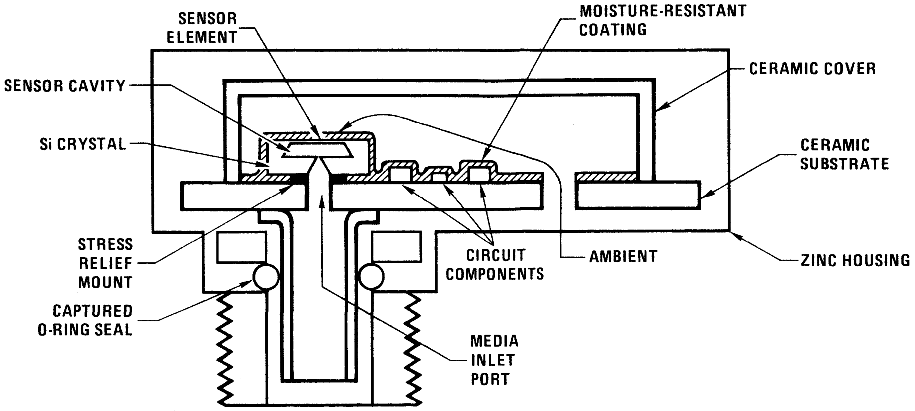


FIGURE 1. Basic LX18XXGB Series IC Pressure Transducer

Application Guide

ACCURACY SPECIFICATIONS — AUTO-REFERENCING

Error parameters are specified separately for offset and span. These errors are independent which allows easy computation of error bands, recalibration, and use of auto-referencing, a technique of automatic recalibration. For a detailed discussion of accuracy specifications and auto-referencing, see Section 6.

Signal Conditioning

The LX18XX series transducers are fully signal-conditioned pressure transducers with temperature compensation, single-ended 10V output span, and internal voltage regulation to allow operation with a single 15V supply. They offer easy electrical interface and high accuracy over a wide temperature range.

LX18XXGBR

The LX18XXGBR series devices are LX16XXGB devices enclosed in rugged zinc housings, with internal O-ring seals and 1/8″ NPT fittings. These O-rings are specially selected to be compatible with typical freons used in refrigeration and a/c systems. The circuit components and electrical connections are coated with a special coating which allows the parts to operate in moist environments typically associated with freon systems.

Application Guide (Continued)

MEDIA COMPATIBILITY

The LX18XXGBR can be used with a number of aqueous or freon working media. Since the device is designed to operate in backward gage mode, the working fluid comes in contact with the backside of the silicon diaphragm. In particular, the LX18XXGBR series has a special O-ring seal which is compatible with most of the common freons. Specifically, Freon 12, 13, 13B1, 14, 21, 22, 31, 32, 113, 114, 114B2, 115, 142B, 152A, 218, C316, C318, BF, and TF are all compatible with the LX18XXGBR devices.

All the circuit componetns and electrical connections which come in contact with the ambient are coated with a special coating. This allows the device to operate in high humidity or moist environments. For questions concerning specific media compatibility problems, please consult the factory.

LEAK RATE

The PX8 (LX18XX) packages are not hermetic. Sensym's pressure transducers are guaranteed to have an effective leak area less than 10^{-7} cm^2 as defined in Section 9. Each transducer is leak tested at room temperature with 45 psig compressed air.

However, the user should be aware that the leak rate can depend on the type, viscosity, pressure, and temperature of the working fluid and can increase with fatigue resulting from pressure cycling.

INPUT/OUTPUT

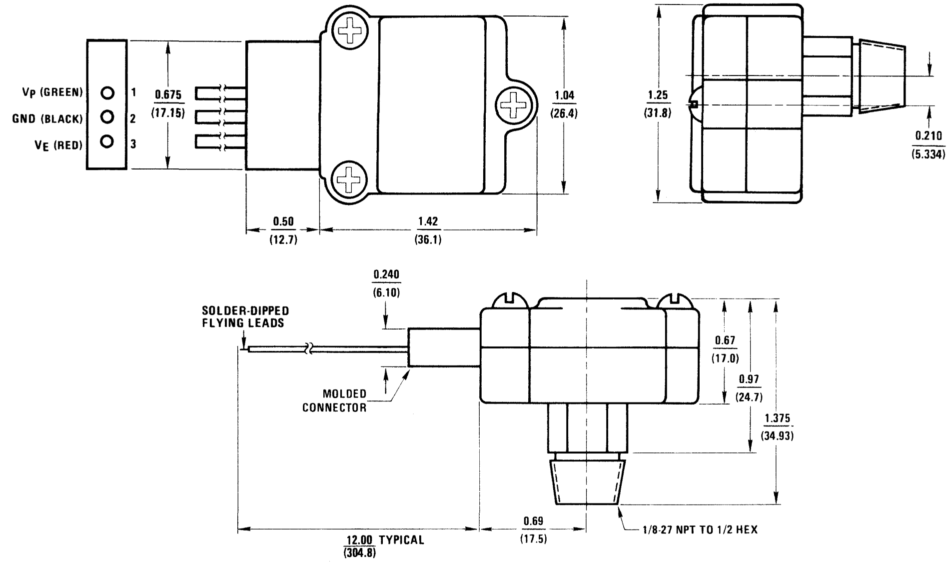
The output signal of backward gage transducers is positive-going for increasing pressure applied to the backward gage port.

WARNING

The LX18XX series is not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Electrical connection is made through the three flying leads.

Typical Physical Dimensions inches (millimeters)



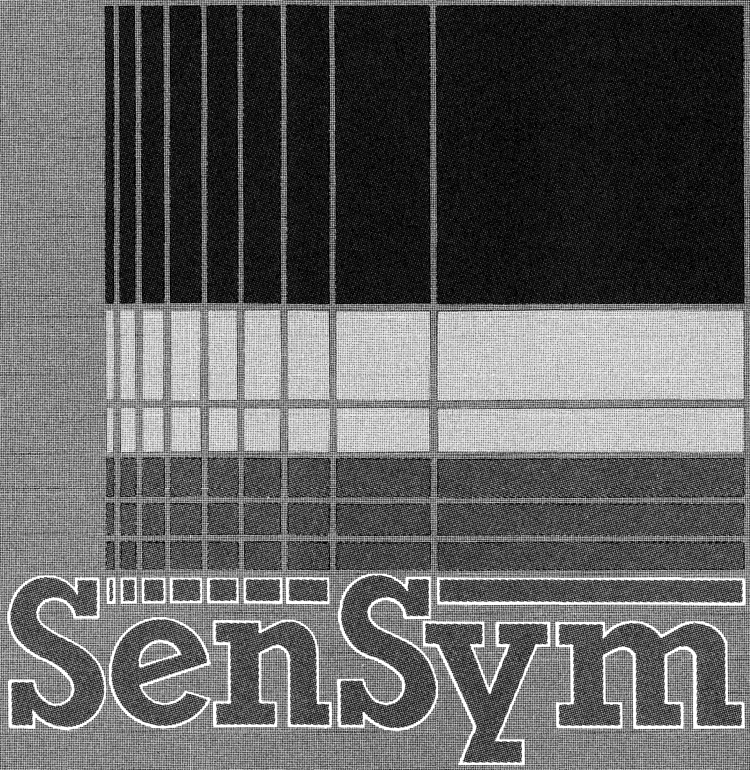
PX8B (Z)

Package for LX18XXGBR Series Pressure Transducers

Weight: 100 Grams

Section 5

Mid- and High-Pressure Range Absolute Pressure Transducers



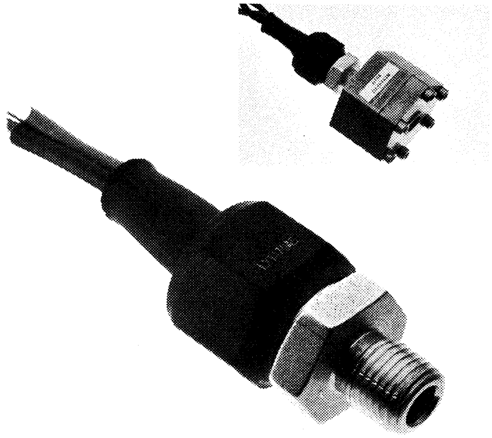
SenSym

LX14XXA Series Mid-and High-Pressure Range Signal Conditioned Absolute Pressure Transducers — 10 Volt Output

General Description

The LX14XX Series provides a selection of ruggedly packaged absolute transducers with operating pressure ranges of 0-100 psia to 0-5000 psia. These devices feature compact concentric brass or stainless steel housings for easy installation with a crescent wrench and 10-inch flying leads for easy soldering and secure electrical connection. The leads are epoxy-sealed to provide protection against hostile exterior environments. Fluid-filled housings are also available for systems using corrosive or conductive working fluids.

Like other Sensym IC pressure transducers, the LX14XXA units are designed to provide high accuracy and excellent stability. They are field interchangeable and can be easily interfaced with auto-reference, control and display systems. Each device is signal-conditioned, including internal temperature compensation, voltage regulation and with low-impedance 10V output span.



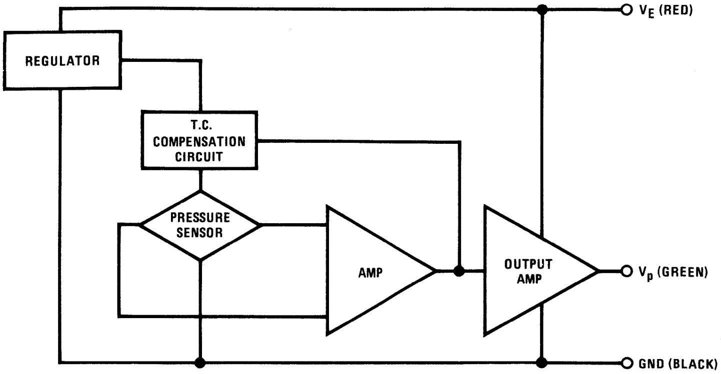
Features

- 0-100 psia to 0-5000 psia
- Rugged concentric housing
- Flying leads
- Submersible fluid-filled versions
- High accuracy and stability
- Temperature compensation
- High level output voltage, 2.5V to 12.5V
- Field interchangeability
- Available from local stocking distributors

Applications

- Engine diagnostics
- Hydraulics
- Off-road vehicles
- Pneumatics
- Pressurized tanks and lines
- Deep well pumps
- Oceanography
- Welding machines

Schematic Diagram



Pressure Transducer Characteristics

Maximum Ratings

Excitation Voltage (Note 1)	30V
Output Current	
Source	20mA
Sink	10mA
Transducer Bias Current	20mA
Operating Temperature Range (Note 2)	−40°C to +105°C

Reference Conditions (Note 3)

Excitation Voltage, V_E (Note 1)	15V
Reference Temperature	25°C
Reference Temperature Range	0 to 85°C
Reference Offset Pressure	0psia

Typical Characteristics

Output Voltage Sensitivity to Excitation Voltage	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leqslant f \leqslant 1$kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	>100kHz
Transducer Bias Current	7 − 10mA
Full Pressure Cycle Life	
LX1420A, LX1430A	~1,000,000 cycles
LX1440A	~500,000 cycles
LX1450A	~100,000 cycles
LX1460A	~50,000 cycles
LX1470A	~10,000 cycles
All Fluid Fills	~5,000 cycles

Performance Characteristics

			Guaranteed Specifications				
			Offset Characteristics		Span Characteristics		
Device Type	Operating Pressure Range	Maximum Over Pressure	Offset Calibration	Shift w/ Temperature 0°C to 80°C	Shift w/ Temperature 0°C to 80°C	Linearity Hysteresis Repeatability (Note 6)	
			V	±%FS	±%FS	±%FS	±psi
LX1420A	0 to 100psia	150psia	2.5 ± 0.25	2.2	2.75	0.67	0.67
LX1430A	0 to 300psia	450psia	2.5 ± 0.25	1.65	2.75	0.67	2.0
LX1440A	0 to 1000psia	1500psia	2.5 ± 0.25	1.65	2.75	1.0	10
LX1450A	0 to 2000psia	3000psia	2.5 ± 0.25	1.65	2.75	1.5	30
LX1460A	0 to 3000psia	4500psia	2.5 ± 0.25	1.65	2.75	2.0	60
LX1470A	0 to 5000psia	5000psia	2.5 ± 0.25	1.65	2.75	3.0	150

			Typical Specifications						
			Offset Characteristics				Span Characteristics		
Device Type	Operating Pressure Range	Maximum Over Pressure	Repeatability (Note 7)		Stability (Note 8)		Sensitivity Calibration	Stability (Note 8)	
			±%FS	±psi	±%FS	±psi	mV/psi	±%FS	±psi
LX1420A	0 to 100psia	150psia	0.4	0.4	1.2	1.2	100 ± 20	0.3	0.3
LX1430A	0 to 300psia	450psia	0.4	1.2	1.0	3.0	33.3 ± 0.67	0.3	0.9
LX1440A	0 to 1000psia	1500psia	0.4	4.0	1.0	10	10 ± 0.2	0.4	4
LX1450A	0 to 2000psia	3000psia	0.4	8.0	1.0	20	5 ± 0.1	0.4	8
LX1460A	0 to 3000psia	4500psia	0.4	12	1.0	30	3.33 ± 0.067	0.4	12
LX1470A	0 to 5000psia	5000psia	0.4	20	1.0	50	2 ± 0.04	0.4	20

Specification Notes:

Note 1: The LX16XX and LX18XX series are not polarity protected. Incorrect application of excitation voltage or ground to the wrong pin can cause electrical failure.

Note 2: Device performance characteristics apply 0 to +85°C, device is functional from −40°C to 0°C and 85°C to +105°C and all the temperature dependent errors are typically doubled over the additional temperature range.

Note 3: Conditions at which device performance characteristics apply.

Note 4: Offset Reference Pressure — for gage and differential devices offset pressure is ambient pressure, for absolute devices offset pressure is the lowest pressure in the pressure range.

Note 5. Temperature tested at 80°C relative to 25°C.

Note 6: Linearity — the maximum deviation of measured output, at constant temperature (25°C), from "best straight line" through three points (offset pressure, full scale pressure, one-half full scale pressure).

$$\%\ \text{FS error} = \frac{V_{\frac{1}{2}\ \text{full scale}} - \left\{\left(\frac{(V_{\text{full scale}} - V_{\text{offset}})}{\text{full scale pressure}}\right) \times \left(\tfrac{1}{2}\ \text{full scale pressure}\right) + V_{\text{offset}}\right\}}{2} \times 100\%$$

(V = measured value for each device)

Note 7: Offset Repeatability — the transducer's ability to reproduce offset voltage at constant temperature (25°C) when cycled through its full operating pressure range.

Note 8: Stability — the transducer's ability to reproduce the output voltage corresponding to a specific pressure and temperature in a period of one year during which maximum ratings are not exceeded.

Note 9: Pressure cycle fatigue is a package related parameter. For LX18XX devices the maximum cycle life is limited by pressure magnitude and package O-ring. LX16XX devices are not limited by O-ring.

Application Guide

The LX14XX Series devices are enclosed in rugged concentric housings that protect the basic integrated circuit pressure transducer from physical abuse and corrosive environments. However, many applications require special consideration of device characteristics.

1. Accuracy Specifications — Auto-referencing

Error parameters are specified separately for offset and span. These errors are independent which allows easy computation of error bands, recalibration, and use of auto-referencing, a technique of automatic recalibration. For a detailed discussion of accuracy specifications and auto-referencing, see Section 6.

2. Use of Absolute as Gage — Altitude Effect

The LX14XXA devices are *absolute* pressure transducers with a vacuum enclosed in the silicon chip for reference. The measured pressure is therefore equal to gage pressure plus the local barometric pressure. This appears as an offset in output signal and can vary from 15 psia near sea level to about 10 psia at 10,000 ft. altitude. The local variations in barometric pressure (≤ 0.5 psi) are normally insignificant, even for the 100 psia device (the LX1420A); but a change from sea level to 10,000 ft. would reduce the apparent gage pressure by 5 psi. If not "zeroed out", this variation could appear as a significant gage error for the LX1420A or LX1430A (300 psia) transducers. To measure gage pressure in these ranges, other Sensym transducers, such as the LX1820GZ, or the LX1830GZ, should probably be used. However, in going to transducers with higher pressure ranges, the barometric offset and variations become less significant, which allows these devices, LX1440A through LX1470A, to easily be used as "pseudo" gage transducers.

3. "Dead-Ending" Feature

If the pressure applied to the transducer greatly exceeds proof pressure (maximum specified operating pressure), the silicon diaphragm could rupture. But, unlike gage transducers, the LX14XXA devices are "dead-ended" so that diaphragm rupture does not influence fluid leakage. However, excessive overpressure can cause deformation of the inner seal which would allow a slow leak of working fluid through the body of the transducer (see *Figure 1*).

4. Leak Rate — Static Systems

The LX14XXA series packages are not hermetic. Sensym's pressure transducers are guaranteed to have an effective leak area less than 10^{-7} cm^2 as defined in Section 9. Each transducer is leak tested at room temperature with 100 psig compressed air.

However, the user should be aware that the leak rate can depend on the type, viscosity, pressure, and the temperature of the working fluid and can increase with fatigue resulting from pressure cycling. This is especially important in static systems where a fluid under pressure is to be maintained for an extended period in an enclosure without replenishment. In such cases it may be necessary to enclose the transducer in the pressure vessel and bring the leads out via a hermetic feedthrough connector installed in the enclosure wall.

5. Fatigue Life — Cyclic Systems

In systems requiring a large number of pressure cycles, such as machine tools, brake systems, and other cyclic pneumatic and hydraulic equipment, the fatigue life of the transducer becomes important. Although the basic sensor can withstand more than one million full operating pressure cycles, the seal between the header assembly and the transducer body degrades such that significant leakage typically occurs within the first several hundred thousand pressure cycles. For enhanced life, the transducer can be completely enclosed in the pressure system as described above for static pressure systems. Some typical values for full-scale pressure cycle life are given in the specification table.

6. Pressure Spikes — Importance of Snubbing

In many cyclic pressure systems, large pressure spikes can occur as a result of pumping action, valve closure, or mechanical resonance. Such spikes can damage the transducer as well as other components in the pressure system. In addition to limiting valve closure rate and avoiding undesirable mechanical resonance, it is good design practice to protect critical components, including the transducer, with adequate snubbing or other damping methods. This can greatly improve reliability by reducing fatigue and avoiding catastrophic failure of the transducer.

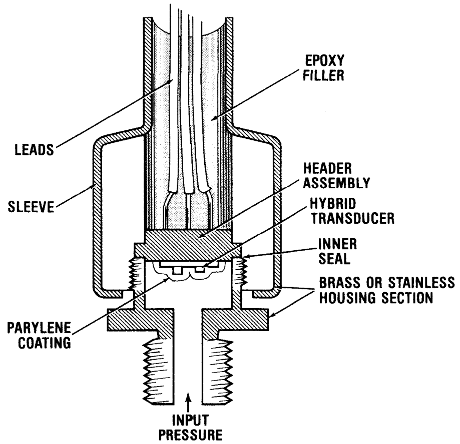


FIGURE 1: LX14XXA Series Transducer Structure

Application Guide (Continued)

7. Fast Response — Measuring Transients

The snubbing problem is also complicated by the fact that older mechanical-type transducers and manometers do not have fast enough response to measure the magnitude of pressure spikes; hence the spikes could go undetected. The LX14XXA series can accurately measure and characterize sub-millisecond pressure transients, if system plumbing does not limit the response time (as is the case in most systems). This fast response capability of the LX14XX series transducers (the overall response time is limited to about 10 kHz by the amplifier circuit) can be used in measuring and evaluating pressure transients as well as for closed-loop operation in fast pneumatic and hydraulic systems. Response time is degraded by damping in the fluid-filled LX14XXA(E,F) series.

8. Compatible Fluids — Humidity

Since the basic integrated circuit pressure transducer element is coated with a thin, compliant materal, the LX14XXA is compatible with many non-aqueous fuels, oils, refrigerants, hydraulic fluids, and non-corrosive gases. But moisture condensate or other ionic, acidic, or corrosive fluids can cause erroneous readings followed by electrical failure.

Fluid-Filled Option

For ionic or corrosive working fluids, such as water, the fluid isolator (E or F version) is recommended. The chart below describes which version (E or F) is more suitable for a given media. Please consult the factory with specific media compatibility questions.

Both fluid-filled isolators (E and F) are recommended for use below 105°C. For high temperature applications, please consult the factory.

9. Submersibility

Although the LX14XXA housing is not fully "hermetic", it is externally submersible as long as ambient pressure doesn't significantly exceed working fluid pressure. For example, it can be used in equipment that must be steam cleaned, or mounted out-of-doors in rain or snow, as long as the working fluid port is properly sealed.

The LX14XXAF series fluid-filled version is fully submersible. For example, it could be immersed directly in water to measure depth.

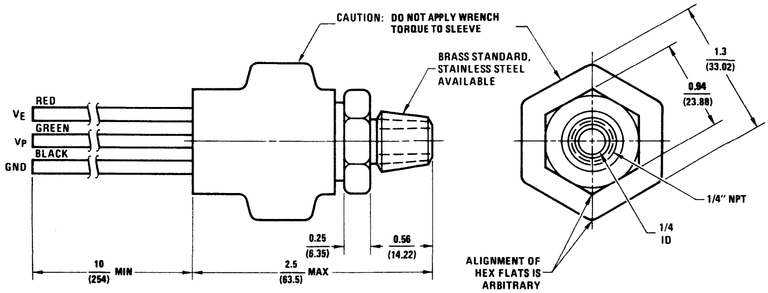
10. Product Options

Option	Description
A—	Absolute Pressure (Brass Housing Standard)
AE—	Fluid Filled—Ethylene-Propylene Diaphragm
AF—	Fluid Filled—Viton Diaphragm
AS—	Stainless Steel Housing
AES—	Fluid Filled (Ethylene-Propylene), Stainless Steel
AFS—	Fulid Filled (Viton), Stainless Steel

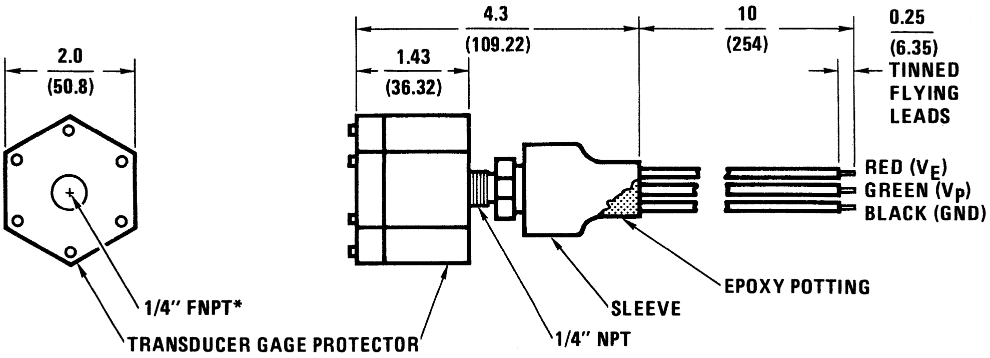
RECOMMENDED DIAPHRAGM MATERIAL

Media	AES (Ethylene-Propylene)	AFS (Viton)
Acid, Inorganic		X
Acid, Organic	X	
Alcohols	X	
Aldehydes, Alkalis, Amines	X	
Animal Oils		X
Ester, Alkyl and Aryl Phosphate	X	
Esters, Silicate		X
Hydrocarbon Fuels		X
Hydrocarbon Oils		X
Hydrocarbon, Halogenated		X
Ketone	X	
Vegetable Oils		X
Water/Steam	X	

Typical Physical Dimensions inches (millimeters)



Package for LX14XXA(S) Series Pressure Transducers
Weight: 105 grams

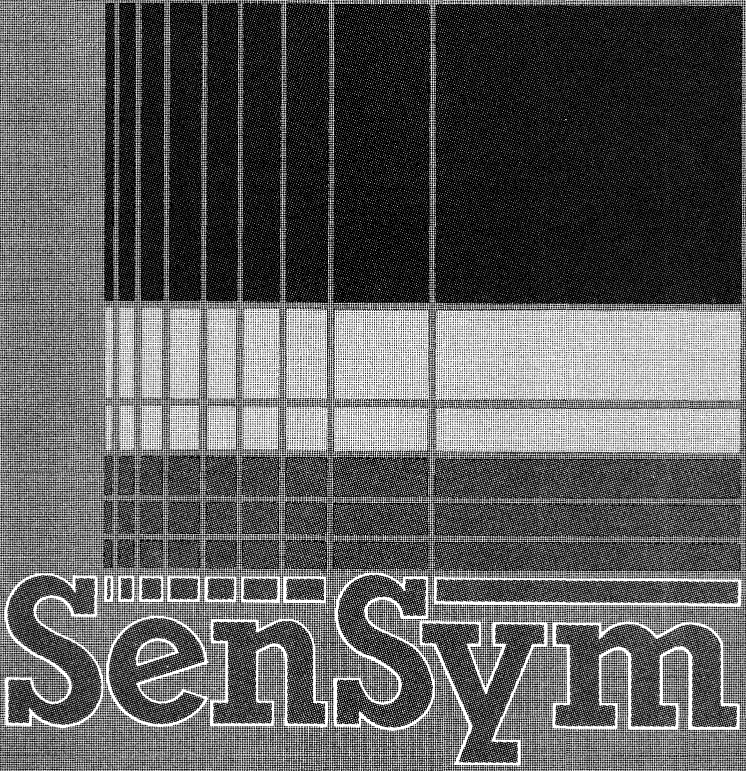


* Insertion of sharp objects into ports will result in permanent damage and, ultimately, device malfunction.

Package for LX14XXA(E,F)(S) Series Pressure Transducers
Weight: 700 grams

Section 6

Pressure Transducer Accuracy and Auto-Referencing



Pressure Transducer Accuracy in Application

SenSym

SSAN-1

After taking environmental (and hence, reliability) requirements into account, the second most important consideration for transducer selection concerns the required accuracy of the device. The concepts and formulas presented here provide a tool with which a user can calculate transducer accuracy for the specific conditions of his application.

A SYSTEM MODEL

To see how transducer performance parameters are related to system accuracy, consider the IC pressure transducer system shown in *Figure 1*. The problem is to determine the magnitude of error for given values of the *major input* (applied pressure) and the *minor inputs* (temperature, time and excitation voltage). The *error sources* are inherent to the transducer, but the magnitude of error from each one may depend on the major and minor inputs to the transducer system.

To simplify our model, we first divide the error sources into two groups: those that are dependent on applied pressure and those that are not. *Figure 2* gives a typical response curve for the transducer, with applied pressure, P_A, on the X-axis and output voltage signal, V_S, on the Y-axis. P_{REF} is the pressure used as a reference in measuring transducer errors. For each of Sensym's transducers, this is defined as the minimum value of the operating pressure range given in the data sheet. V_O, the offset voltage, is the transducer output signal obtained when the reference pressure is applied. P_{MAX} is the high endpoint pressure applied to the device and this yields an output voltage, V_{MAX}. The range and span are then defined as (P_{MAX}-P_{REF}) and (V_{MAX}-V_O) respectively. Device sensitivity, S, is the slope of the line, (Span/Range), and has units of volts/psi.

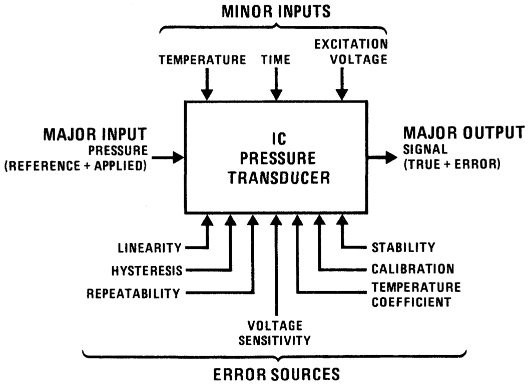
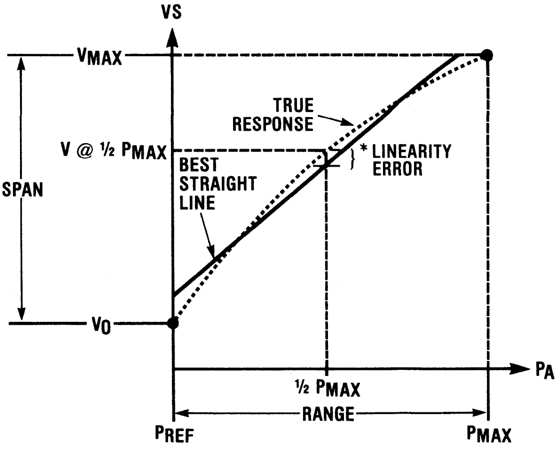


FIGURE 1



* LINEARITY ERROR

$$\% \text{ ERROR} = \frac{V @ \frac{1}{2} P_{MAX} - (V_O + S \cdot \frac{1}{2} P_{MAX})}{2}$$

$$S = \text{SENSITIVITY} = \frac{\text{SPAN}}{\text{RANGE}}$$

FIGURE 2

Because Sensym's transducers are inherently linear, the output signal can be given by:

$$V_S = V_O + S \bullet (P_A - P_{REF}) = V_O + \text{Span} \bullet \frac{(P_A - P_{REF})}{\text{Range}}$$

As a further result, the error in output signal, ΔV_S, can be expressed as:

$$\Delta V_S = \Delta V_O + \Delta \text{Span} \bullet \frac{(P_A - P_{REF})}{\text{Range}}$$

This equation shows that ΔV_O, the offset error, is independent of applied pressure while

$$\Delta \text{Span} \bullet \frac{(P_A - P_{REF})}{\text{Range}},$$

the span error, is proportional to the applied pressure range, $(P_A - P_{REF})$.

Offset errors, being independent of the major input variable (applied pressure), are equivalent to system *common-mode* errors, as shown in *Figure 3*. Because the offset error is the same regardless of pressure, it has the effect of translating the response line up or down, while the slope or sensitivity remains constant.

Span errors, being proportional to applied pressure, are equivalent to system *normal-mode* errors, as shown in *Figure 4*. Because the span error increases linearly with applied pressure, it has the effect of rotating the response line around the offset-reference pressure point.

While independent, the *offset* and *span* error groups both contain errors that are dependent on the minor input variables, as shown in Table I. These coefficients are used to specify the errors in Sensym's pressure transducers and to calculate overall accuracy.

TABLE I. OFFSET AND SPAN ERRORS

OFFSET (Common-Mode)	SPAN (Normal-Mode)
Calibration	Calibration
Repeatability	Linearity-Hysteresis-Repeatability
Stability	Stability
Temperature Coefficient	Temperature Coefficient
Excitation Voltage Coefficient	Excitation Voltage Coefficient

SYSTEM ACCURACY

With the errors divided into 2 groups of independent coefficients, we can now compute both the worst-case error and the most probable error for any IC pressure transducer system.

Worst-Case Error: The worst-case overall error ϵ_{WC} is obtained by simple addition of all applicable errors:

$$\epsilon_{WC} = \sum_{1}^{n} \epsilon_j$$

where ϵ_j is the error resulting from the j^{th} error coefficient and n is the number of error terms included in the calculation.

Most Probable Error: The most probable error ϵ_{MP} is obtained by computing the square root of the sum of the squares:

$$\epsilon_{MP} = \sqrt{\sum_{1}^{n} \epsilon_j^2}$$

We can now select the applicable error coefficients, calculate the error terms, ϵ_j, from the specifications given for any individual pressure transducer, and plug into the appropriate formula above to get system accuracy.

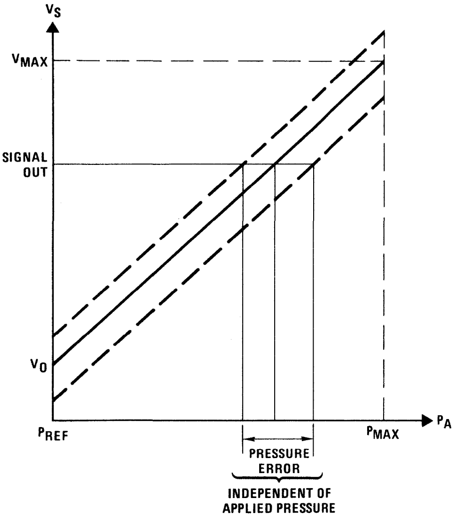


FIGURE 3

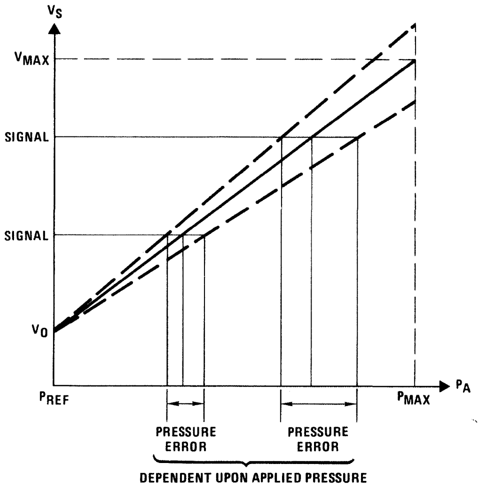


FIGURE 4

ACCURACY SPECIFICATIONS

By convention, system accuracy is expressed in the dimensions of the major input variable, in this case, psi. However, transducer accuracy is typically expressed as percent of full span (%FS). Fortunately, the transposition from one dimension to the other is analytically simple. An error coefficient expressed as %FS is changed to psi by multiplying by the range, ($P_{MAX} - P_{REF}$), of the device under consideration and dividing by 100. So the user can perform accuracy calculations in either dimension, both %FS and psi error values are given in the data sheets for linearity, hysteresis, repeatability, stability, and temperature coefficient.

Three additional points should be noted relative to the data sheet accuracy specifications. Offset calibration error is given directly as volts, since this is the parameter most users actually measure. To convert from volts to %FS, divide offset calibration error by the span voltage (typically 10V for signal-conditioned devices) and multiply by 100. If psi is desired, divide offset calibration error by the device sensitivity (mV/psi) and multiply by 1000 (mV/V). In a similar fashion, sensitivity calibration error is given directly as mV/psi. To convert to %FS, divide by the device sensitivity and multiply by 100. (Because these are linear devices, the ratio of sensitivity error to sensitivity is the same as the ratio of span error to span.) To get psi, divide sensitivity calibration by the sensitivity and multiply by the range.

Finally, supply voltage coefficient (voltage regulation error) is given directly as percentage of supply voltage change. Conversion to psi from %FS would use the same technique discussed in the first paragraph of this page.

OFFSET SPECIFICATIONS

The offset characteristics are measured at reference temperature with reference pressure applied. Although measured at the reference pressure, offset errors given in the data sheet, ΔV_O, are the same regardless of pressure and should be used in the accuracy formulas without any modification for user pressure range. They are defined as follows:

Offset Calibration: Defines the offset voltage and its maximum deviation from unit to unit, including long-term stability (1 year). The deviation is specified in volts and must be divided by full span voltage to express the error band as %FS, or divided by sensitivity to express it as psi, for accuracy calculations.

Offset Temperature Coefficient (TC_O): Defines the maximum deviation in offset voltage as temperature is varied from T_{REF} (25°C) to any other temperature, T, in the operating temperature range. It is specified as %FS/°C or psi/°C and must be multiplied by the temperature difference $|T - T_{REF}|$ to obtain the error at T as %FS or psi. For example, the maximum error for the operating temperature range of Sensym's hybrid transducers (0 to 85°C) would be:

$$TC_O \bullet (T_{MAX} - T_{REF}) = TC_O \bullet (85°C - 25°C) = TC_O \bullet (60°C).$$

Offset temperature coefficient is factory calibrated at 25°C ± 3°C and at 80°C ± 3°C. Any calculation of temperature related error must account for these temperature variations. Typically, errors would be calculated between two points that are at least 15°C apart.

Offset Repeatability: Defines the maximum deviation in offset voltage when applied pressure is cycled through its full range.

Offset Stability: Defines the maximum deviation in offset voltage over a one year period, during which time the pressure and temperature do not exceed their specified maximum ratings.

SPAN SPECIFICATIONS

Full span corresponds to the entire operating pressure range, (P_{REF} to P_{MAX}), specified on the data sheet for each device type. This yields a span voltage, measured at the reference temperature, equal to ($V_{MAX} - V_O$). If an application utilizes a transducer's full operating pressure range, then the span error values given in the data sheet, ΔSpan, can be plugged directly into the error formulas to determine system accuracy. However, if only part of the range is used, the data sheet span errors must be reduced proportionally, since they are a linear function of applied pressure. This is accomplished by taking the actual pressure range used in the application, dividing by the range of the device, and then multiplying each of the data sheet span errors by this ratio (which is a number between 0 and 1). Note that although application span error,

$$\Delta\text{Span} \bullet \frac{(P_A - P_{REF})}{\text{Range}},$$

is defined to include P_{REF}, this is not a user requirement. Span error is simply

$$\Delta\text{Span} \bullet \frac{\text{User Range}}{\text{Range}}$$

for any user range. The data sheet span errors, ΔSpan, are specified as follows:

Sensitivity Calibration: Sensitivity is defined as span divided by the range, $(V_{MAX} - V_O)/(P_{MAX} - P_{REF})$. Sensitivity calibration defines the maximum deviation of sensitivity from unit to unit, including long term span stability (1 year). The deviation is specified as mV/psi and must be divided by the sensitivity to express the error as %FS, or divided by the sensitivity and multiplied by the range to express it as psi, for accuracy calculations.

Span Temperature Coefficient (TC_S): Defines the maximum deviation in span voltage as temperature is varied from T_{REF} to any T in the specified operating temperature range. The coefficient is specified as %FS/°C or psi/°C and must be multiplied by the temperature difference $|T - T_{REF}|$ to obtain the span error as %FS or psi.

Linearity-Hysteresis-Span Repeatability: Linearity defines the maximum deviation of output voltage over the full operating pressure range from this BSL. Hysteresis and span repeatability define the transducer's ability to reproduce an output voltage when cycled through its full operating pressure range. This error is generally lumped with linearity error because it is small by comparison and is usually contained within any real measurement of linearity.

Span Stability: Defines the maximum deviation in span voltage over a one year period during which time pressure and temperature do not exceed their specified maximum ratings.

SYSTEM ACCURACY CALCULATIONS

Voltage Regulation

In the example calculations that follow, we will assume that user excitation voltage is sufficiently regulated so as to make the voltage regulation error, ϵ_{VR}, negligible ($\leq 0.1\%$FS). ϵ_{VR} is an output signal change due solely to a change in excitation voltage. The percent regulation required to satisfy this condition is derived as follows. For signal-conditioned devices, ε_{VR} is given by:

$$\epsilon_{VR} = 0.5\% \bullet \Delta V_e$$

where 0.5% is the specified transducer output voltage change to excitation voltage change and ΔV_e is the excitation voltage deviation [from nominal (15V)]. To keep the regulation error below 0.1%FS, the required external power supply regulation is given by:

$$\frac{\Delta V_e}{V_e} = \left(\frac{1}{0.5\%}\right) \bullet \left(\frac{\epsilon_{VR}}{V_e}\right) = 200 \bullet \left(\frac{\epsilon_{VR}}{\text{Span}}\right) \bullet \left(\frac{\text{Span}}{V_e}\right)$$

Since $\frac{\epsilon_{VR}}{\text{Span}} = 0.1\%$,

$$\frac{\Delta V_e}{V_e} = 20\% \bullet \left(\frac{\text{Span}}{V_e}\right)$$

For Span = 10V and $V_e = 15V$,

$$\frac{\Delta V_e}{V_e} = 20\% \bullet \left(\frac{2}{3}\right) = \pm 13\% \text{ Regulation}$$

which holds for any signal-conditioned pressure transducer.

For monolithics, which do not have any internal regulation or signal conditioning, the formulation is not quite as neat since output characteristics vary from device to device. However, as an approximation, it can be assumed that output signal changes are roughly proportional to changes in excitation voltage. Therefore, to ensure $\epsilon_{VR} \leq 0.1\%$FS would require a power supply with $\leq 0.1\%$ regulation.

If the signal conditioning or monolithic regulation requirements calculated above are met, then regulation error can be eliminated from essentially all error calculations, with the possible exception of ultra-high accuracy applications. However, the greater the deviation from these requirements, the more necessary it becomes to include ε_{VR} in the accuracy calculations. Since both ΔV_O and ΔSpan are affected, ε_{VR} would be included in both segments of the error calculation.

Interchangeable vs. Calibrated Accuracy

Interchangeable Accuracy: In calculating overall accuracy, the first question is whether each pressure transducer will be field calibrated upon installation or replacement. If you're going to just plug it in with no adjustments, you'll need the *interchangeable accuracy*, which allows for unit-to-unit calibration errors. In this case, you include Sensym's calibration errors but exclude stability error (the specified calibration error includes both calibration and stability errors). ε_I, the overall error allowing for direct exchange of transducers of the same type, includes calibration, TC, linearity, hysteresis, and repeatability errors.

Calibrated Accuracy: If you intend to calibrate each device upon installation, you will want to use the *calibrated accuracy*, ε_C, which holds only for one specific transducer. The calibrated overall accuracy excludes Sensym's calibration errors, but includes all other applicable specified errors including stability, TC, linearity, hysteresis, and repeatability.

Example Calculations

The LX1604D is chosen to show how error calculations would be performed for a typical pressure transducer under various conditions. Analogous procedures apply to any Sensym IC pressure transducer and can be extended for use in evaluating errors in a complete pressure system.

Table II is a reproduction of the applicable LX1604D data on page 5-5. The LX1604D operating pressure range is −15 psid to +15 psid. Therefore, $P_{REF} = -15$ psid, $P_{MAX} = +15$ psid, and Range $= (P_{MAX} - P_{REF}) = 30$ psid. V_O (at −15 psid) = 2.5V (from the offset calibration column) and $V_{MAX} = V_O + S \bullet (P_{MAX} - P_{REF}) = 2.5 + (0.333)(30) = 12.5V$ (where the sensitivity value is obtained from the sensitivity calibration column and converted into V/psi). Therefore, Span $= V_{MAX} - V_O = 10V$.

To be consistent with Table I, the data divides the error terms into two categories: those for offset, ΔV_O, and those for span, ΔSpan. Table II further identifies each component of error as follows: ΔV_{O1} is the offset calibration error, ΔV_{O2} is the offset temperature coefficient error, ΔV_{O3} is the offset repeatability error, and ΔV_{O4} is the offset stability error. Likewise, sensitivity (and thus span) calibration error is ΔSpan_1, ΔSpan_2 is the span temperature coefficient error, ΔSpan_3 is the combined linearity, hysteresis, and repeatability error, and ΔSpan_4 is the span stability error. As mentioned previously, where appropriate, both %FS and psi errors are included.

The following calculations are performed using %FS error values. However, completely analogous results would be obtained using psi errors (psi results for each calculation are included for reference purposes).

Maximum Error—Case I

The maximum possible error would occur for the case where the full temperature and pressure ranges are used. Under these temperature conditions, each temperature coefficient is converted to %FS by multiplying the data sheet errors by $(T_{MAX} - T_{REF}) = (85°C - 25°C) = 60°C$. Then:

$$\Delta V_{O2} = 0.03 \times 60 = 1.8\%\text{FS}$$

and

$$\Delta\text{Span}_2 = 0.03 \times 60 = 1.8\%\text{FS}$$

Since the full pressure range is being used, it is not necessary to decrease any of the span errors proportionally. The %FS table values would be plugged directly into the accuracy formulas.

The only conversion remaining is to change calibration errors in the data to %FS. Offset calibration is converted by dividing by span voltage (10V) and multiplying by 100 while sensitivity calibration is converted by dividing by sensitivity (333 mV/psi) and multiplying by 100.

$$\Delta V_{O1} = \frac{100(0.35)}{10} = 3.5\%\text{FS}$$

and

$$\Delta\text{Span}_1 = \frac{100(6.7)}{333} = 2\%\text{FS}$$

Having all %FS values, it is now possible to calculate ϵ_I, interchangeable overall error, and ϵ_C, calibrated overall error, worst-case and most probable error values.

TABLE II. LX1604D PRESSURE TRANSDUCER SPECIFICATIONS

<table>
<tr><th colspan="7">Offset Characteristics</th></tr>
<tr><th rowspan="2">Offset Calibration V ± ΔV_{O1}</th><th colspan="2">Temperature Coefficient ΔV_{O2}</th><th colspan="2">Repeatability ΔV_{O3}</th><th colspan="2">Stability ΔV_{O4}</th></tr>
<tr><th>± %FS/°C</th><th>± psi/°C</th><th>± %FS</th><th>± psi</th><th>± %FS</th><th>± psi</th></tr>
<tr><td>2.5 ± 0.35</td><td>0.03</td><td>0.009</td><td>0.4</td><td>0.12</td><td>1.7</td><td>0.5</td></tr>
<tr><th colspan="7">Span Characteristics</th></tr>
<tr><th rowspan="2">Sensitivity Calibration mV/psi $\Delta Span_1$</th><th colspan="2">Temperature Coefficient $\Delta Span_2$</th><th colspan="2">Linearity Hysteresis & Repeatability $\Delta Span_3$</th><th colspan="2">Stability $\Delta Span_4$</th></tr>
<tr><th>± %FS/°C</th><th>± psi/°C</th><th>± %FS</th><th>± psi</th><th>± %FS</th><th>± psi</th></tr>
<tr><td>333
± 6.7</td><td>0.03</td><td>0.009</td><td>0.67</td><td>0.20</td><td>0.3</td><td>0.1</td></tr>
</table>

For interchangeable overall error, offset stability, ΔV_{O4}, and span stability, $\Delta Span_4$, are eliminated. The remaining offset and span errors are plugged into the ϵ_{WC} and ϵ_{MP} formulas to yield

Worst-case: ϵ_{WCI}

$$= \Delta V_{O1} + \Delta V_{O2} + \Delta V_{O3} + \Delta Span_1 + \Delta Span_2 + \Delta Span_3$$

$$= \underbrace{(3.5 + 1.8 + 0.4)}_{\text{Offset}} + \underbrace{(2 + 1.8 + 0.67)}_{\text{Span}} = \pm 10.17\%FS$$

Most probable: ϵ_{MPI}

$$= \sqrt{\Delta V_{O1}^2 + \Delta V_{O2}^2 + \Delta V_{O3}^2 + \Delta Span_1^2 + \Delta Span_2^2 + \Delta Span_3^2}$$

$$= \sqrt{\underbrace{3.5^2 + 1.8^2 + 0.4^2}_{\text{Offset}} + \underbrace{2^2 + 1.8^2 + 0.67^2}_{\text{Span}}} = \pm 4.83\%FS$$

This corresponds to ± 3.05 psid and ± 1.45 psid respectively.

For calibrated overall error, both calibration errors, ΔV_{O1} and $\Delta Span_1$, are eliminated from the above calculation and the two stability errors, ΔV_{O4} and $\Delta Span_4$, are inserted.

Worst-case: ϵ_{WCC}

$$= \Delta V_{O2} + \Delta V_{O3} + \Delta V_{O4} + \Delta Span_2 + \Delta Span_3 + \Delta Span_4$$

$$= \underbrace{(1.8 + 0.4 + 1.7)}_{\text{Offset}} + \underbrace{(1.8 + 0.67 + 0.3)}_{\text{Span}} = \pm 6.67\%FS$$

Most probable: ϵ_{MPC}

$$= \sqrt{\Delta V_{O2}^2 + \Delta V_{O3}^2 + \Delta V_{O4}^2 + \Delta Span_2^2 + \Delta Span_3^2 + \Delta Span_4^2}$$

$$= \sqrt{\underbrace{1.8^2 + 0.4^2 + 1.7^2}_{\text{Offset}} + \underbrace{1.8^2 + 0.67^2 + 0.3^2}_{\text{Span}}} = \pm 3.17\%FS$$

This corresponds to ± 2.00 psid and ± 0.95 psid respectively.

Reducing Temperature Errors—Case II

Since the temperature coefficients are two of the main error components, a reduced temperature range can greatly reduce overall error. For 80% effective temperature compensation (reducing effective range from 60°C to 12°C), the offset and span temperature coefficients would be

$$\Delta V_{O2} = 0.03 \times 12 = 0.36\%FS$$

and

$$\Delta Span_2 = 0.03 \times 12 = 0.36\%FS$$

The interchangeable overall errors would then be reduced to

Worst-case: ϵ_{WCI}

$$= (3.5 + \underbrace{0.36} + 0.4) + (2 + \underbrace{0.36} + 0.67) = \pm 7.29\%FS$$

Reduced TC Errors

Most probable: ϵ_{MPI}

$$= \sqrt{3.5^2 + 0.36^2 + 0.4^2 + 2^2 + 0.36^2 + 0.67^2}$$

$$= \pm 4.14\%FS$$

This corresponds to ± 2.19 psid and ± 1.24 psid respectively, reduced from ± 3.05 psid and ± 1.45 psid in Case I.

A corresponding improvement is achieved for the calibrated accuracy:

Worst-case: ϵ_{WCC}

$$= (\underbrace{0.36} + 0.4 + 1.7) + (\underbrace{0.36} + 0.67 + 0.3) = \pm 3.79\%FS$$

Reduced TC Errors

Most probable: ϵ_{MPC}

$$= \sqrt{0.36^2 + 0.4^2 + 1.7^2 + 0.36^2 + 0.67^2 + 0.3^2}$$

$$= \pm 1.96\%FS$$

This corresponds to ± 1.14 psid and ± 0.59 psid respectively, reduced from ± 2.00 psid and ± 0.95 psid by 80% effective temperature compensation.

Reduced Pressure Range—Case III

When the full specified pressure range of a particular device is not being used, all span errors should be reduced by the ratio R, where R is defined as:

$$R = \frac{\text{User Range}}{\text{Device Specified Range}}$$

Assume, for example, that the user application is for +5 psid to + 15 psid. Then R = 10 psid/30 psid = 0.333, and each application span error would be

$$\Delta Span_1 = 2 \times 0.333 = \pm 0.67\%FS$$

$$\Delta Span_2 = 0.03 \times 0.333 = \pm 0.01\%FS/°C$$

$$\Delta Span_3 = 0.67 \times 0.333 = \pm 0.22\%FS$$

$$\Delta Span_4 = 0.3 \times 0.333 = \pm 0.1\%FS$$

If Case II conditions above are maintained, then the interchangeable overall errors would now be reduced to

Worst-case: ϵ_{WCI}

$$= (3.5 + 0.36 + 0.4) + \underbrace{(0.67 + 0.12 + 0.22)}_{\text{Reduced Span Errors}} = \pm 5.27\%FS$$

Most probable: ϵ_{MPI}

$$= \sqrt{3.5^2 + 0.36^2 + 0.4^2 + 0.67^2 + 0.12^2 + 0.22^2}$$

$$= \pm 3.61\%FS$$

This corresponds to ± 1.58 psid and ± 1.08 psid respectively, reduced from ± 2.19 psid and ± 1.24 psid in Case II.

NOTE: The reduced pressure range decreases span error values only. Offset errors remain unchanged!

For calibrated overall error

Worst-case: ϵ_{WCC}

$$= (0.36 + 0.4 + 1.7) + \underbrace{(0.12 + 0.22 + 0.1)}_{\text{Reduced Span Errors}} = \pm 2.90\%\text{FS}$$

Most probable: ϵ_{MPC}

$$= \sqrt{0.36^2 + 0.4^2 + 1.7^2 + 0.12^2 + 0.22^2 + 0.1^2}$$

$$= \pm 1.80\%\text{FS}$$

This corresponds to ± 0.87 psid and ± 0.54 psid, respectively, reduced from ± 1.14 psid and ± 0.59 psid in Case II, by using 1/3 of the LX1604D pressure range.

Auto-Reference Compensation—Case IV

A powerful, easy-to-use, and generally applicable technique, auto-referencing, can often eliminate all offset errors by period sampling of the offset voltage at reference pressure. With this technique, (see Section 6), only the span errors apply. Again, using the LX1604D specifications and assuming all Case III conditions hold, the interchangeable accuracy is:

Worst-case: ϵ_{WCI}

$$= \underbrace{(0.67 + 0.12 + 0.22)}_{\text{Span Errors}} = \pm 1.01\%\text{FS}$$

Most probable: ϵ_{MPI}

$$= \sqrt{0.67^2 + 0.12^2 + 0.22^2} = \pm 0.72\%\text{FS}$$

This corresponds to ± 0.30 psid and ± 0.22 psid, respectively, reduced from ± 1.58 psid and ± 1.08 psid in Case III.

Calibrated overall error would be

Worst-case: ϵ_{WCC}

$$= \underbrace{(0.12 + 0.22 + 0.1)}_{\text{Span Errors}} = \pm 0.44\%\text{FS}$$

Most probable: ϵ_{MPC}

$$= \sqrt{0.12^2 + 0.22^2 + 0.1^2} = \pm 0.27\%\text{FS}$$

This corresponds to ± 0.13 psid and ± 0.08 psid, respectively, reduced from ± 0.87 psid and ± 0.54 psid in Case III.

Auto-Reference + Temperature Control—Case V

For very high accuracy applications, both auto-referencing and complete temperature range reduction may prove valuable. In these cases, the additional temperature compensation may take the form of a temperature-controlled chamber designed to hold temperature within a few degrees of T_{REF} (which may be shifted to a higher temperature to allow use of an oven). In such a case, the only errors included are linearity, hysteresis, span repeatability and either span calibration or span stability. For interchangeable accuracy, span calibration error is included:

Worst-case: ϵ_{WCI}

$$= \underbrace{(0.67 + 0.22)}_{\text{Span Errors without TC}} = \pm 0.89\%\text{FS}$$

Most probable: ϵ_{MPI}

$$= \sqrt{0.67^2 + 0.22^2} = \pm 0.71\%\text{FS}$$

This corresponds to ± 0.27 psid and ± 0.21 psid respectively.

For calibrated accuracy, span stability error is including:

$$\text{Worst-case: } \epsilon_{WCC} = \underbrace{(0.22 + 0.1)}_{\text{Span Errors without TC}} = \pm 0.32\%\text{FS}$$

$$\text{Most probable: } \epsilon_{MPC} = \sqrt{0.22^2 + 0.1^2} = \pm 0.24\%\text{FS}$$

This corresponds to ± 0.10 psid and ± 0.07 psid respectively.

Periodic Span Calibration—Case VI

With overall error down to a fraction of a psi, resulting from auto-referencing and temperature control, the periodic recalibration of span may become worthwhile. Since the span stability error is a slowly aging variation of span voltage, a periodic recalibration may well reduce this error by an order of magnitude. This procedure eliminates calibration error, so only calibrated accuracy applies.

$$\text{Worst-case: } \epsilon_{WCC} = (0.22 + \underbrace{0.01}_{\text{Reduced Stability Error}}) = \pm 0.23\%\text{FS}$$

$$\text{Most probable: } \epsilon_{MPC} = \sqrt{0.22^2 + 0.01^2} = \pm 0.22\%\text{FS}$$

This corresponds to ± 0.07 psid in both cases.

Linearity Compensation—Case VII

For ultra-high accuracy applications, the remaining error, linearity-hysteresis-span repeatability, must be reckoned with. The hysteresis and repeatability components of this coefficient are so small as to approach the noise in the operational amplifier included in the signal-conditioned IC pressure transducer. This noise is about 0.4%FS for a 1 kHz bandwidth and may require narrow bank filter techniques if ultra-high accuracy is to be achieved. We do know, however, that the linearity error is a large fraction of the remaining error, perhaps as high as 90%, and that it can be successfully compensated via curve-fitting techniques to reduce overall calibrated error to about ±0.1%FS, worst-case.

SUMMING IT UP

The foregoing offers the reader a quantitative technique for separating transducer errors and evaluating their contribution to system accuracy, as well as describing several methods for system optimization. It is hoped that this will encourage the transducer user to take a closer look at system requirements as they relate to each of the parameters and optimization techniques discussed, thereby allowing him to make optimum accuracy/cost design tradeoffs. Too often, transducer application specifications are unnecessarily tight, simply because an analysis similar to the one performed above has not been done. The result of this over-specification is unnecessary cost.

Basics of Auto-Referencing

SenSym

SSAN-2

Auto-referencing is a family of powerful techniques used to compensate time and temperature errors by periodic correction of the output signal with respect to one or more reference pressure levels. The error correction circuits are usually simple and low in cost, and at least one pressure level suitable for referencing is usually accessible or can be easily produced. So, it's natural to want to use auto-referencing, since the alternative (an expensive precision pressure transducer) is usually more trouble than it's worth and definitely more expensive than an auto-referenced pressure transducer with comparable accuracy. While it's never wise to declare that a technique is "universal", some techniques are so powerful that it becomes easier to cite instances where the technique should not be used than where it should. Auto-referencing is just such an "almost universal" technique. Why then is this technique not more widely used with transducers? Traditionally, transducer users and producers are "linear/analog" oriented people, to whom "digital" people are those other guys in the soft world. Factually, analog approaches to auto-referencing are less cost effective. So, there's a natural reluctance for analog people to employ digital circuitry for an analog function. Yet, all mensuration theorists and educators highly recommend the technique. Therefore, the message is...get on board, fellow analogers, digital auto-referencing is good for you.

Which pressure transducer users should *not* use a common-mode auto-referencing circuit? In applications involving a short measurement cycle, where the zero point is either read or manually adjusted at the start of the cycle, an auto-referencing circuit is of no value. In acoustic measurements where the transducer is AC coupled such that DC or steady state response is of little value, common-mode auto-referencing won't help. In all other applications, common-mode auto-referencing yields the optimum accuracy for the lowest cost.

COMMON-MODE AUTO-REFERENCING — EASY AND EFFECTIVE

Common-mode errors are generally the largest (especially at lower pressures, where it really counts in some applications) and therefore give way to the greatest accuracy improvement when auto-referenced. They are also the easiest to auto-reference as shown in *Figure 2,* since all that's required is to sample the signal at reference pressure and subtract the error from the signal at any "measure" pressure. This is expressed by the formula

$$V_{SCM} = V - \Delta V_o$$

where V is any measure pressure signal, ΔV_o is the error pressure signal and V_{SCM} is the output signal corrected for common-mode error by subtracting the error from the measure signal. As seen in *Figure 2*, no slope correction is involved.

The basic auto-reference functions required to implement this formula are shown in *Figure 3.* They include a switch, a sample-and-hold, and interconnecting logic for synchronizing with the measure-reference cycle.

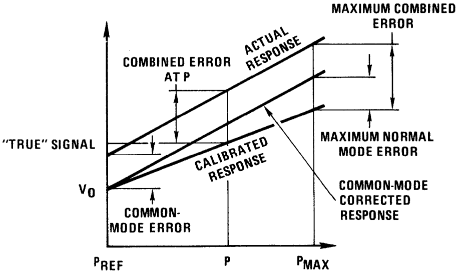


FIGURE 1. Transducer Errors

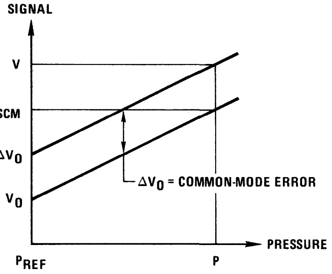


FIGURE 2. Common-Mode Error Correction

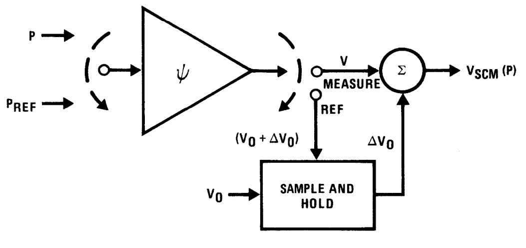


FIGURE 3. Basic Common-Mode Auto-Reference Functions

What's the best way to use auto-referencing? The correct, but imprecise, answer is...as often as you can. The object is to have those measurements of greatest interest closest in time to an auto-reference command. The kind of duty cycle naturally best suited to auto-referencing is "short repeated cycles", each containing a reference point. Another well suited kind of duty cycle is a short interest period immediately preceded by a referencing point, but followed by a long no-interest period. In either case, a measurement point of interest is within several hours of the preceding reference point. Most applications have duty cycles that are in one of the two aforementioned "naturally well suited for auto-referencing" categories. Equally important, many applications that have duty cycles not naturally well suited can be converted to the short repeated cycle situation with relative ease if the value of doing so is recognized by the designer early enough. The simplest of the best suited applications involve things that go up, then go down, and then rest awhile. Ideally, the pressure increases rapidly to the range of interest, hovers at the measurement condition, decreases quickly, and hovers at the reference condition.

Some applications very closely resemble the ideal description. For example, a weighing scale is ideal. Also ideal are filling washing machines, beer bottles, and toilet tanks. Another ideal category is pressure sumps such as tire pressure, oil pressure, and blook pressure.

In these cases, the measurement apparatus is usually turned-on at a reference condition before experiencing the measurement condition of interest. Less ideal, but certainly improved by auto-referencing, are flow measurement and control applications. Examples are fuel pumps, pulmonometers, and even machines that smoke cigarettes. In these cases, the flow rate is zero at some point in a relatively short cycle...usually at turn-on.

The trick is to cause the command signal at the right time. The best time is after the transducer is warmed up and when the application is hovering at a reference condition. All the previous examples were of a type wherein the reference condition exists at and shortly after turn-on. This makes life easy. If the warm-up error is of little concern, then the turn-on signal can be used directly as the command signal, as shown in *Figure 4*.

Other ways of getting the required momentary command signals often present themselves as appropriate to the application. For example, in weighing systems, some displacement is inherent just as the load is applied to the scale pan barely before pressure build-up, an invitation to use a mechanical switch.

SIMPLE CIRCUIT FOR SIMPLEST CASE

The momentary switch referred to for the simplest case, forms an enable signal for input to the command gate, *Figure 5*.

The basic functions of an auto-reference circuit are shown in *Figure 6*.

The leading edge, negative transition of the enable signal resets the control latch and resets the counter to zero. While in the low state, the enable signal inhibits the

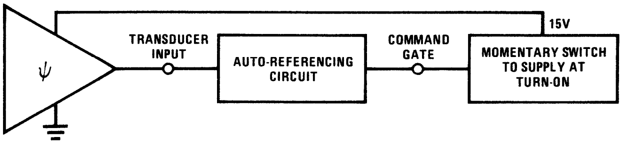


FIGURE 4. Auto-Reference Commanded by Turn-on

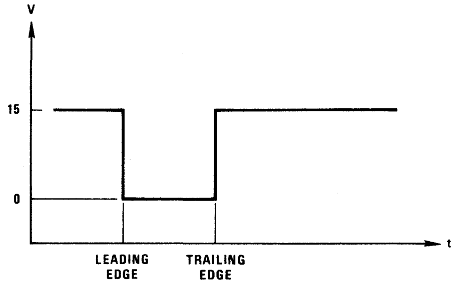


FIGURE 5. Typical Auto-Reference Enable Signal

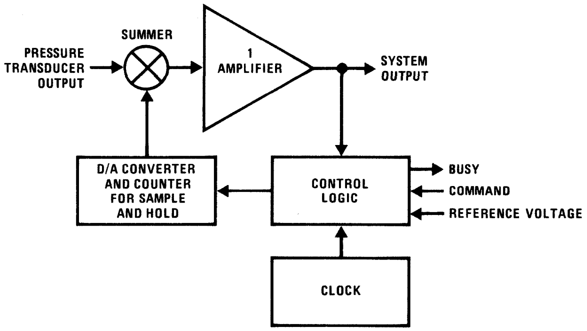


FIGURE 6. Basic Functions of Digital Auto-Reference Circuit

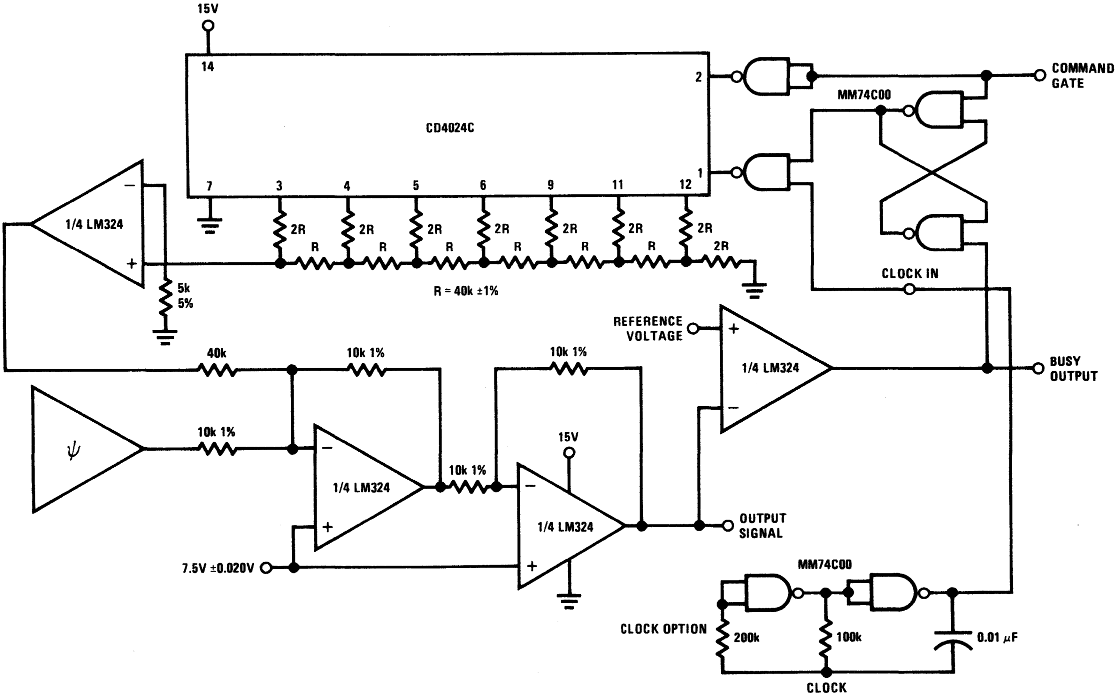
counter from accepting input pulses to allow time for stabilization of pressure. The referencing sequence is initiated on the trailing edge, positive transition of the enable signal. The D to A converter is used as an infinite sample-and-hold as well as a programmable voltage source, supplying and maintaining the desired correction voltage. The output of the transducer is summed with the auto-reference correction voltage at the summing junction of the first amplifier. The circuit is shown in *Figure 7.*

The "bit" rating of the (D/A) determines the resolution of the output signal. The quality of regulation of the reference voltage applied to the (D/A) determines the system stability. Thus, these easily attained circuit parameters take control of the transducer system's key accuracies. The control logic resets the (D/A), steers clock pulses into the (D/A) until the system output is at reference voltage and sends a busy signal to the sequence logic *(Figure 7).*

SIMPLE PLUMBING FOR TOUGHER CASE

Duty cycles fall into two main categories...*batch process* and *continuous process.* In batch process, the reference condition generally exists right at process turn-on. For example, a weighing scale would be turned on before the load is applied and would be at reference conditions before and after loading. Similarly, the washing machine water level is zero both before and after the duty cycle and turn-on coincides with zero level. A sphygmomanometer is inflated during blood pressure measurement and is deflated both before and after duty cycle and in particular at turn-on. Whether at turn-on or not, at some point in a batch process, there is an obvious reference condition. In continuous process, the reference condition generally doesn't exist at all unless plumbed. In these cases, a solenoid is actuated as often as application allows. Generally, a cyclic pattern is developed. A clock circuit is often involved. In all cases, solenoid actuation causes reference pressure, so that auto-reference command is in sync with solenoid actuation.

Suppose you needed to know the flow rate of a river at various locations along its length. You'd need to know the cross sectional area, of which depth is a variable factor... and you'd need to know the flow velocity. Pressure transducers are likely choices for sensing both variables. Clearly, this application lacks features of the "naturally well suited for auto-referencing" kind. Unlike the toilet tank, there is no time at which the depth and velocity are known. In the previously described applications, there was always a known reference condition when the user consciously or inadvertently gave the command signal immediately preceding a measurement condition. In other words, the user knew when the measurand was at reference condition...thereby commanding auto-referencing at the reference condition and reading or controlling at the measurement condition. In this new breed of application, we need to access the reference condition rather than lay in wait. That is, there is a reference condition available. It won't walk up and attach itself to our pressure tube— but it is accessible if plumbed.



Capture Range	± 2V
Least Significant Bit	30 mV
Supply Current	10 mA
Recommended Reference Voltage	2.5V at 0 psi
Signal Input Impedance	10 kΩ

Busy Output	
Conversion in Process	0V
Conversion Complete	15V
Command Gate Should be Kept at	15V
Momentary Grounding Initiates Auto-Reference Command	

FIGURE 7. Auto-Reference Circuit with D/A Converter

ACCESS PLUMBING AND ACTUATION

In addition to the "transducer/auto-reference/enable" system for the simple case, a reference condition actuator is required. The actuator can be turned-on by the user, or by some usage condition (like power-up), or by a timer circuit (clock). Some actuators are self-limiting in duration... others must be turned-off after auto-referencing, as shown in *Figure 8.*

Busy signal duration is substantially longer than is enable signal duration so as to allow reference pressure stabilization and time to reach reference signal, as shown in *Figure 9.*

Consider the depth measurement in our river. Suppose we use either a gage or absolute pressure transducer near the bottom with a vent tube to the surface (along with the bundle of wires). A 3-way solenoid valve plumbed between the transducer inlet port, the water, and the vent tube... serves as the reference actuator. A timer circuit acts as enabler *(Figure 10).*

Consider the velocity measurement in that river. This requires a differential pressure transducer. A 2-way solenoid valve plumbed between the two inlet ports of the transducer serves as reference actuator, as shown in *Figure 11.*

COMMANDING AUTO-REFERENCING

Starting

Now that we know when to auto-reference, how do we command it? Electrically, the command gate of the auto-reference circuit must see a positive voltage transient exceeding a threshold voltage and a return to a voltage below the threshold. The model of a momentary switch from ground to supply, as shown in *Figure 12,* is practical but overly restrictive. There are three levels of sophistication that can be used to command auto-reference.

The simplest way is *manual command.* A momentary contact pushbutton switch can be used that turns on auto-reference alone or in conjunction with display or even with total electronics. If the switch function used approximates a step, as would be the case for bias turn-on, then the signal must be differentiated by the command circuit to initiate the zeroing sequence.

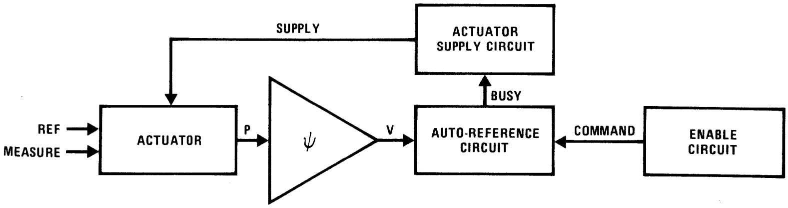


FIGURE 8. Auto-Reference with Reference Condition Actuators

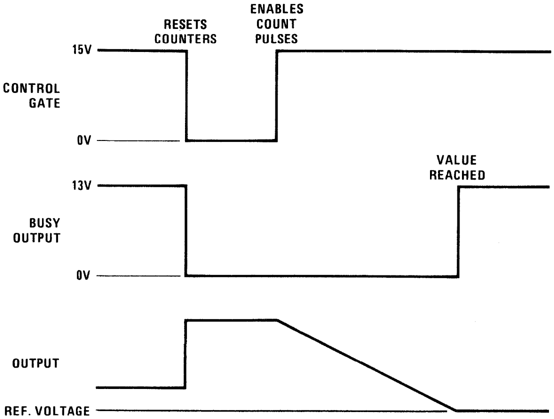


FIGURE 9. Timing Pulses for Reference Condition Actuator Circuit

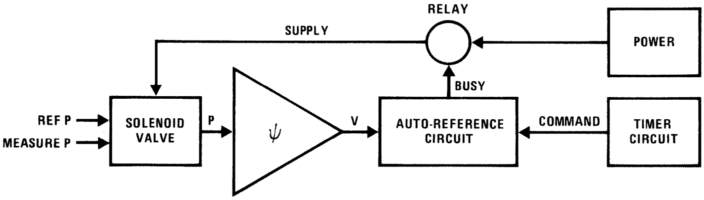


FIGURE 10. Timer-Actuated Circuit — Single-Port Transducer

More elegant is the *semiautomatic command.* Consider a stepping switch. It could be manually initiated in a manner described for manual command. But, it could then sequence through such steps as solenoid actuation, followed by auto-reference command, followed by return to measurement mode. A shift register or a sequence counter would be a more electronic and less expensive substitute for the stepping switch.

Most sophisticated is the *automatic command.* Consider now a stepping switch that actuates the solenoid, commands the auto-reference, then triggers the timing circuit that upon expiration will restart the sequence, and finally returns to measurement mode. Again, the register or counter can substitute for the switch. However, consider a stepping switch that also contains both the timing circuit and the auto-reference circuit and even drives the display. This, of course, is a microprocessor.

Sequencing

The actuation and auto-reference command block diagram is shown in *Figure 13.* Within the sequence function, coincidence logic assures that the start signal and reference conditions occur simultaneously. Coincidence detection is commonly provided by an "exclusive OR" circuit like an NSC MM74C86 CMOS. Steering logic receives the coincidence signal and the auto-reference completion (end busy) signal and instigates stepping. Steering commonly employs "NAND gates" and "Flip Flops" like NSC MM74C00 CMOS and NSC MM74C74 CMOS respectively. Stepping logic takes signals from the steering logic and directs the output function. If a timer is controlling the start function, the stepper may also be used to reset the timer, thereby directing sequence. Stepping commonly uses "shift registers" like NSC MM74C164 CMOS or "counter/dividers" like NSC MM5622A CMOS. The entire sequence function controls the output function.

Accuracy

The beauty of the auto-reference technique can now be examined in terms of system accuracy and resolution. The common-mode errors contributed by the pressure transducer, which appear as a reference drift due to various effects and a lack of reference resolution, are totally replaced by the accuracy limits of the auto-reference circuit. Reference drift is solely a function of voltage regulation since it is as stable as the reference voltage. That error can be made virtually zero. Resolution is a function of the "bit" rating of the D/A converter. Auto-reference circuits can vary greatly in cost depending on such application requirements as offset capture range and resolution. If the pressure transducer is properly chosen, the circuit can reduce offset (common-mode) error to from 1/4% span to 1/2% span, leaving only the substantially less severe sensitivity based (normal-mode) transducer errors to contribute to system error. . . not a bad trick for the price of an inexpensive circuit and possibly a solenoid valve. Needless to say, we at Sensym recommend auto-referencing for everybody.

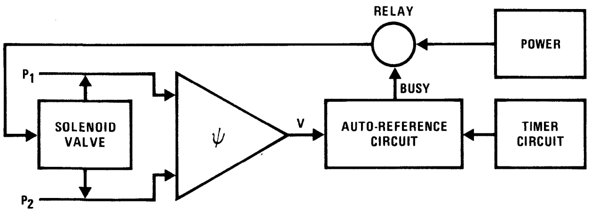


FIGURE 11. Timer-Actuated Circuit — Dual-Port Transducer

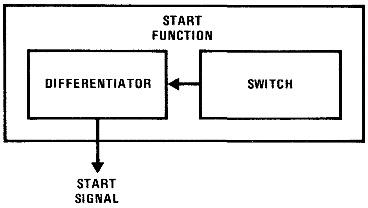


FIGURE 12. Momentary Switch Start Signal

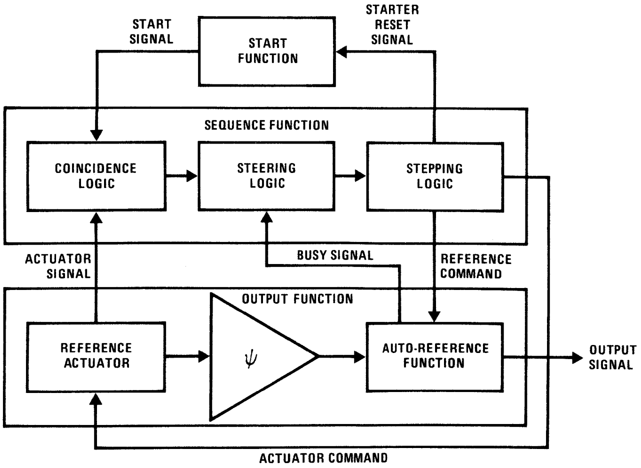


FIGURE 13. Auto-Reference Sequencing Logic

LIMITED AUTO-REFERENCING...EXAMPLE ANALYSIS

Example Conditions:

1. System to operate over an extended temperature range (−40°C to +105°C).
2. System monitors both pressure and temperature.
3. Auto-referencing is to be employed at start-up when pressure is known to be zero. Temperature at auto-reference condition can be over the full operating range and is known.
4. Interchangeability is required.

Example Analysis:

1. A Look at the System without Auto-Referencing...

   The sole purpose of the auto-referencing feature of this system is to periodically eliminate pressure offset errors due to time. These can be associated with the sensor itself or be part of the sensor signal conditioning. Therefore, the entire focus of this analysis will address only offset errors due to stability of offset over time and temperature related errors. *Figure 14* displays the two key offset error terms of this system without auto-referencing.

   This is for the LX1830GZ device. A constant-error budget for stability for one year is taken at one percent full-scale. Additional error must be added for temperature related error associated with device temperatures different from the factory calibrated temperature of 25°C. This error is, an additional error, added at a rate of 0.02% full-scale per degree centigrade from 25°C. For this device these two errors contribute slightly greater than 2% full-scale error over the specified operating temperature range and would contribute in excess of 3% full-scale error over extended operating temperature range of the device. Temperature errors are added at twice the rate outside the specified operating temperature range.

2. A Look at the System with "Blind" Auto-Referencing...

   Figure 15 has added two curves, auto-reference #1 and auto-reference #2 to *Figure 14* curves. Auto-reference #1 is the resulting error due to auto-referencing occurring at maximum specified operating temperature. Auto-reference #2 is the resulting error due to auto-referencing occurring at maximum extended operating temperature. In auto-reference #1 case, more error has been added to the system when operated below t_1 (~35°C) than was eliminated, as much as 0.6% full-scale. For auto-reference #2 additional error is added when the system is operated below t_2 (~55°C). A person may attempt to eliminate this error by using the temperature to remove temperature error as well. This would eliminate interchangeability, since temperature compensation varies from device to device and would be extremely costly to implement in software.

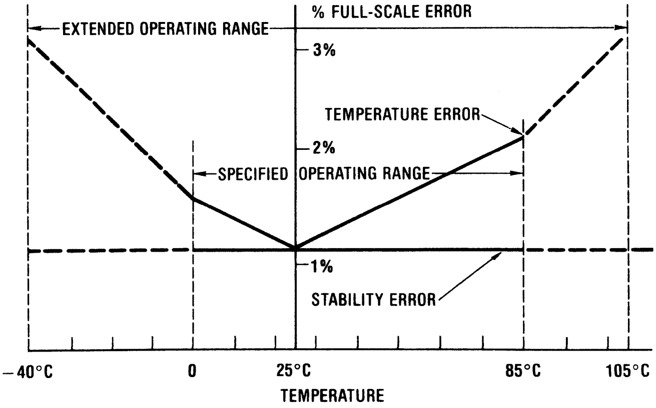


FIGURE 14. Typical Offset Stability and Offset Temperature Errors

Example Solution...

Figure 16 shows effects of auto-referencing over a limited temperature range, the auto-reference temperature band. Since the temperature is known, it becomes a simple matter to set an auto-reference "enable" condition for the system. In the "enable" state auto-referencing takes place, if not "enabled" then no auto-referencing can occur. The auto-reference temperature band must be set to "enable" auto-referencing on a periodic basis.

Close:

Worse case conditions for this example were chosen by having auto-referencing occur at maximum temperatures. Most systems will have auto-referencing occurring at a low temperature and then the system will heat up during operation. A similar analysis is still valid in that case. Except for this temperature difference this example is very similar to what is desired for pressure monitoring systems of vehicles such as diesel or gasoline engines.

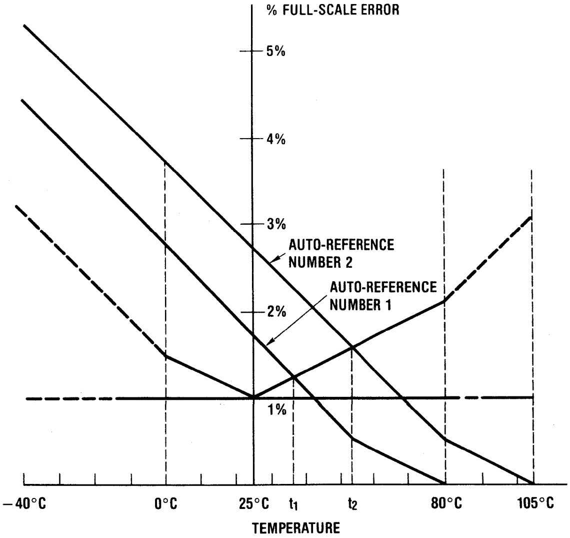


FIGURE 15. ***Figure 1*** **with Auto-Reference #1 and Auto-Reference #2 Curves Added**

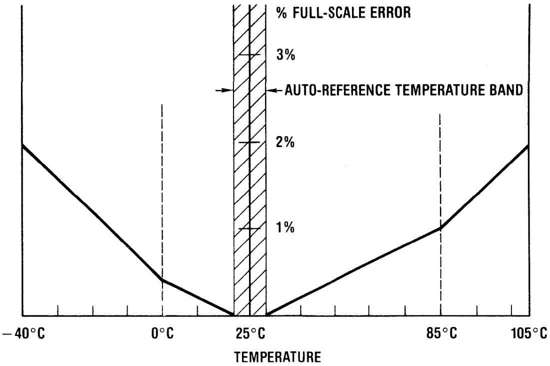


FIGURE 16. Limited Auto-Referencing

Section 7 Standard Product Options

SenSym

Introduction

Standard Options

The options described in this section are available for a variety of devices as an addition to the standard product features. These options generally allow the devices to be used in a wider range of applications.

Policies

The standard options are designed to allow some degree of product customization without the typical lead times, minimum quantities, and costs associated with "custom" products. Typically, only the following policies will apply:

- Ten (10) piece minimum order quantity.
- Small added charge (quantity dependent).
- Less than one week additional processing time.

Ordering Information

To order any devices with a standard option, the option number(s) are added to the standard part number. For example, an LX1601A with high humidity protection would be ordered as an LX1601A-1. If in addition to high humidity protection, data logging was also required, the part would be ordered as LX1601A-1-4.

Pressure Transducer Moisture Resistant Coating -1 Option

SenSym

Purpose

There are two primary reasons for ordering the moisture resistant coating herein referred to as the "−1" option.

1. For GB style parts, the "−1" option offers protection against high humidity ambients.
2. For A or D style parts, the "−1" option provides protection against intermittent contact with room temperature water and high humidity air.

This coating is not recommended for applications where long-term contact with water is required.

Features

The basic features of the "−1" option are:

- Moisture resistant coating of the electronics
- Molded connector with flying leads for electrical connection (LX18XX devices only)

Discussion

The "−1" option is recommended primarily for use with backward gage (GB) style parts which are used in high humidity ambients. These are typically found in energy management or environmentally exposed applications.

The (GB) style parts have been tested at 85°C/85% relative humidity for 1,000 hours.

This option can also be used with low pressure A or D style parts in certain applications as a barrier against H_2O and "other" fluids. Please consult the factory on applications where "other" fluids are used.

When using the "−1" option with A or D style parts, the maximum pressure must not exceed 60 psi. The A and D style parts have been tested with room temperature water and 85°C/85% relative humidity air for 1,000 hours.

Availability

The following parts can be ordered with the "−1" option.

Low Pressure*

LX0603GB
LX1601GB
LX1602GB
LX1603GB
LX1801GB (Z, N)
LX1802GB (Z, N)
LX1803GB (Z, N)
LX1804GB (Z, N)

LX0503A
LX1601A
LX1602A
LX1603A
LX1801A (Z, N)
LX1802A (Z, N)
LX1803A (Z, N)
LX1804A (Z, N)

High Pressure

LX1604GB
LX1610GB
LX1620GB
LX1810GB (N, Z)
LX1820GB (N, Z)
LX1830GB (N, Z)

*Low pressure differential devices used in wet/wet applications may be available if common-mode pressure is below 60 psi.

Ordering Information

To order parts with the "−1" option, add the "−1" suffix to the part number. For example, an LX1601A with the "−1" option is ordered as an LX1601A−1.

Flying Lead Option for LX18XX Series Pressure Transducers

-2 Option

SenSym

General Description

This option, standard feature for all LX18XXGBR devices, uses flying wire leads in lieu of a molex connector for electrical connection. For this option, leads are internally soldered to a sensor versus insertion force snugging with a molex connector. This feature provides added protection to prevent intermittent contact in high vibration applications. A rubber interlock holds wires in place and provides a barrier against the possibility that a fluid, water or other, might seep through the connector interface. Additionally, this option minimizes the risk of not having a mating molex connector or pins when the part is to be used. Given the advantages of this option, it should be the preferred interconnect method for most applications.

Ordering Information

All LX18XX series devices with zinc or nylon housings can have this option simply by adding a "-2" to the part number, i.e., LX1802GBZ-2.

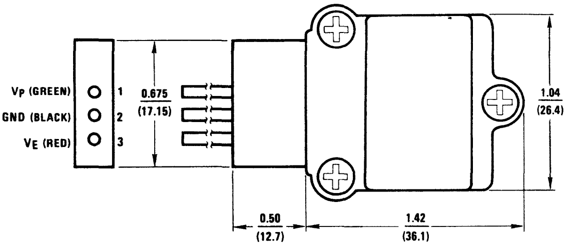
Connection

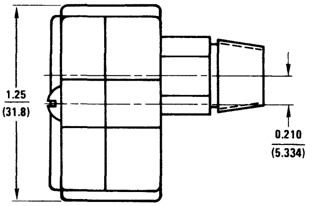
Red Wire—Supply Voltage
Black Wire—Ground
Green Wire—Output Voltage

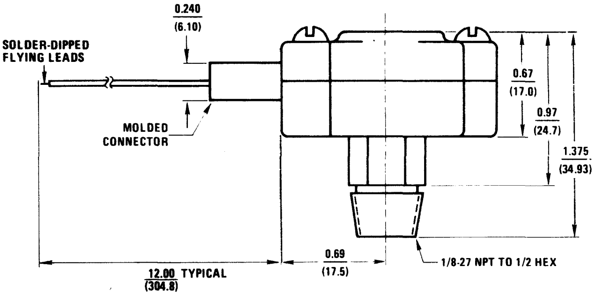
WARNING

Do not reverse red and black wires.

Typical Physical Dimensions inches (millimeters)







Data Log Option for Any Sensym Pressure Transducer

-3 Option

SenSym

Available for any of Sensym's pressure transducer products is a standard option "-3" that provides precise correlation data for each part so ordered.

Data Log Procedure

1. Each part is serialized with a unique serial number for that part. Factory records for this part are maintained for at least one year.
2. Each part is tested and data recorded at three pressure points, ½ full scale offset pressure, full scale pressure and ½ full scale pressure.
3. Linearity error, sensitivity, and pressure hysteresis error are computed and recorded.
4. Each part is tested and data recorded at 0°C, 25°C, and 85°C for offset voltage and full scale voltage.
5. Temperature coefficient of offset and full scale pressure is computed and recorded.
6. A Data Log Summary sheet is sent out with each part. (See example on next page.)

Equipment

1. For pressure measurements to 100psia. A MENSOR model #10205 with an accuracy of 0.010% of reading is used as a pressure source.
2. For pressure measurements from 100psia to 5000 psia, an Ametek dead weight with an accuracy of 0.05% of reading is used as a pressure source.
3. Voltage measurements are made using a Systron Donner 5½ digit multimeter with an accuracy of 0.01% of reading is used.

Ordering Information

Any part may be ordered with this option by simply adding a "-3" to the part number, i.e., LX1420A-3. If, in addition to this option, another standard option is ordered then the numbers are put in sequence, i.e., LX1601GB-1,3.

Data Log Summary Sheet
(Example)

Customer ____________________ Serial #________________

Part # ____________________ Date ________________

Pressure Response: Temperature = _______°C

V_{OUT} @ full scale: Pressure = ____________ V_{OUT} = ____________

V_{OUT} @ offset: Pressure = ____________ V_{OUT} = ____________

V_{OUT} @ ½ full scale: Pressure = ____________ V_{OUT} = ____________

V_{OUT} @ full scale: Pressure = ____________ V_{OUT} = ____________

Linearity Error = ________________________ % full scale

Sensitivity = ________________________

Pressure hysteresis error = ________________________ % full scale

Temperature Data:

Temperature = 0°C: Pressure = ____________ V_{OUT} = ____________

Pressure = ____________ V_{OUT} = ____________

Temperature = 25°C: Pressure = ____________ V_{OUT} = ____________

Pressure = ____________ V_{OUT} = ____________

Temperature = 85°C: Pressure = ____________ V_{OUT} = ____________

Pressure = ____________ V_{OUT} = ____________

Temperature coefficient of offset = ________________________

Temperature coefficient of span = ________________________

Grease-Fill Isolation for the LX04XXA Series Pressure Transducer -4 Option

SenSym

Purpose

The grease-fill option is designed for use in applications where the LX04XXA must be exposed on a short-term basis to a corrosive media, most typically, water. In many of these cases, the "-4" option can offer a relatively low-cost, compact solution to corrosive media problems.

Discussion

The "-4" option is made by taking the standard LX04XXA and injecting a petroleum-based automotive grease into the housing. (See *Figure 1.*) The grease then provides a barrier between the media and the transducer's electronic circuitry.

The grease is not sealed in behind any diaphragm and it can therefore flow out of the device over a period of time. This unit is not then recommended for use in applications where temperatures exceed 50°C or where significant media flow would cause the grease to "wash out" of the device. For applications above 50°C or where grease "wash out" is a possibility, the "-5" option should be used. The grease-fill may also damp frequency response.

CAUTION

Do not use the "-4" option for oxygen isolation.

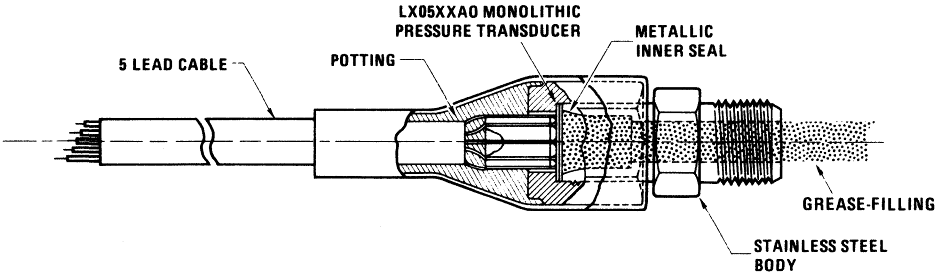
In general, the "-4" option is not a good isolation technique to use for gases, and with oxygen in particular, an explosive reaction can occur. When using the "-4" option with any media other than water, please consult the factory.

Ordering Information

The "-4" option is available for the following parts:

LX0420A
LX0420AB
LX0440A
LX0440AB
LX0460A
LX0460AB
LX0470A
LX0470AB

To order parts, add the "-4" suffix to the part number. For example, the LX0420A with the "-4" option is ordered as an LX0420A-4.



Fluid Isolation for the LX04XX and LX18XX Series Pressure Transducer -5 Option

SenSym

Purpose

The "-5" fluid isolation option is designed to be used in applications where direct media contact with the standard LX04XX or LX18XX transducer is not recommended. Typically, this is for LX04XXA or LX18XXA style parts which must be used with aqueous fluids or other corrosive media.

General Description

The " – 5" option provides an oil-filled isolator which buffers the transducer's electronic circuitry from a corrosive media. See *Figure 1.* The media is then required only to be compatible with stainless steel and Viton. This will then provide the necessary buffering for a wide variety of otherwise corrosive media. Please consult the factory for questions regarding specific media.

Parts ordered with the "-5" option will be tested and delivered with the stainless steel isolator oil-filled and attached to the transducer. Pressure hook-up is then made via the 1/8″ female NPT input port. Electrical connection and all specifications are as per the standard LX04XX and LX18XX specifications, with the exception of response time which will be dampered by the fluid isolator.

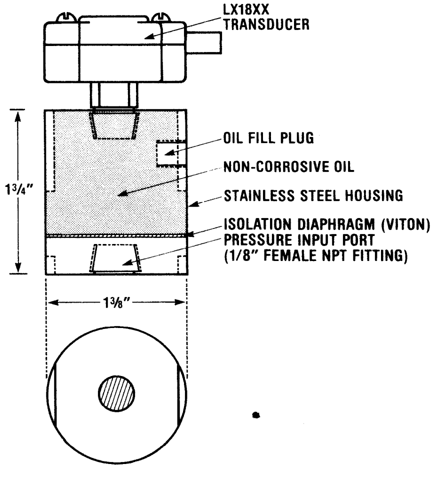


FIGURE 1. LX18XX Fluid Isolator

Snubbing Option for the LX18XXXZ Series Pressure Transducer -6 Option

SenSym

Purpose

Snubbing is designed to restrict short pressure bursts or spikes from reaching the transducer's sensor element. These short pressure spikes can permanently damage or even rupture the sensor diaphragm. This snubber is designed to stop these short-term, high-pressure transients from damaging the transducer.

General Description

The standard snubber used in our LX18XXXZ series has a constriction opening of 0.060″ (see *Figure 1.*) This is designed to provide high-pressure impulse protection for a variety of media without significantly decreasing frequency response.

This option should generally be used in cases where infrequent, short-term pressure spikes beyond the transducer's rating may be encountered. This option will not provide protection against longer term, high-pressure situations and, as in all cases, care should be taken where possible to avoid high-pressure transients. Please see the application note on snubbing for more information.

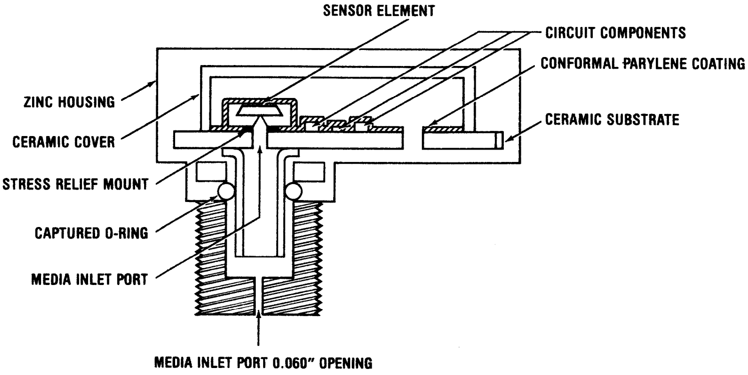
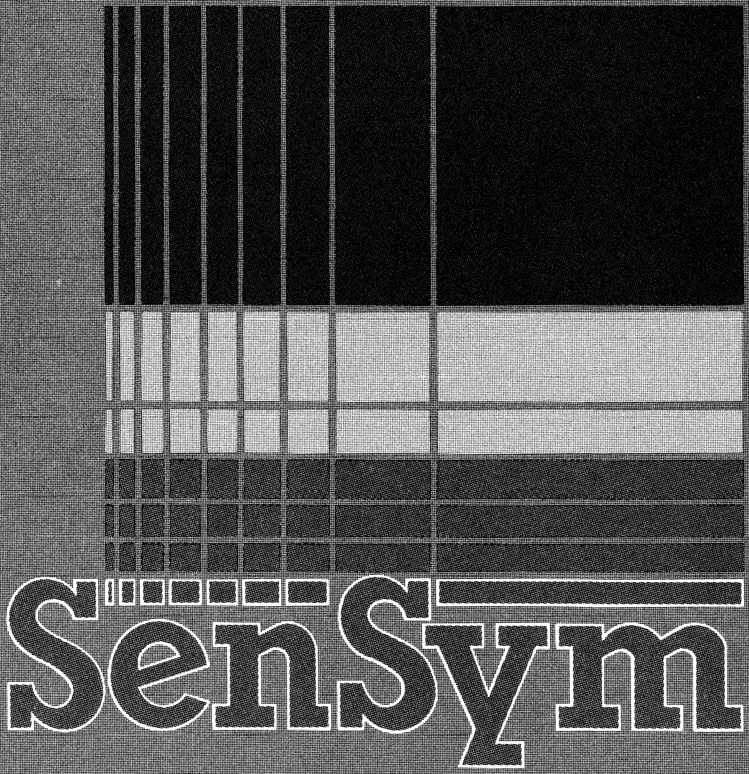


Figure 1. Snubbing Option

Section 8 Installation Hints



PRESSURE TRANSDUCER INSTALLATION

Although Sensym's pressure transducers are ruggedly built for high performance and reliability, they require reasonable care in electromechanical interface design and assembly to ensure high accuracy and trouble-free service in a pressure flow system. To ensure interface integrity, this section provides recommended methods for mechanical mounting and electrical connection plus assembly tips for a wide range of applications. The interface requirements are generally different for each package type, but the following rules apply to all Sensym IC pressure transducers.

Anchor by Pressure Port or NPT Filling Only

Sensym pressure transducers are designed to be anchored by the pressure port or NPT fitting threads and should *not* be supported by gripping the transducer housing. The only exception to this rule is the PX8D housing which includes two female screw fittings for panel mounting as well as two female 1/8″ NPT pressure ports. The port is rigidly connected on all models and fully capable of supporting the transducer weight without causing stress. Gripping the transducer body *causes* stress. For specific mounting methods, see discussions for individual package types.

Don't Stress the Ceramic or Pins

As with any integrated circuit package, the basic ceramic package and pins should be protected from mechanical abuse in assembly and in final use. This can cause inaccuracy and premature failure. The ceramic is especially vulnerable in the PX6 since it is not protected by an external housing. To avoid stress in the PX6, use only flexible tubing mounted firmly in a "stress-relief" bracket near the transducer and carefully aligned with it. Only the PX4 fully protects both the ceramic and the leads from stress. However, it is still good practice to tie down the leads near the PX4 housing. For specific stress prevention methods, see discussion of individual package types.

Bypass V_E to Prevent Oscillation (LX14XX, LX16XX, LX18XX Series Only)

As with any device containing operational amplifiers, the signal-conditioned IC pressure transducer may require a power supply bypass capacitor to prevent oscillation in electrically noisy environments. The exception is the LX16XX when it is connected to a nearby active device on the same PC board. An unbypassed transducer may oscillate at 1 to 20 MHz, which causes anomalous behavior of its low frequency response, as shown in *Figure 1.* To prevent oscillation, a 0.22μF ceramic or 1μF tantalum capacitor is usually sufficient (*Figure 2*). The capacitor should be connected as near the transducer as possible and must be within 4″ of the transducer connector pins. For specific capacitor mounting and connection, see discussions of individual package types.

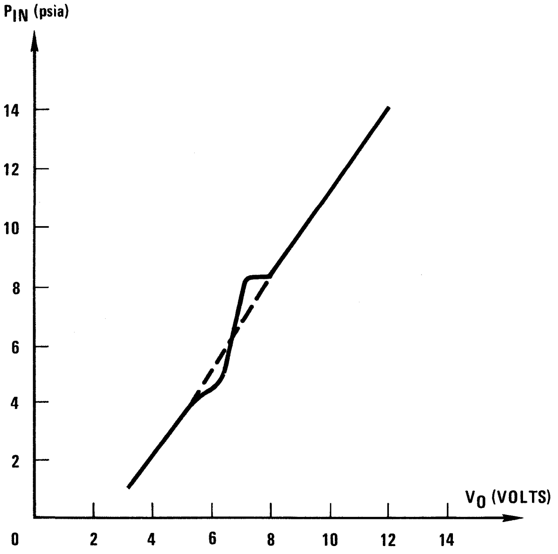
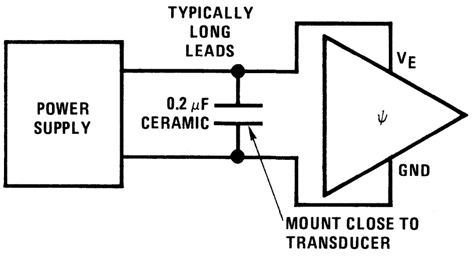
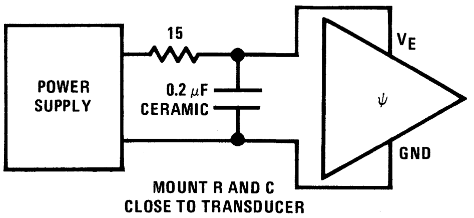


FIGURE 1. Typical Response Anomaly Caused by Unbypassed Transducer



(a) Simple Capacitor Bypass



(b) RC Supply Bypass for Long Inductive Cables

FIGURE 2. Power Supply Bypass for IC Pressure Transducers

TESTING THE TRANSDUCER

In testing the transducer, be sure to stay within its maximum specifications and avoid tests in which moisture may enter the pressure port.

> **Important:** *Do not* blow in the port to see if the transducer is working. This can cause moisture to condense on the circuit or leads and cause performance degradation.

For high accuracy applications (~1%), each transducer must be tested and calibrated, since calibration and linearity errors may vary from one transducer to another by a considerable magnitude.

The test set-up should provide a simple electromechanical interface that doesn't mistreat or stress the transducer and which generally adheres to the rules outlined above and those that apply to the specific transducer under test. The test jig should use an appropriate connector rather than solder for electrical contact. For the LX16XX series, a standard dual-in-line socket can be used. For the LX14XX series, use alligator clips or similar connector devices.

THE PX6 SERIES — PC BOARD MOUNT

The LX16XX series pressure transducer is provided in the basic PX6 hybrid IC package for PC board mounting only. This package must be supported only by the pressure port and connected only to flexible tubing. The PX6 can be mounted either horizontally or vertically on the PC board as shown in *Figures 3* through *6*. The horizontal mount is preferred since it is less sensitive to alignment and provides a stress-free mount with a simpler assembly procedure.

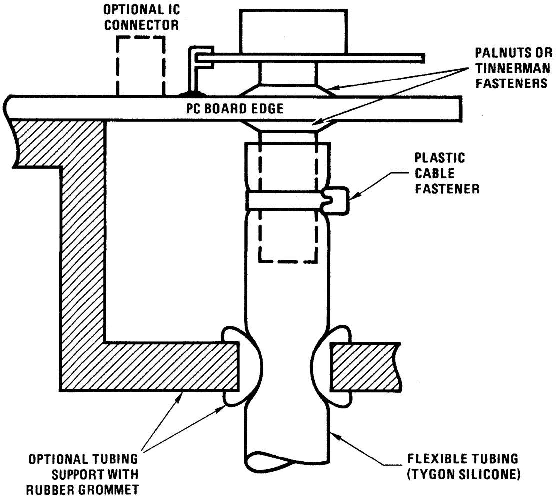


FIGURE 3. Preferred Horizontal PX6 Installation (Single Port)

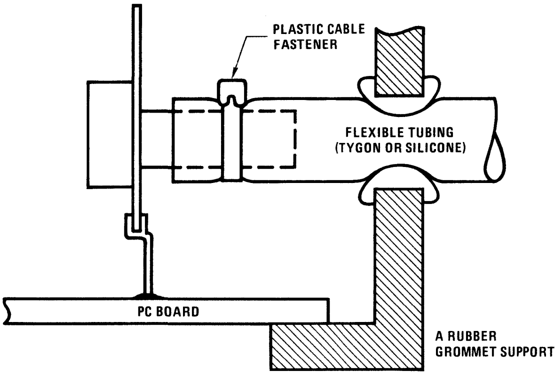


FIGURE 4a. Rubber Grommet Support

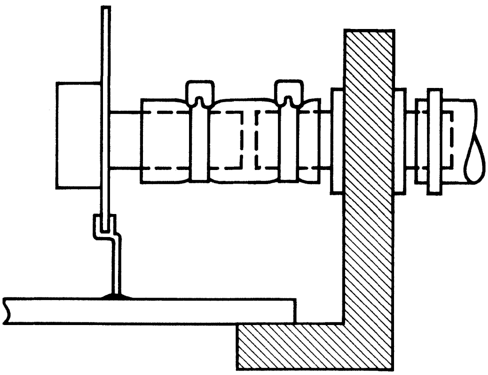


FIGURE 4b. Quick Disconnect Support (Recommended for Dual-Port (PX6D) Packages)

PC BOARD ASSEMBLY TIPS

The assembly procedure will depend on whether the PX6 is to be mounted horizontally or vertically and whether dip or spot soldering is to be used. In either case, ensure that the soldering profile is not exceeded (260°C for 10 seconds) and that the flexible tube is aligned with the pressure port and does not cause stress on the ceramic package or leads once final mechanical connection is made.

DIP OR WAVE SOLDERING

To avoid soldering the pressure port or tube bracket, the transducer is first inserted in the PC board as shown in *Figure 7* then dip soldered before final mechanical connection.

Horizontal Mount—Preferred: After soldering, the transducer is tilted from its vertical soldered position into its final horizontal position with its port inserted through the slot in the PC board and held securely with two Palnuts or Tinnerman fasteners (only one port fastened if dual-port PX6D). The support bracket for the flexible tube can then be added and the port-tube connection made. For the single port PX6 package this mount is not sensitive to tube-port alignment and easily results in a stress-free mount. However, with the dual-port PX6D version, great care is required in maintaining port-tube alignment to prevent stress in the ceramic package.

Vertical Mount—Acceptable: After soldering, the tube support bracket is added and connection made between the pressure port and flexible tubing. To prevent stress (especially for the dual-port version), a spacer should be used to accurately position the transducer before soldering.

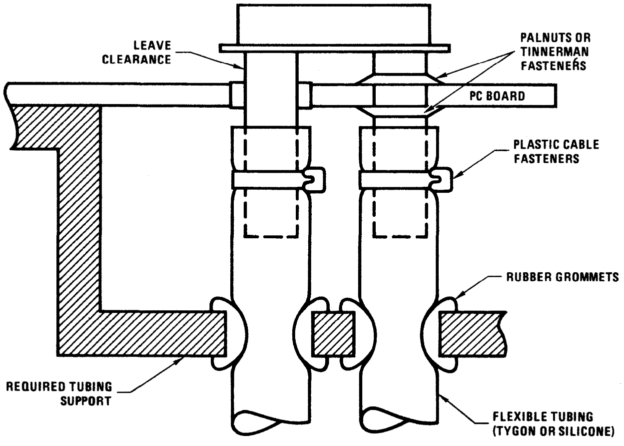


FIGURE 5. Preferred Horizontal PX6D Installation

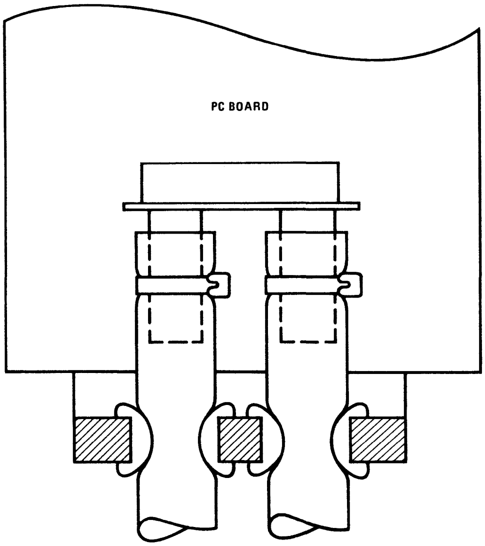


FIGURE 6. Optional Vertical PX6D Installation (Top View)

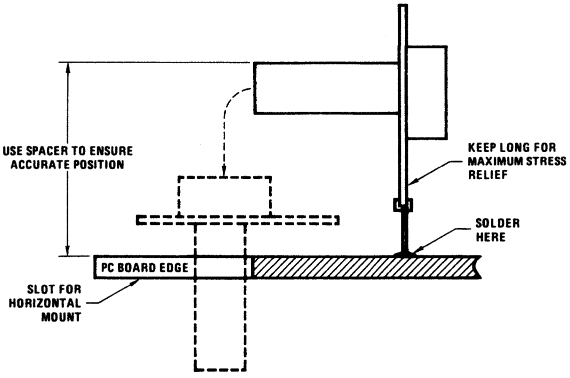
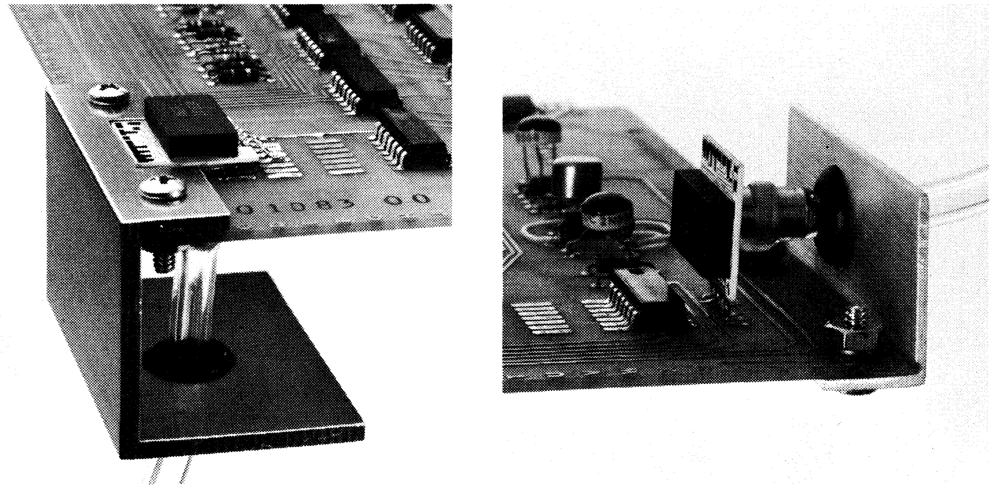


FIGURE 7. PX6(D) in PC Board for Dip Soldering



(a) Horizontal FIGURE 8. PX6 in Horizontal and Vertical Mount (b) Vertical

SPOT SOLDERING

If the transducer leads are to be spot soldered the transducer can be inserted in the PC board and final mechanical connection made before soldering. To prevent damage to the package apply solder only to the tip of the lead and keep solder and heat of soldering away from the lead-ceramic interface. Before soldering, be sure that the pressure port and flexible tubing are aligned and securely fastened with the transducer in its final vertical or horizontal position.

SPECIAL ELECTROMECHANICAL PRECAUTIONS

The LX16XX transducer provides reliable service when properly installed, but its performance or service life can be impaired with an improper electromechanical interface. To ensure reliable service, adhere to the following additional rules:

Mechanical: The ceramic package should never be potted or allowed to touch or be constrained by another hard surface. Either of these can severely damage the ceramic base or lid.

Electrical: Pins 3 and 4 should never be grounded, and no connection at all should be made to pin 4. Pin 3 is the temperature sensor output and, if used, should only be connected to a high impedance amplifier (see temperature sensor discussion below). The transducer output signal (pin 1) should *never* be connected to an impedance of less than 1k. Unless the output signal is connected to another active device nearby on the same PC board, a bypass capacitor (0.22 μF ceramic or 1 μF tantalum) should be connected between pin 5 (V_E) and pin 2 (ground), to prevent oscillation in noisy electrical environments. The capacitor should be mounted on the PC board as near the transducer as possible (within 4 inches trace length). The power supply leads must never be reversed, and the operating voltage, V_E should *always* be at least 10V. With this voltage the maximum output signal is 8V. The recommended minimum normal operating voltage, V_E is 15V. This provides the full signal output of 13V maximum.

PX6(D) "DO'S AND DON'T'S"

DO

- Insert transducer in PC board and *dip solder* before mechanical connection.
- Insert transducer in PC board and make mechanical connection before *spot soldering.*
- Use flexible tubing (tygon or silicone) and anchor to PC board for stress relief.
- Use plastic cable wraps to clamp tube to pressure port.
- Anchor port to PC board in *horizontal mount* with two Palnuts or Tinnerman fasteners or with adhesive, without directly supporting the ceramic package.
- Install capacitor for V_E-to-ground bypass, within 4 inches trace length on PC board (0.22 μF ceramic or 1 μF tantalum).
- Take special care to align pressure ports with flexible tubes with PX6D.

DON'T

- Anchor both ports of PX6D.
- Pot the ceramic.
- Submerge in water.
- Block gage port.
- Allow ceramic base or lid to touch other mechanical constraints.
- Misalign pressure port with flexible tube.
- Leave long catenary tube between bracket and port.
- Expect connector pins to take much punishment.
- Attempt to measure water or other corrosive fluid without backward gage or fluidic isolation.
- Ground pins 3 and 4.
- Make connection to pin 4.
- Reverse power supply leads or allow V_E below 10V.
- Operate with V_E higher than 30V
- Connect signal output to less than 1k impedance.

PX8 SERIES HOUSINGS

The LX18XX series transducer is provided in a rugged outer housing with 1/8″ NPT fitting(s) and Molex connector for use with a 3-pin mating connector. For mating connector, see Section B4.

PX8 SERIES MECHANICAL INTERFACE

Single-Port: The single-port housings each have a single 1/8″ NPT male fitting. The housing must be anchored by this fitting and the connection sealed with teflon tape as shown in *Figure 9*. It is especially important to use teflon tape between the two fittings when the zinc housing (PX8) is fit to a dissimilar metal. The nylon NPTS fitting (PX8N) should be used for a gasket or O-ring seal when it is inserted in a metallic female fitting and the system must work over a large temperature range. In either case, the female fitting must be rigidly held to minimize vibration. A typical PX8 installation is shown in *Figure 10*.

Dual-Port: The dual-port housing (PX8D) has two in-line 1/8″ NPT female fittings for pipe mounting and two 1/4-20 threaded female screw holes for optional panel mounting. The housing is made of zinc for extra strength and can be mounted either in-line as shown in *Figure 11* or on a panel as shown in *Figure 12*. As with the single-port versions, it is good practice to seal the PX8D pressure connections with teflon tape and use a rigidly held mount to minimize vibration.

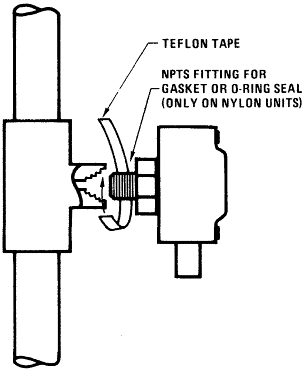


FIGURE 9. PX8 Housing Interface

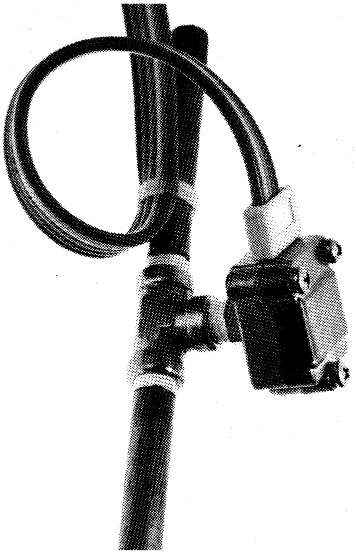


FIGURE 10. Typical Single-Port Installation

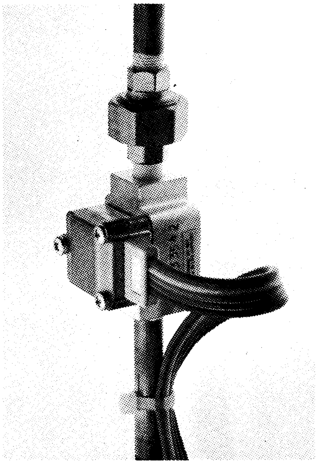


FIGURE 11. Typical In-Line Pipe Mounting with Rotary Unit

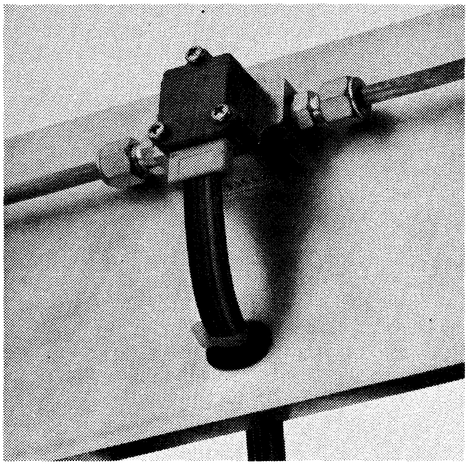
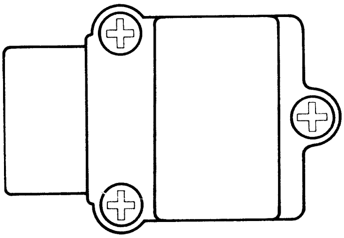


FIGURE 12. Typical Panel Mounting



PX8 SERIES "DO's AND DON'T's"

Do

- Anchor by pipe threads into a rigid fitting.
- Use teflon tape to seal connection.
- Use NPTS thread on nylon PX8N package to make gasket or O-ring seal when metal fitting is used and system has wide temperature range.
- Use threaded holes for optional panel mounting or PX8D.
- Use moisture resistance option in humid environments
- Use recommended mating connector.
- See Section B4.

Don't

- Screw zinc housing into dissimilar metal fitting unless teflon tape is used for chemical isolation.
- Allow moisture to enter transducer (seal is environmental, not hermetic).
- Submerge transducer in water.
- Attempt to measure water or other corrosive fluid without backward gage or fluidic isolation.
- Connect signal output to less than 1k impedance.
- Reverse power supply leads or allow V_E below 10V.
- Operate with V_E higher than 30V.

PX4 SERIES HOUSINGS

The LX14XX series transducers are provided in a concentric brass (PX4) or stainless steel (PX4S) housing with a 1/4″ NPTS male fitting (female on PX4F or PX4FS) and three flying leads. The lead-transducer interface is epoxy sealed for hermetic protection, which allows the PX4 to be used in extremely humid environments. With fluidic isolation (PX4 or PX4FS) the LX14XX series transducer can be submerged in water without damage, but an outer hermetic enclosure is recommended if it is to be submerged in a saline solution or in water for an extended period (see next section). The PX4 series housing is ruggedly built for easy interfacing in any pressure-flow system, and will provide high performance and reliable, trouble-free service if the following simple rules are adhered to in its electromechanical interface.

PX4 MECHANICAL INTERFACE

The PX4 series housing is designed to be supported by its 1/4" NPTS fitting and must *not* be anchored by gripping the housing body. As shown in *Figure 14*, the PX4 (or PX4S) must be installed by applying a crescent wrench to the 0.94" hex nut immediately above the NPT fitting.

> **Important:** The wrench must never be applied to the larger, rubber-covered hex section, especially when backing the transducer out of a fitting, since this will disassemble the transducer and render it useless.

The pressure connection should be sealed with teflon tape between the fittings for low pressure fluids and with an additional gasket or axial O-ring seal in high pressure (especially gaseous) systems. The NPTS thread allows such an axial seal against the hex shoulder. Although the flying leads are secured by epoxy, it is good practice to fasten them to the transducer body with a plastic cable wrap or tape, leaving a loop for stress relief, to prevent long-term wire fatigue. Typical installation of the basic PX4 housing is shown in *Figures 14* and *15*.

PX4 ELECTRICAL INTERFACE

The power supply leads must never be reversed, and V_E should always be at least 10V. With this voltage, the maximum signal output is 8V. The minimum recommended normal operating voltage is 15V, which provides the full signal output of 13V maximum. The signal output (pin 1, green) should be connected only to an impedance of at least 1k.

PX4 SERIES "DO's AND DON'T's"

Do

- Anchor by pipe threads in a rigid fitting.
- Use teflon tape to seal pressure connection.
- Use NPTS threads for a gasket or O-ring seal in high pressure systems.
- Apply crescent wrench only to 0.94" hex nut.
- Use separate outer hermetic enclosure for submersion in water.
- Secure leads to housing with plastic cable wrap or tape.

Don't

- Anchor transducer by gripping the housing.
- Submerge PX4 or PX4S in water.
- Submerge PX4F or PX4FS fluid-filling housing in water for extended periods.
- Apply wrench to housing.
- Reverse power supply leads or allow V_E below 10V.
- Connect signal output to less than 1k impedance.
- Operate with V_E higher than 30V.
- Attempt to measure water or other corrosive fluid without fluidic isolation.

EXTERNAL HERMETIC ENCLOSURES

The Submersion Problem

As with any electromechanical device, direct submergence in water or other corrosive fluid can cause immediate or long-term damage to the transducer, depending on the hermeticity of its package. The parts most vulnerable to moisture are the circuit components and connector leads. Although the circuit components can be fully protected by fluidic isolation with the "F" or "E" option, the leads are protected in various degrees, depending on the package type, all of which fall short of full hermetic protection against very corrosive liquids. For such applications, a hermetic outer enclosure such as described in this section is recommended.

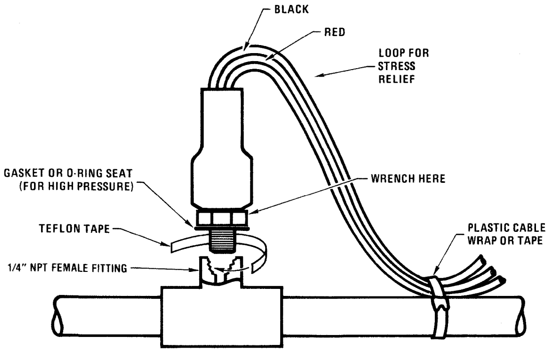


FIGURE 14. PX4 Housing Interface

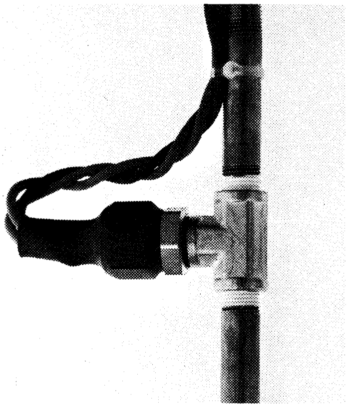


FIGURE 15. Typical PX4 Installation

TRANSDUCER SUBMERSION SUITABILITY

PX4F Series: The PX4F leads are hermetically protected by an epoxy seal at the lead-housing interface. This allows the PX4F to be submerged in water for short periods, but an external hermetic enclosure is required for submergence in more corrosive fluids, such as saline solutions, or for extended periods in water.

SUBMERSIBLE ENCLOSURES

A submersible enclosure for a pressure transducer must normally provide four utilities:

1. Pressure port interface
2. Electrical interface
3. Suspension or mounting
4. Maintenance access.

Standard hermetic enclosures normally provide for these needs using a rigid housing with machined O-ring seals and costly hermetic electrical feed-through connections. A hermetic pipe-section enclosure for the PX4F is shown in *Figure 16*. While providing the necessary utilities, this enclosure is unnecessarily complex and expensive for most transducer submergence applications.

COMPLIANT HOUSINGS — THE "RUBBER GLOVE"

Since the basic pressure transducer interface requires only pressure coupling and electrical connection, a simple, low-cost submersible pressure transducer assembly can be affected by inserting the transducer in a fluid-filled compliant bag. The ideal "bags" for this application are rubber gloves, inner tubes, football bladders and beachballs. These enclosures are similar to those used for marine submergence of pressure transducers and other electronics. The main advantage of this approach is that flexibility eliminates the requirement of strength in the outer enclosure. It is only a fluid separation membrane.

As shown in *Figure 17*, the rubber glove provides fluidic protection and pressure coupling similar to the "sock" used in the fluid-filled versions. Like the sock, it has a high surface-to-volume ratio and high resistance to corrosive fluids. Since the glove is low in cost and easy to assemble, it can merely be discarded when no longer needed.

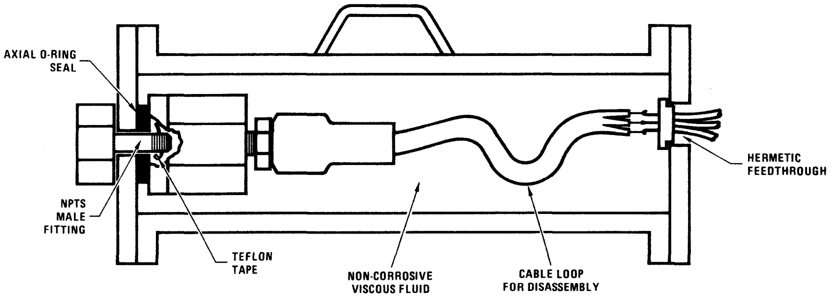


FIGURE 16. LX14XXF Transducer in Rigid Hermetic Housing

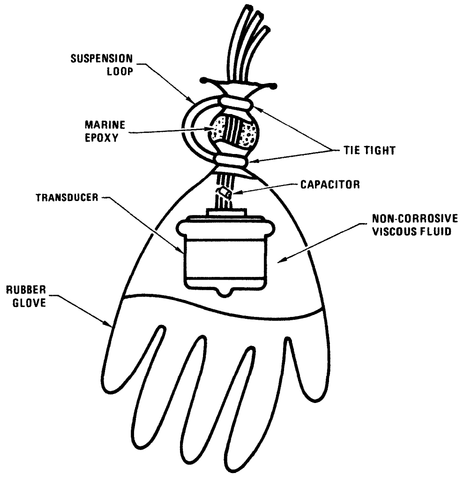


FIGURE 17. Transducer in Rubber Glove Assembly

GLOVE BUOYANCY

The glove assembly is lightweight for easy suspension, and its buoyancy can be controlled by the density of the enclosed fluid. The fluids normally used in marine applications have a density similar to plastic, about 2g/cc. The silicone fluids have a density of 0.7g/cc and may be useful for submergence in low-density industrial fluids such as gasoline. Note that the density of the transducer and enclosed wire must be included in the buoyancy determination.

GLOVE ASSEMBLY

Assembly of the glove enclosure is simple but slightly more difficult if air bubbles are to be minimized as shown in *Figure 18*. Since the epoxy is slightly permeable to air, the air will eventually escape under pressure of deep submergence. This is of little consequence for most applications and only reduces buoyancy by a small amount. As shown in *Figure 19*, the PX6 must be firmly mounted on a small PC board for use in the rubber glove.

THE TEMPERATURE SENSOR

The internal temperature sensor (pin 3) of the LX16XX pressure transducers currently provides a near-linear response sensitivity of 2 to 4mV/°C. This sensitivity can vary for each transducer and may change as improvements are made in Sensym's pressure transducer circuits. It should therefore be calibrated for each transducer when the temperature sensor output is used.

As shown in *Figure 20*, the currently used temperature sensing element is a zener diode. To prevent excessive heating, current through the diode must be limited to 150μA by a resistor connected between V_E (pin 5) and the temperature sensor output (pin 3). Pin 3 should be connected only to a high impedance amplifier.

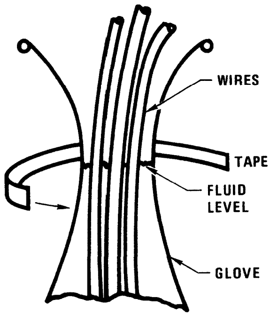


FIGURE 18. Assembling Glove with Minimum Air Content

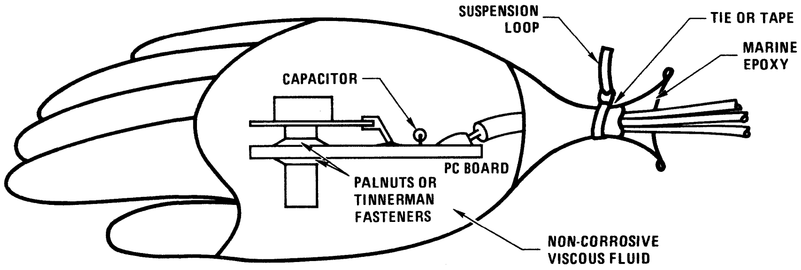
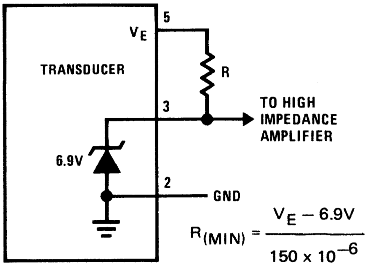


FIGURE 19. LX16XX Installed in Rubber Glove Assembly



$$R_{(MIN)} = \frac{V_E - 6.9V}{150 \times 10^{-6}}$$

FIGURE 20. Temperature Sensor Connection

Section 9

Application Notes

SenSym

Pressure Transducer Leak Test: Effective

SenSym

SSAN-4

It is uncommon today for pressure transducer manufacturers to specify the working fluid leak rate of standard transducers offered for general usage. Yet, it is likely that reputable manufacturers conduct some tests for leakage and yield to some internal specification. A major aspect of the problem is that the definition of leakage of concern to the user is difficult to model in the dimensional terms of interest to the user without exactly duplicating several other test variables whose relationship to leakage is poorly understood. What is required and herein presented is a single variable to be specified, related to the user requirements by a simple expression, such that considerably different test conditions and application conditions are adequately correlated by acceptance of that specified variable as a figure of merit. That variable is the "effective area of leakage."

TEST vs APPLICATION

In general, it is wise for the pressure transducer user's incoming leak test to approximate the end application condition as closely as practical. Real applications deal either in liquid or gas working fluids. Liquid working fluid tests are too messy and slow to incorporate into a manufacturer's outgoing or a user's incoming test procedure. It is better for a user to model his liquid leakage needs in terms of an acceptable gas leak. Such modeling, though not difficult, is not the subject of this document. The most practical working fluid for acceptance testing is air.

The user is generally interested in one of several leak criteria. For a given line pressure (common-mode pressure), the mass or volume of working fluid lost during a duty cycle or a fixed period of pressurization is of interest. Alternatively, for a given system volume, the change in pressure due to loss of working fluid during a fixed period of pressurization is of interest. A variation on the theme for a vacuum system makes the increase in system pressure due to inward leakage of ambient air during a fixed period of evacuation of interest. Duplicating a quantitative leak rate in terms of volume loss or mass loss per period or in terms of pressure loss or gain per period is extremely test set-up plumbing dependent.

PERFECT GAS vs UNIVERSAL CRITERION

In a leak test system, and if very fortunate in application, using air working fluid source pressures ranging from nearly a full atmosphere below ambient to several atmospheres above ambient, the air can be treated as a perfect gas. Then, a very simple and powerful (approaching universal) test criterion can be utilized. One equation expresses the test system's total "effective area of leakage" (A) as a function of system volume (V), working air temperature (T), test duration (t), and the ratio of initial test pressure (P_o) to final test pressure (P_f). It should be noted that the equation requires that the ratio (P_o/P_f) is a number greater than unity. Thus, if the test system is initially pressurized to a value greater than ambient pressure such that leakage causes a decrease in pressure, then the correct ratio is (P_o/P_f). If, however, the system is initially evacuated relative to ambient such that the leakage would cause an increase in pressure, then the correct ratio is (P_f/P_o).

The expression in English dimensions is given by Equation [1].

$$[1] \qquad A = \frac{1.47\,V}{t\sqrt{1716\,T}} \ln\left(\frac{P_o}{P_f}\right)$$

where:

$A \equiv$ effective leak area (square feet)
$V \equiv$ system air volume (cubic feet)
$t \equiv$ measurement period (seconds)
$T \equiv$ system air absolute temperature (°R)
Note: °R = (°F + 460)
$P_o \equiv$ initial system gauge air pressure (psig)
$P_f \equiv$ final system gauge air pressure (psig)

The expression in Metric dimensions is given by Equation [2].

$$[2] \qquad A = \frac{1.58 \times 10^{-3}\,V}{t\sqrt{3.325\,T}} \ln\left(\frac{P_o}{P_f}\right)$$

where:

$A \equiv$ effective leak area (square centimeters)
$V \equiv$ system air volume (cubic centimeters)
$t \equiv$ measurement period (seconds)
$T \equiv$ system air absolute temperature (°K)
Note: °K = (°C + 273)
$P_o \equiv$ initial system gauge air pressure (psig)
$P_f \equiv$ final system gauge air pressure (psig)

Appendix A gives a derivation of Equations [1] and [2] complete with notes helpful in relating the effective leak area to the mass flow rate of leakage.

TEST SYSTEM DESIGN AND USE

Clearly, the understanding and use of an effective leak area criterion for specifying leakage allows significantly different test system designs to yield the same result. A test systems schematic is shown in Figure 1.

Extreme care must be exercised to assure that the leak test system including the reference transducer is itself leakproof compared to the leak area to be measured. Another important consideration is the system volume. The volume of the test system in Equations [1] and [2] must include the internal volume of both the reference transducer used to determine the pressure change and the transducer whose leak is to be measured. Obviously, if the plumbing volume of the system is large, error in the expression due to omission or misestimates of transducer volume is small. However, the larger the system volume, the more difficult it is to construct a leak free system. Therefore, it is better to keep system volume small and measure both plumbing and transducer volume accurately. The shaded portion of the test system shown in Figure 1 is the volume of concern. For improved accuracy, Table 1 shows the internal volume of standard National Semiconductor configuration transducers.

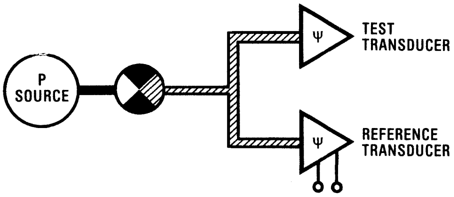


FIGURE 1. Test System Schematic

Table 1. Internal Volume of Standard Sensym Transducers

Device Family	Package Configuration	Internal Volume
LX06XXGB, LX16XXGB	PX6B	0.3 cc
LX16XXG, LX16XXA	PX6	0.8 cc
LX18XX	PX8B	0.5 cc
LX18XXG, LX18XXA	PX8	1.1 cc
LX14XXA	PX4	5.0 cc

It should be noted that Sensym transducers are extremely stiff, such that at the recommended test pressures the internal volumetric displacement may be ignored. It is recommended that the reference transducer be either manually or automatically set to null or zero pressure change condition at the beginning of each test.

TESTS

Sensym leak tests 100% of its transducers before shipment. Sensym's transducers are guaranteed to have effective leak area of less than 10^{-7} square centimeters. Appendix B shows the application of a user leak specification to effective leak area testing.

APPENDIX A

Consider a pressurized chamber of a known volume of air leaking through a hole to the surrounding ambient air. A dimensional analysis of the mass flow rate of the air is given by Equation [A1].

$$\text{[A1]} \qquad \frac{dM}{dt} = f(P, A, \varrho)$$

where:

$\frac{dM}{dt} \equiv$ mass flow rate of air from the chamber to ambient = (M/t)

$P \equiv$ gauge pressure of air in the chamber = (M/Lt^2)

$A \equiv$ area of leak hole(s) in the chamber = (L^2)

$\varrho \equiv$ air density in the chamber = (M/L^3)

The dimensional analysis indicates the expression of proportionality [A2].

$$\text{[A2]} \qquad \frac{dM}{dt} \propto A\sqrt{\varrho P}$$

Assuming air acts as a perfect gas at the pressure and temperature conditions of the chamber yields the expression of proportionality [A3].

$$\text{[A3]} \qquad \varrho \propto \frac{P}{RT}$$

where:

$T \equiv$ absolute temperature

$R \equiv$ universal gas constant (L^2/t^2T)

Combining expressions [A2] and [A3] gives Equation [A4].

$$\text{[A4]} \qquad \frac{dM}{dt} = \frac{AP}{K\sqrt{RT}}$$

where:

$K \equiv$ proportionality constant for air

It should be noted that when mass flow rate of a working fluid is the main concern of a user for a gaseous system, Equation [A4] can be empirically or analytically related to his needs.

Since the chamber volume remains constant, an equation of continuity is [A5].

[A5] $$V\frac{d\varrho}{dt} = \frac{dM}{dt}$$

For a constant temperature system, anholonomic expression [A3] can be converted to a simple differential equation [A6].

[A6] $$d\varrho = \frac{dP}{RT}$$

Combining Equations [A4], [A5], and [A6] yields the differential equation [A7].

[A7] $$K\frac{dP}{P} = \frac{A}{V}\sqrt{RT}\,dt$$

Integrating Equation [A7] yields the effective leak area equation [A8].

[A8] $$A = \frac{KV}{t\sqrt{RT}}\ln\left(\frac{P_o}{P_f}\right)$$

Values for K and R are given in the text for both English system dimensions (Equation [1]) and Metric system dimensions (Equation [2]).

APPENDIX B

As an application example, consider a user of Sensym pressure transducers in an air working fluid system. Suppose the application involves installation of the transducer in a system whose internal volume including that of the transducer is 75 cubic centimeters. Further suppose the system duty cycle is such that the internal volume is evacuated to an air pressure of 3 psia (155 mm Hg abs) and an air temperature of 25°C for 30 seconds. Relative to local ambient air pressure, the system pressure is approximately -11.7 psig (-605 mm Hg gauge). The application may require that the pressure change in the system during that duty cycle be less than 0.01 psig (0.5 mm Hg). Substitution into Equation [2] yields a maximum allowed effective leak area of 10^{-7} square centimeters. Clearly, this example was chosen such that Sensym's guaranteed maximum effective leak area is exactly adequate.

A Pressure Microcontroller: Pressure Controlled by Microprocessor with Digitally Interfaced Pressure Transducer and Solenoid Valves

SenSym

SSAN-5

SUMMARY

A board-level circuit is presented that monitors and delivers programmed pressures. Features include autoreferencing, 8-bit accuracy, and user programmed software. The key components are Sensym's monolithic pressure transducer, single chip data acquisition system, SC/MP microprocessor, and NIBL MAXI-ROM™. Simple variations and additions of hardware and software offer application flexibility so as to accomodate a broad spectrum of robotic measurement and control.

PRESSURE CONTROLLED SYSTEMS

In all hydraulic or pneumatic measurement and control applications, one or more values of pressure need to be delivered to 1 or more pressure actuated machines from 1 or more pressure sources. The job of the pressure controller is to measure and control the values, sequence, and timing of pressure delivery. The simplest such system is shown in *Figure 1.*

PRESSURE ACTUATED MACHINES

Typical pressure actuated machines resemble a piston-cylinder mechanism in principle. As shown in *Figure 2,* though found in various states and degrees of camouflage, there are usually 2 pressure chambers, 1 on either side of the piston.

The pressure difference between the 2 chambers determines the direction and magnitude of force that the piston exerts against a spring. If the spring is part of the machine, then the job of the machine is usually to position a tool attached to the piston relative to some work object. If the spring is part of the work object, then the job of the machine is usually to create a force between the tool and the work object.

PRESSURE SOURCES

Primary pressure sources include the ocean, the atmosphere, compressors, and pumps. Generally, the primary pressure source is chosen so as to be capable of delivering higher pressure values than those required by the pressure actuated machine. Most commonly, a pressure controlled system incorporates a pressure vessel as a secondary pressure source to the machine. As shown in *Figure 3,* one job of a pressure controller may be to regulate the value of pressure delivered from the primary source to the pressure vessel. In simple systems, one of the chambers of the pressure actuated machine can also serve as the pressure vessel.

FIGURE 1. Pressure Controlled System

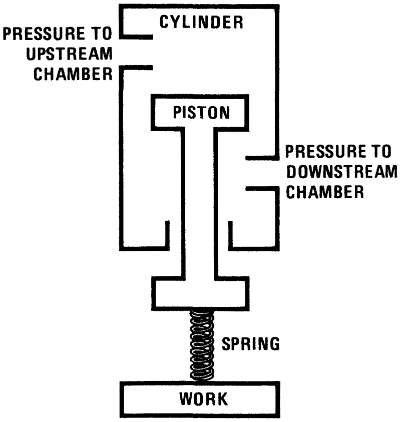


FIGURE 2. Pressure Actuated Machine

FIGURE 3. Regulated Pressure Source

PRESSURE MICROCONTROLLER

The primary job of the pressure microcontroller as indicated in *Figure 1* is to control the sequence, timing, and value of pressure delivered from the pressure source to the pressure actuated machine. As shown in *Figure 2,* this involves controlling the pressure difference between the upstream and downstream chambers of a piston-cylinder mechanism. Also, as shown in *Figure 3,* the control function may involve regulating the pressure delivered from the primary source to a pressure vessel, which vessel may in fact be a chamber of the machine. To accomplish these ends, the pressure microcontroller includes control plumbing, a pressure transducer, and control electronics. *Figure 4* shows a pressure transducer based pressure microcontroller.

PRESSURE REGULATION

A secondary job that can be performed by the pressure microcontroller of *Figure 4* is to serve as the pressure regulator of *Figure 3.* In this function, the pressure to be delivered to the pressure actuated machine is that of the pressure vessel. This pressure is measured by the pressure transducer. The microcontroller decides whether to increase or decrease the pressure of the pressure vessel. To increase the pressure, the 2-way solenoid valve (S3) is energized by the microcontroller such that pressure is delivered from the primary source to the pressure vessel. To decrease the pressure, the 2-way solenoid valve (S4) is energized such that the pressure vessel is bled to atmosphere. *Figure 5* is a schematic of this kind of pressure regulator. To simplify this subject matter, the hardware and software of the pressure regulation will be left to a future publication. For this article, the pressure source is assumed to be a regulated source.

BASIC CONTROL PLUMBING

Figure 6 shows the basic valve control plumbing necessary to deliver pressure from the regulated source to a pressure actuated machine as programmed. The regulated pressure source of *Figure 6* need be such that the desired delivery pressure be within the regulation range. For example, the pressure source may be regulated by the method shown in *Figure 5,* such that its pressure cycles between 20 psig and 30 psig. Further, suppose the desired delivery pressure is 25 ±1 psig. Then, it is the job of the control plumbing to deliver pressure whenever the regulated pressure source is at the desired delivery pressure.

Unenergized, the 3-way solenoid valve for measurement (S1) shorts pressure points 2 and 3. This is the auto-referencing condition, wherein the transducer reads atmospheric pressure regardless of the pressure at point 1. When energized, S1 shorts pressure points 1 and 2. This is the source measurement condition.

Unenergized, the 2-way solenoid valve for pressure delivery (S2) blocks the path from pressure point 1 to point 4. When the measured pressure is between 24 psig and 26 psig, S2 is energized and shorts pressure points 1 and 4.

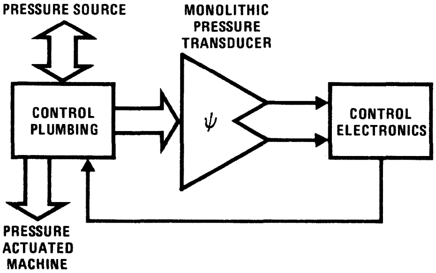


FIGURE 4. Pressure Microcontroller

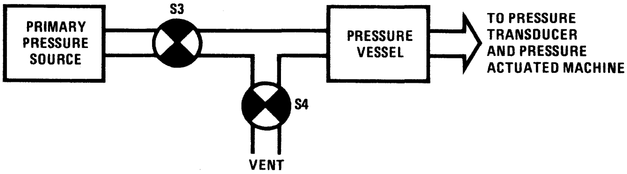


FIGURE 5. Pressure Regulator

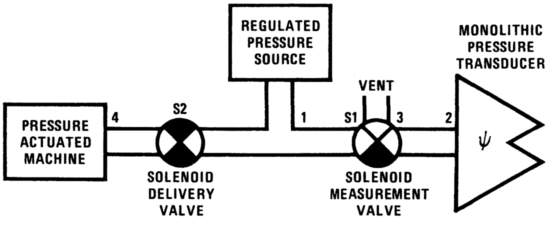


FIGURE 6. Basic Control Plumbing

TRANSDUCER AND CONTROL ELECTRONICS

The pressure transducer and control electronics of the pressure microcontroller comprise 4 printed circuit cards. The first card, or pressure control card, includes the pressure transducer, signal conitioning, analog to digital conversion, sample and hold, decode logic, and valve driving. The circuitry of the pressure control card is described in detail within this publication. The other 3 cards are the SC/MP CPU microprocessor card, the NIBL ROM program language card, and a 2k X 8-bit RAM memory card. For those interested in developing more complex pressure control systems, it should be noted that the SC/MP, NIBL, and RAM card set can control several pressure control cards.

Figure 7 is a schematic of the transducer and control electronics portion of a pressure microcontroller, indicating the 4 card functions.

PRESSURE CONTROL CARD

The functions included within the pressure control card are pressure transduction, transducer signal conditioning, analog to digital conversion (A/D), sample and hold (S/H) address decode logic, and valve driving. *Figure 8* is a schematic of the circuit functions comprising the pressure control card. A prototype pressure control card is shown in photo on page 8. The total circuit of the pressure control card is shown in *Figure 9*.

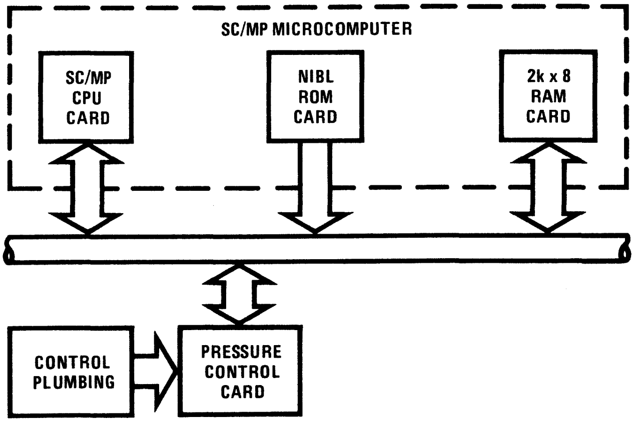


FIGURE 7. Transducer and Control Electronics

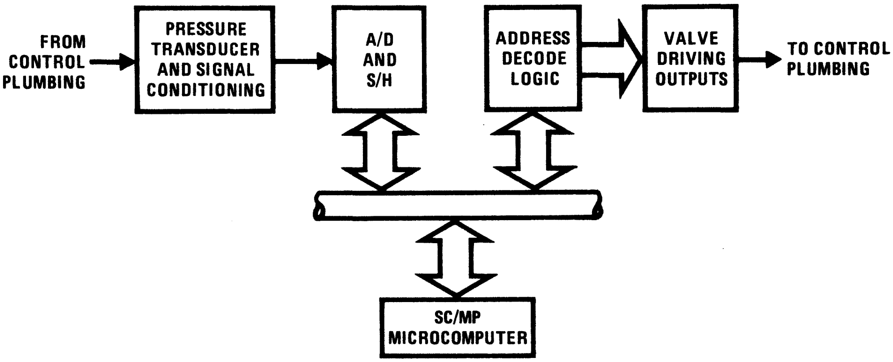


FIGURE 8. Pressure Control Card Functions

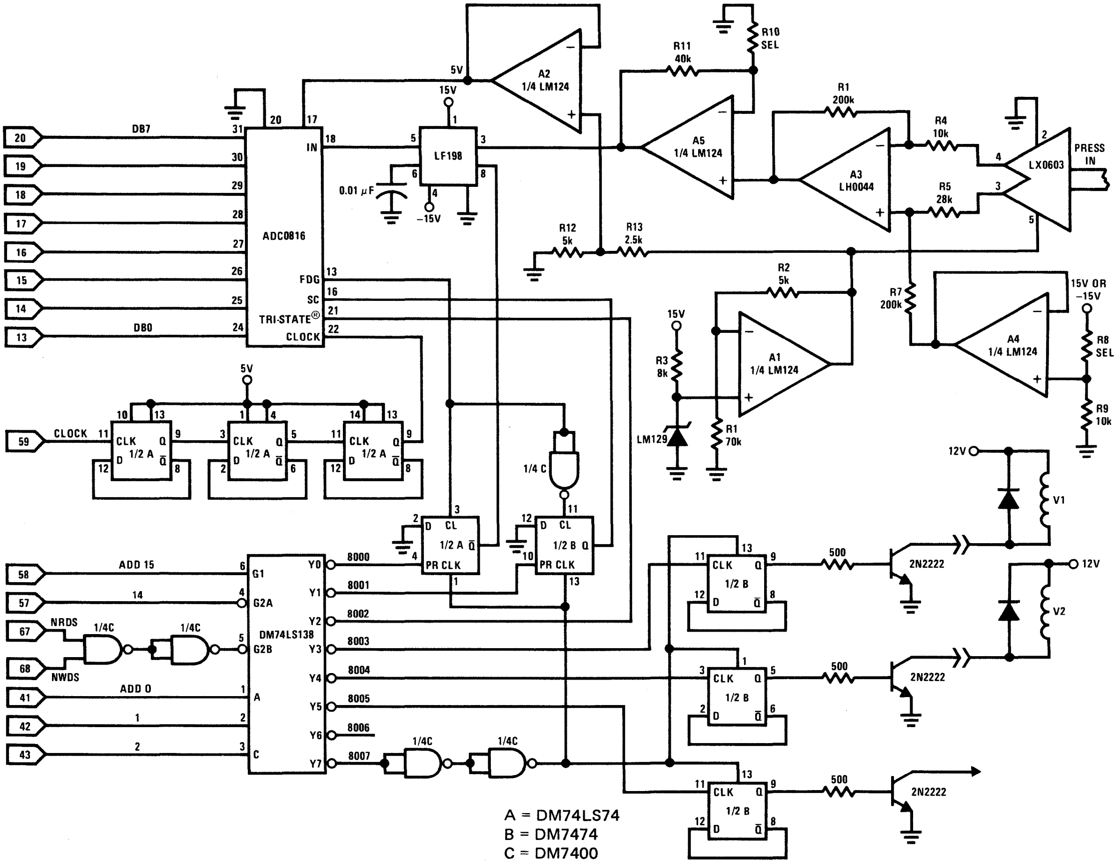


FIGURE 9. Pressure Control Card Circuit

PRESSURE TRANSDUCER AND SIGNAL CONDITIONING

The upper right quadrant of *Figure 9* shows the pressure transducer and signal conditioning portion of the pressure control card circuit. The pressure transducer selected is a Sensym LX0603GB monolithic gage transducer.

The transducer circuitry has been designed for a 0.5V to 4.5V span corresponding to a 0 psig to 30 psig pressure range. The 4V span is directly compatible with the input of an ADC0816 analog to digital converter (A/D) and allows for correction of common-mode errors associated with time and temperature of as much as ±0.5V.

The LM129 and amplifier A1 make a stable 7.5V reference for the LX0603GB. Amplifier A3 is a fixed gain of 10 stage which converts the differential output of the LX0603GB to a single ended output for driving amplifier A5. Resistors R4 through R7 should be matched to within 1% to optimize common-mode rejection. Amplifier A5 is the gain stage used to adjust sensitivity. R10 is selected to achieve a 4V output change corresponding to a 30 psig change in pressure. Divider R8/R9 and amplifier A4 make up the offset adjust circuit. If the offset is negative, resistor R8 is selected and connected to +15V to set the output of amplifier A5 to +0.5V at 0 psig. If the offset is positive, resistor R8 is connected to −15V for the same adjustment. It should be noted that transducer sensitivity has been temperature compensated within the LX0603GB. Further, note that no special circuitry need be incorporated to compensate errors in transducer offset due to temperature changes (one source of common-mode error) because autoreferencing is employed within the basic plumbing and software.

ANALOG-TO-DIGITAL CONVERSION AND SAMPLE AND HOLD

The upper left quadrant of *Figure 9* shows the A/D and S/H circuitry. The signal conditioned transducer output goes to an LF198 sample and hold (S/H) which supplies the input to the A/D. The multiplexer (MUX) in the A/D is not shown, but could be connected between several transducer outputs and the S/H to allow conversion of multiple inputs. The +5V reference for the A/D is supplied by amplifier A2. The 4 MHz SC/MP system clock is divided by 8 via 3 cascaded "D" flip-flops (DM74LS74) to serve as the clock input for the A/D. The output of the A/D is an octal TRI-STATE® latch, making it compatible with the microprocessor.

ADDRESS DECODE LOGIC

The lower left quadrant of *Figure 9* shows the address decode logic circuit. Since the SC/MP microprocessor treats any interfaced device as a memory location, the designer is obliged to do likewise. Benefits to the user are the capabilities to cause actions as a direct result of the address decode (data are irrelevant).

A useful tool is an illustration depicting memory that is used (i.e., a memory map). This map provides the designer with an overall picture of the memory locations occupied by RAM, ROM and addressable operating hardware.

In this case, the hardware consists of A/D *start* and *enable output control,* S/H, and valve drivers. The sequence of events in this system is *holding* the S/H, *starting* the A/D, *enabling* A/D output and *turning* valves ON or OFF. *Figure 10* illustrates the memory map of this system.

Addressing is achieved by hardware decoding of the address bits (up to 16), using a DM74LS138. The decoder is activated when address bit 15 is 'Hi' and bit 14 is 'Lo' and a read or write strobe is present. The address decode of location 8007 causes the *init* or set command. In similar fashion, decoding 8007 sets the S/H to sample state, sets *start convert* low, and de-energizes the valves. The decode of 8000 sets the S/H to *hold* state. Decoding 8001 triggers *start convert* to the A/D. The *end of convert* signal from the A/D resets the S/H and *start convert* flip-flops. Decoding 8002 enables the TRI-STATE outputs of the A/D on the SC/MP data bus. Decoding 8003, 8004 or 8005 produces a pulse that toggles the valve driver latches. These latches are set up as toggle flip-flops so that they change state each time they are addressed. For multiple inputs, the decode of 8006 could be used to control the 16-channel input multiplexer on the ADC0816. To use the multiplexer, the pins should be connected as shown in *Figure 11.* To address channels 1 through 16, write 0 through 15 via the data bus to location 8006.

Note that the NIBL interpreter must occupy address space 0000 0FFF (hexadecimal). Support RAM for NIBL must start at 1000 and as a minimum, continue through location 111D. Also, when using address decode with the SC/MP CPU card, insure that a logic "0" is presented to pin 65 (MEMSEL) whenever user memory devices are accessed. Alternatively, pin 65 can be hard grounded.

VALVE DRIVING

The valve drivers are set up to drive 12V$_{DC}$ valves. Clippard EV or EVO series or Linear Dynamics series 11 valves were used in breadboarding the system. A separate 12V supply should be used for the valves to avoid inductive spikes on the power supplies. Address memory locations 8003 through 8005 *toggle* the 3 valves.

FFFF		
	UNUSED LOCATIONS	
C000		
BFFF		
	UNAVAILABLE LOCATIONS	
8008		
8007	INIT.	A/D BOARD AND VALVE DRIVERS
8006	USED FOR MUX OPTION	
8005	VALVE 3 CONTROL FLIP-FLOP	
8004	VALVE 2 CONTROL FLIP-FLOP	
8003	VALVE 1 CONTROL FLIP-FLOP	
8002	A/D OUTPUT	
8001	A/D START FLIP-FLOP	
8000	SAMPLE AND HOLD FLIP-FLOP	
7FFF	UNUSED LOCATIONS	
2800		
27FF	ROM PROGRAM – CONTAINS PROGRAM OF TABLE I	
2000		
1FFF	USER AVAILABLE RAM	2k x 8 RAM CARD
1800		
17FF	USER AVAILABLE RAM	
111E		
111D	SUPPORT RAM FOR NIBL	
1000		
0FFF		
	NIBL INTERPRETER	
0000		

FIGURE 10. Memory Map

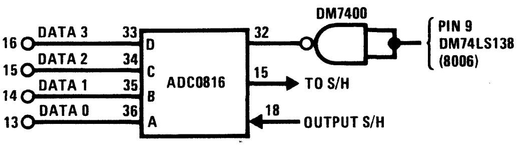


FIGURE 11. MUX Connection Diagram

SOFTWARE

The NIBL ROM card allows the use of high level language (Tiny Basic) for programming of the pressure microcontroller. It is best to demonstrate software by treating a typical control problem. As was discussed in the treatment of control plumbing *(Figure 6)*, let us assume the pressure source is preregulated by some means (perhaps by the method indicated in *Figure 5*) such that the source pressure periodically varies between 20 psig and 30 psig. Further, suppose it is desired to deliver pressure to (or actuate) the machine whenever the source pressure is between 24 psig and 26 psig. From the viewpoint of the machine, this is the equivalent of further regulating the source at 25 ±1 psig.

Figure 12 is the flow diagram and Table I shows the NIBL program to regulate pressure delivered to the machine at 25 psig. Instructions 10 through 50 initialize and autoreference. Instructions 60 through 100 measure pressure. Instructions 110 and 120 compare measured pressure with desired pressure. Instructions 130 through 160 deliver desired pressure continuously, if available, and provide continuous measurement.

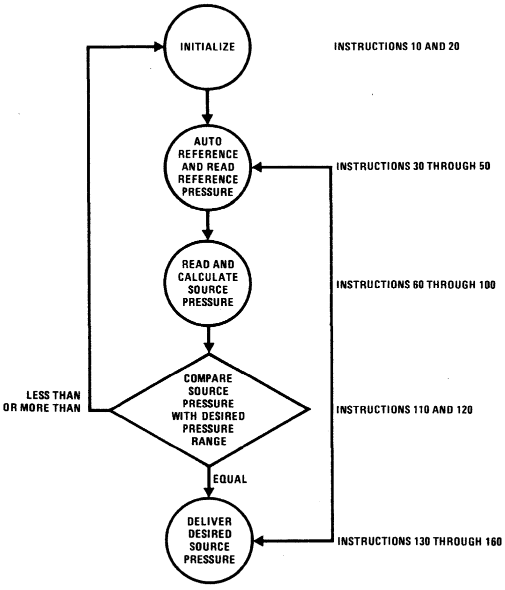


FIGURE 12. Flow Diagram to Deliver Desired Pressure

The comparison numbers in instructions 110 and 120 need explanation. NIBL requires that data be entered in binary numbers, or in number of least significant bits (LSB). As was indicated in the discussion of the pressure transducer (LX0603GB) and signal conditioning, the output voltage span (N) for an input pressure (P) of 30 psig is 4V. Equation (1) gives the sensitivities of the signal conditioned pressure transducer in mV per psi.

$$S = \frac{N}{P} = \frac{4V}{30\ \text{psi}} = 133\ \text{mV/psi} \qquad (1)$$

The 8-bit A/D can convert a maximum of 5V with 1-bit resolution. Equation (2) gives the binary resolution (R) of the A/D.

$$R = \frac{5V}{256} = 19.5\ \text{mV/LSB} \qquad (2)$$

Therefore, the binary limits of instructions 110 and 120 are given by Equations (3) and (4).

$$\text{Binary 24 psig} = \frac{133\ \text{mV/psi}}{19.5\ \text{mV/LSB}} \times 24\ \text{psi} = 166 \qquad (3)$$

$$\text{Binary 26 psig} = \frac{133\ \text{mV/psi}}{19.5\ \text{mV/LSB}} \times 26\ \text{psi} = 179 \qquad (4)$$

TABLE I. NIBL PROGRAM TO DELIVER 25 PSI

10	@ #8007 = 0	Initialize valves, *de-energize;* Initialize S/H, *sample;* Initialize A/D, *ready.*	Initialize and Autoreference
20	B = 0	Assign state of S2, *de-energize;*	
30	@ #8000 = 0	S/H, *hold.*	
40	@ #8001 = 0	A/D, *start conversion.*	
50	Z = @ #8002	Read A/D and store atmospheric (REF) pressure.	
60	@ #8003 = 0	Change state of S1, *energize;* read source pressure.	Measure Source Pressure
70	@ #8000 = 0	S/H, *hold.*	
80	@ #8001 = 0	A/D, *start conversion.*	
90	A = @ #8002	Read A/D and store source pressure.	
100	N = A − Z	Subtract REF reading from source reading.	
110	If N < 166 THEN GO TO 10	Start over if source pressure is less than 24 psi.	Compare
120	If N > 179 THEN GO TO 10	Start over if source pressure is greater than 26 psi.	
130	If B=0 THEN @ #8004 = 0	Change state of S2 if required, *energize.*	Deliver 25 psi
140	B=1	Assign state of S2, *energize.*	
150	@ #8003 = 0	Change state of S1, *de-energize.*	
160	GO TO 30	Start over at autoreferencing.	

ADDITIONAL SOFTWARE

Starting with the basic pressure microcontroller, a sophisticated measurement system can be constructed by the simple addition of software. As an example, consider the requirements of a microcontroller system designed to test the characteristics of other pressure transducers. That is, one wherein several transducers in a manifold need to be pressurized, data taken and stored, and parameters subsequently calculated. A program can be developed such that several different pre-selected pressures are sequentially supplied to the manifold. This is, of course, exactly the process shown in *Figure 12,* where the pressure actuated machine is replaced by a test manifold. The additional MUX capability of the A/D can be used to scan the transducers on test at each pressure and store their readings. Arithmetic routines in the characterization program allow comparison of each transducer's output with a programmed reference pressure characteristic. The calculated deviations can be used to display pass/fail decisions.

ADDITIONAL HARDWARE

The basic pressure microcontroller can be extended in function to provide feedback for robotic control. In fact, a sophisticated robot can be created with the addition of some software and hardware to the pressure microcontroller. The keyword is "feedback" for that is what distinguishes a robot from the aforedescribed microcontroller. The major function described thus far has been to select a desired pressure as it became available from a pressure source and cause that pressure to be delivered to the machine. A variation on this theme was described in less detail wherein pressure was regulated by the pressure microcontroller, then selected and delivered to the machine. But, in neither case was the pressure at the machine measured. Nor was the pressure microcontroller used in the control of pressure actuated machine functions.

If, in addition to the pressure source, the machine pressure or pressures were measured, and if those measurements were used in the actuation and control of the machine, then a true robot would be created. In concept, notice that the robotic system of *Figure 13* differes from the pressure controlled system of *Figure 1* by the mere addition of 1 arrowhead representing feedback from the machine.

FIGURE 13. Pressure Controlled Robot

Once again, it is best to treat a specific application as an example of robotic control. As was indicated in the discussion of pressure actuated machines, a piston-cylinder mechanism can be used to exert a force between a tool and a work object. Consider the case wherein the tool is a welding electrode attached to the piston and the work is the body of an automobile to be projection welded. The addition of one 3-way solenoid valve to the piston-cylinder mechanism of *Figure 2* allows the pressure microcontroller to vent the lower chamber of the cylinder when the delivered pressure represents the electrode force. When the lower chamber is vented, the upper chamber loads the electrode against the work object. *Figure 14* is one station of such a welding machine.

It should be noted that the pressure control card provides a third output stage which can be used to control the extra value of *Figure 14.* As indicated in the discussion of control electronics, 1 set of microprocessor (SC/MP), memory (RAM), and program language (NIBL) boards can control many pressure control boards. Thus, regulation of the pressure source and operation of many welding stations only requires additional pressure control boards, logic, valves, and software to expand the basic pressure microcontroller into a larger, more complex system. Considerable imagination is encouraged in treat-

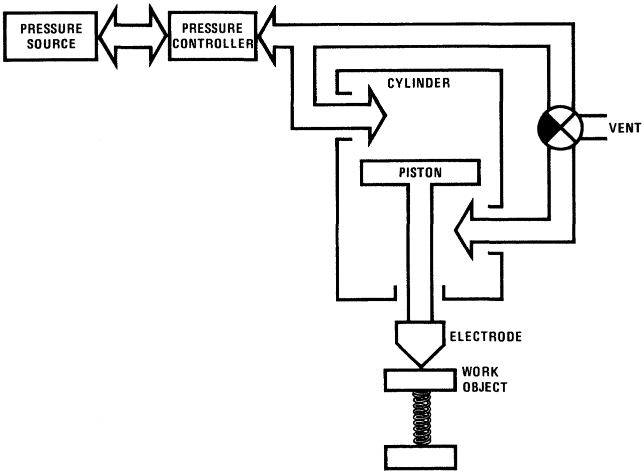


FIGURE 14. Robot Welding Station

ing this application since, in reality, a total welding machine of this kind may occupy a sizeable building that ingests steel and spits out car bodies. More detailed treatment of this system and other applications where the basic pressure microcontroller serves as the heart of sophisticated robots will be given in future publications.

Transducers in Fluid Flow Applications

SenSym

SSAN-6

INTRODUCTION

People have been building fluid systems for many millenia and the knowledge of how to measure pressure in the fluids is centuries old. So what's so special about the line of transducers introduced by Sensym? In a nutshell, the solid state transducer allows much better sensing and, therefore, much better control of fluid systems for a given amount of money spent on system control.

To give the electrical engineer a better understanding of the strange worlds of mechanical, chemical, aeronautical, civil, and acoustical engineers we will describe the three basic classes of transducer applications. All transducer usages will fit into one of the following categories:

1. Pressure Vessel
2. Open Flow
3. Closed Flow

Each is thoroughly described and the key equations of each class are derived.

For a mental model think of "open flow" as represented by the flow of a fluid in which the main energy involved is simply kinetic. Water in an aqueduct or a long pipe where the potential energy at the dam up in the mountains or the compressive energy of the pump has long since been converted to the kinetic energy of the flowing stream.

For "closed flow," think of a compressor as used for example in refrigeration systems. Here the fluid density is changing and thus significantly contributing to the energy of the system, still primarily kinetic.

In a "pressure vessel" a stationary fluid is assumed.

Now on to the system modeling.

"PRESSURE VESSEL" APPLICATION

The simplest application of an absolute pressure transducer is the direct measurement of absolute pressure of a fluid at rest within a pressure vessel.

The concept of a pressure vessel is very general here . . . it merely represents that container of fluid which keeps the fluid free of dynamics. Thus, using this broad view, on a calm day . . . the world is a pressure vessel. Likewise, a vacuum chamber is a pressure vessel.

As indicated in *Figure 1,* the LX Series can be plumbed into the pressure vessel, thus adding its own package volume and that of the plumbing to the volume of the pressure vessel. Where the pressure vessel is small, this additional volume must be considered if the measurement or control function involved seeks some relationship between pressure and volume.* It is important to recognize that the change in volume of the transducer package with pressure change is entirely negligible.

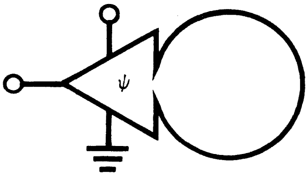


FIGURE 1

As indicated in *Figure 2,* the LX Series can be totally enclosed within the pressure vessel, working fluid chemistry allowing, so that little volume change in the system is experienced. When the volume of the vessel is large compared to that of the LX Series package, as is usually the case, the two alternative hook-ups are equivalent.

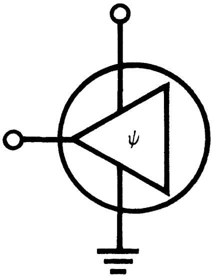


FIGURE 2

Finally, when the walls of the pressure vessel disappear, we have a barometer . . . a very good application of the LX1602A.

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*Care must be taken to avoid any temperature gradients between the pressure vessel and the transducer.

Pressure — Temperature Measurements

Another important family of "pressure vessel" applications for the LX-series involves the measurement of temperature used in conjunction with an absolute pressure reading. The integrated temperature sensing diode reads the temperature of the silicon diaphragm in the transducer package. This temperature signal may be used for the additional temperature compensation of the pressure signal.

The accuracy of the transducer depends primarily upon the temperature coefficients of the pressure signal. This is typically one to two orders of magnitude looser than the precision, which depends upon hysteresis and deadband. Therefore, for such devices, if one were to calibrate the pressure signal temperature error in terms of the temperature signal, then a correction table could be established to increase its accuracy to the same order as its precision.

Other Fluid Functions

By suitably combining the temperature with the pressure signal other fluid variables within the pressure vessel can be formulated. Two important fluid variables are density and heat content.

Density of a known gaseous fluid can be calculated without knowledge of the fluidic thermodynamic process going on simply by measuring simultaneously the pressure and temperature at the same point as described in equation 1.

Equation 1:

$$\rho = C_2 \frac{P}{T}$$

where

ρ = density
P = pressure
T = temperature
C_2 = inverse gas constant

Knowing the pressure, temperature and the density of the fluid at one or more points simultaneously, much can be learned about the nature of the processes causing change in the fluid. In a bounded pressure vessel, one variable often of concern is the heat transfer or energy exchange within some portion of a cycle or during some specific period. The change in heat content at a specific point in the system can be traced most easily in the bounded pressure vessel by tracking the fractional change in pressure as shown in equation 2.

Equation 2:

$$dh = C_3 \frac{P}{\rho}\left(\frac{dp}{P}\right);$$

where: dh = change in heat content

$\left(\frac{dp}{P}\right)$ = fractional change in pressure with time

C_3 = inverse Joule's constant

If one were willing to track the fractional change of temperature and density as well as that of pressure, then complete knowledge of the state of the enclosed fluid as well as a complete characterization of the changing process results. Expressing equation 1 in terms of fractional changes yields equation 3.

Equation 3:

$$\left(\frac{dp}{P}\right) - \left(\frac{dT}{T}\right) = \left(\frac{d\rho}{\rho}\right)$$

where

$\frac{dT}{T} \quad \frac{d\rho}{\rho}$ = functional change of temperature and density with time

Define a process characterization constant C_4 as shown in equation 4 and substitute in equation 3.

Equation 4:

$$C_4 \equiv \frac{\left(\frac{dp}{P}\right)}{\left(\frac{d\rho}{\rho}\right)} = 1 + \frac{\left(\frac{dT}{T}\right)}{\left(\frac{d\rho}{\rho}\right)}$$

Figure 3 is a table of this characterization constant under a number of important practical conditions.

So, by measuring absolute pressure changes and absolute temperature changes in an enclosed fluid system, one is able to characterize the process which caused the change of fluid properties. The process characterization constant (C_4) relates original oil changes in system energy to changes in fluid state defined by pressure, temperature, and density.

C_4	FLUID STATE	FLUID THERMODYNAMIC PROCESS	
0	$\left(\frac{dp}{P}\right) = 0$	P = constant	ISOBARIC
1	$\left(\frac{dT}{T}\right) = 0$	T = constant	ISOTHERMIC
$1 < n < k$	$\left(\frac{dp}{P}\right) = n\left(\frac{d\rho}{\rho}\right)$	$\frac{P}{\rho n}$ = constant	POLYTROPIC (Adiabatic and Irreversible)
k	$\left(\frac{dp}{p}\right) = k\left(\frac{d\rho}{\rho}\right)$	$\frac{P}{\rho k}$ = constant	ISENTROPIC (Adiabatic and Reversible)
∞	$\left(\frac{d\rho}{\rho}\right) = 0$	ρ = constant	INCOMPRESSIBLE (If bounded fluid gaseous, then process is ISENTHALPIC)

Note: In all cases dP dT, dρ represent changes with time of the absolute values of P, T, and ρ.

FIGURE 3. State and Process Characterization

Phase Change

The process characterization constant poorly defines thermodynamic processes where changes of phase are involved. Where a phase change from gaseous to liquid fluid is involved, a characteristic energy transfer called latent heat (H_{LATENT}) occurs in accordance with expression given by Clapeyron, shown as equation 5.

Equation 5:

$$H_{LATENT} = \frac{T}{C_2} \cdot \frac{\left(\frac{dp}{P}\right)}{\left(\frac{dT}{T}\right)}$$

where

C_2 = inverse gas constant

For various fluids entering phase change, a new process characterization constant (C_5) given by Clausius/Clapeyron, shown in equation 6.

Equation 6:

$$C_5 = \text{LOG}_e\, P + \frac{C_2}{T} \cdot H_{LATENT}$$

or $$C_5 = \text{LOG}_e\, P + \frac{\left(\frac{dp}{P}\right)}{\left(\frac{dT}{T}\right)}$$

Thus, we have developed the equations of state for fluids undergoing thermodynamic processes with and without phase changes so as to characterize these processes via measurement of pressure and temperature within a pressure vessel using the absolute transducer.

Generally, measurements of pressure and temperature in a multiphase system are difficult. Often for the purpose of measurement, a small parallel tap is made into the main flow channel so as to divert a negligible portion of the fluid flowing; then a sudden expansion is performed in the tap, and a small tap is led back into the main flow channel. This type of device is called a flash chamber and is shown in *Figure 4.*

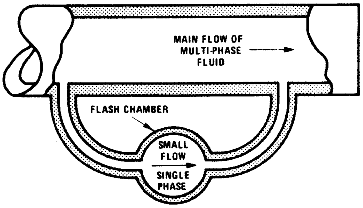

FIGURE 4

The flash chamber accomplishes the conversion of multiphase system (liquid and gas) to a single phase system (gas).

Such a chamber is simply a pressure vessel susceptible to analysis by the aforementioned modeling techniques.

OPEN FLOW APPLICATIONS

Just as pressure vessel processes were characterized by thermodynamic changes in fluid media rather than kinetic or spacial changes, open flow conditions and processes are best characterized as those in which we are primarily concerned with the kinetic properties of a fluid system and their changes, rather than the state and changes of state of a controlled volume of fluid. Whereas in the pressure vessel measurements involve absolute pressure, the kinetic state of an open flow system most often requires gage and differential pressure transducers.

The form of Bernoulli's flow equations most applicable to open flow conditions is given in equation 7.

Equation 7:

$$\left.\frac{P}{\rho}\right)_{\text{STAGNATION}} = \left.\frac{P}{\rho}\right)_{\text{STATIC}} + \frac{V^2}{2g} + y;$$

where:

$\left.\frac{P}{\rho}\right)_{\text{STAGNATION}}$ = Stagnation pressure head

$\left.\frac{P}{\rho}\right)_{\text{STATIC}}$ = Static pressure head

$\left.\frac{V^2}{2g}\right)$ = Kinetic flow head

y = Potential flow head

This particular form of Bernoulli's equation is valid where fluid density remains reasonably constant. As seen in the definition of terms (equation 7), the concept of a head is key to open flow applications. Easiest to conceive is the potential head, wherein a particle of fluid at a different height than at some other location has some potential to flow to that other location. That potential is proportional to the height difference. It is small wonder, therefore, that dimensions of a head are those of a column of fluid; inches of mercury, feet of water, millimeters of mercury or torr. If that particle of fluid were to fall, so as to change location or flow, without changing pressure within that particle, then that potential flow head would convert to a kinetic flow head. Another useful concept in equation 7 is that of stagnation. If you were waiting with a catcher's mit at a fixed location and a particle of fluid at a given pressure flowed into the mit, in order to stop that particle with your mit you would have to bring it to rest. In doing so, assuming the fluid particle remained at the same density and temperature, the particle's pressure head would increase by the absorbed kinetic head. If you were then to pull the mit down to ground level, the stagnation head would in addition increase by the potential head. Therefore, the stagnation head of a given fluid particle is an expression of that particle's pressure were it suddenly brought to rest and dragged to the bottom. Bernoulli's equation indicates that however that particle may meander under open flow conditions, the sum of its static pressure head, its kinetic flow head, and its potential flow head remains constant. In most open flow situations the variable of major interest is flow velocity. In situations where it is convenient to measure both stagnation pressure and static pressure at essentially the same point (y is constant) a differential pressure transducer can be used in a method similar to that of a pitot-tube as shown in *Figure 5.* Equation 7 can then be rearranged as shown in equation 8.

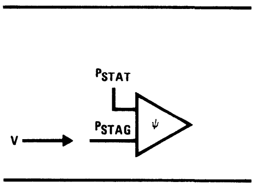

FIGURE 5. Flow Rate Pressure Square Law Relationship

Equation 8:

$$V_y = \sqrt{2g\left[\left.\frac{P}{\rho}\right)_{\text{STAGNATION}} - \left.\frac{P}{\rho}\right)_{\text{STATIC}}\right]}$$

Applications where this type of measurement is common are air speed indication for airplanes and weather balloons, water speed for boats and aqueducts and irrigation ditches, ventilation control, sewage processing, industrial mixing, and others. More generally, where y varies in open flow conditions, changes in flow conditions due to geometric changes in the flow boundaries are monitored by measurements of fluid level changes and fluid pressure changes. Equation 9 gives the applicable form of Bernoulli's equation.

Equation 9:

$$\frac{dv}{g} + \frac{dp}{\rho} + dy = 0,$$

where dv, dp, dy are changes with distance

Figure 6 shows this general case of open flow boundary condition monitoring. Notice that both the fluid level and each of the gage transducers used are vented to atmosphere for reference. In this particular case, the use of a differential

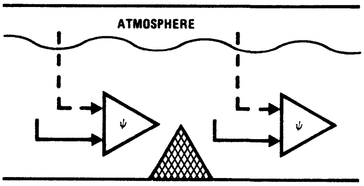

FIGURE 6. Flowmeter Output with Exaggerated Pressure Transducer Common-Mode Inaccuracy

transducer is not practical due to the physical separation of the points of interest. Two transducers must be used. Examples of applications include weir and dam flow and level control, oceanographic measurements, and for the special cases of near zero velocities . . . general level control.

The schemes of both *Figures 5 and 6* are ideal for accuracy improvement via auto-referencing (see auto-referencing section).

Once again there are some cautions that must be respected in the application of transducers in open flow conditions. Perhaps the most often overlooked and frustrating caution involves temperature gradient. As was explained in the pressure vessel section, although good transducers are temperature compensated, temperature gradients within the transducer are deadly enemies producing errors that defy all compensation techniques. If the temperature signal from the LX Series transducers is used in determining the density of the working fluid, then the transducer wants to be thermally well-coupled. However, if the atmospheric environmental temperature is significantly different from that of the working fluid, a severe gradient of temperature can occur within the transducer unless the transducer is totally immersed in the working fluid (a condition usually impractical). Fortunately, in most open flow applications, the temperature reading is not needed to determine density and the dynamics of the flow do not prohibit fairly long tube lengths from the transducer to the point of measurement. The result is that it is practical to provide a situation wherein the working fluid within the transducer is at the same temperature as the surrounding environment.

One extremely useful feature of the LX Series pressure transducers comes into play in applications of the type shown in Figure 6. In many such open flow applications the distance between points one and two is measured in miles. In such cases the system accuracy is not simply dependent upon the accuracies of measurements of pressure point one and point two but rather the difference calculation dp. Obviously that accuracy depends on the transmission of information over several miles. In general, maintaining accuracies under these conditions requires healthy signal to noise ratio at each transducer output as well as a hefty pre-transmission signal and easy interface with the transmitter.

The IC pressure transducers are ideally suited for coupling to VCOs for FM transmission (see Signal Conditioning section) the method favored by all modern trends in instrumentation. Among the many advantages are extremely low noise susceptibility even when bundled with many other signal carrying cables, ease of conversion to digital signals to facilitate interface with modern control logic or input to general purpose digital computers, and ease of combination with other analog FM signals to form a composite system variable.

ACOUSTICS

One special form of open flow application is the case where the pressure wave velocity is high compared to the fluid flow velocity. Such applications are called acoustic. The acoustic energy of a sound wave is directly proportional to the sound pressure as shown in equation 10.

Equation 10:

$$dh = C_3 \frac{dp}{\rho}$$

For acoustics, the open flow approximation of an "incompressible, isothermic medium" must be replaced by the model of a "stationary, isentropic medium." That is, the propagating pressure wave shakes each fluid particle about its stationary location proportional to the sound pressure constituting a dynamic change in density (dp). As shown in equation 11, the proportionality constant between the change in the fluid density and the sound pressure is the inverse squared speed of sound in that medium.

Equation 11:

$$d\rho = C_7 \; dp; \; C_7 = \frac{1}{a^2} \; ;$$

where "a" is the speed of sound.

Sound pressure measurements should be made with differential transducers in which the reference point monitors the quiescent pressure level. sound pressures are very low, so as to require the LX1601G or LX06001G.

High frequency response can be severely limited by bounded chambers. In fact just the tube and lid can limit response normally in the tens of kilo Hertz to the low kilo Hertz region. However, the silicon pressure diaphragm response alone with the tube and lid removed or when liquid coupled is such that calibrated sound pressure measurements can be achieved at frequencies well above 50 kilo Hertz. Thus, the LX Series pressure transducers are capable of calibrated pressure measurements in open flow conditions ranging in dynamics from static to ultrasonic frequency.

CLOSED FLOW APPLICATIONS

Pressure vessel applications require the investigation of time dependent variables at one point. Open flow applications require the investigation of time independent variables at many points. In closed flow applications, we need to investigate both kinds of variables. That is, the processes at work within the fluid system involve state change energies of like order of magnitude as kinetic energies. Perhaps the most obvious examples of systems reliant on such processes are engines of all kinds, as well as refrigerators and air conditioners, compressors, gas pipelines, fire extinguishers, gun cartridges and explosives.

In closed flow the equation used to model the flow between two locations must be altered to include the change of state.

Equation 12:

$$h_{STAGNATION} - h =$$

$$C_3\left[\left(\frac{P}{\rho}\right)_{STAGNATION} - \frac{P}{\rho}\right] = C_3\left(y + \frac{V^2}{2g}\right)$$

In equation 12, $h_{STAGNATION}$ represents the total equivalent heat energy of the system and is constant; h is the heat content of a fluid particle at a particular location such that ($h_{STAG} - h$) represents the kinetic and potential flow energy.

In open flow the density of the fluid is assumed to be known and constant. Consider a working fluid that is gaseous and whose density variation may be described by equation 1 of the pressure vessel applications section. Equation 13 shows the substitution of equation 1 in equation 12.

Equation 13:

$$h_{STAGNATION} - h =$$

$$\left(\frac{C_3}{C_2}\right) T\left[\frac{P_{STAGNATION}}{P} - 1\right] = C_3\left(y + \frac{V^2}{2g}\right)$$

In the same manner in which equation 8 was derived from equation 7 in the section on open flow applications, equation 14 is derived from equation 13 to show flow velocity.

Equation 14:

$$Vy = \sqrt{2g\left[\frac{T}{C_2}\left(\frac{P_{STAGNATION}}{P} - 1\right)\right.}$$

Thus, where the system allows a Pitot tube measurement of the two absolute pressures and temperatures at one point, the closed flow can be modeled by equation 14 and two LX Series transducers. Common applications include high velocity air flow as in compressors, and engine manifold gas flow.

To measure closed flow in small flow channels, it is usual to insert an obstruction in the passage between two points at which fluid properties can be sensed. Again, rather than the incompressible and isothermic conditions applicable to liquids in open flow, heat transfer and in fact heat loss due to flow conditions is experienced. Equation 15 presents Bernoulli's equation for this situation with the energy loss due to obstruction indicated in terms of change in heat content. For extremely long, thin, rough-walled, closed-flow vessels, the fractional loss can actually approach unity.

Equation 15:

$$\left[\frac{Y_2 + \frac{V_2^2}{2g}}{Y_1 + \frac{V_1^2}{2g}}\right] = 1 - \left(\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right);$$

where

$$\left(\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right) = \text{Loss of energy}$$

Structures are used that tend to minimize the distance between sensing points as well as minimize the fractional loss of energy. Commonly used structures range from orifices where losses are up to half of the total energy and sensing points are very closely spaced, to Venturi's where losses are negligible but sensing points are widely spaced. Equation 16, derived from equation 15 shows a typical calibration equation for a specific obstruction over a specific range of flow.

Equation 16:

$$\left(\frac{V_2}{V_1}\right)_y = \sqrt{1 - \left\{\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right\}}$$

Figure 7 shows some typical flow measurement obstructions.

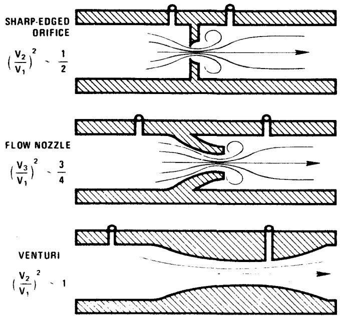

FIGURE 7

It must be remembered that these are rule of thumb examples and fluids undergoing drastic thermodynamic changes will not approximate these processes for these flow conditions. For example, the nearly lossless Venturi of streamlined flow conditions forms a roaring energy loser when turbulent hot gases are pushed through so as to become the converging-diverging nozzle of rocketry fame.

OPEN VS CLOSED FLOW

Conventionally, differential pressure transducers rather than absolute transducers are used for flow measurement. Three arguments are popular for maintaining this convention . . . one of them very good and the other two rather weak.

In low flow rate applications the dynamic head is most often small compared to the static head. The incompressible isothermic model, expressed in the equations of the open flow applications section, is often appropriate under such low flow conditions. The resulting simple expression of Bernoulli's equation that leads to the use of differential pressure transducer is given by equation 17.

Equation 17:

$$d\,(V^2) = C_8\left(\frac{dp}{\rho}\right);\quad \rho \neq \rho\,(p,\,t)$$

In addition to being the analytically obvious best choice when equation 17 is an appropriate model of flow conditions, a single differential transducer can be made to perform with much greater accuracy than a pair of gage or absolute transducers of comparable quality because the differential transducer need only range both the dynamic and static heads. Since the static head is not called for in equation 17, the added ranging requirement merely adds common mode error to the measurement. Under these conditions the differential pressure transducer convention for flow measurement is justified and the differential transducers are highly recommended . . . particularly with auto-referencing.

Equation 18:

$$d\,(V^2) = C_9\,d\left(\frac{p}{\rho}\right);\quad \rho = \rho\,(p,\,t)$$

Traditionally, even in cases where more complex Bernoulli models (equation 18) should be used, the simple incompressible model is substituted. One argument claims that one can always make up for errors in the modeling equation by specifying greater accuracy in the differential pressure transducer. Proponents of this argument consider the alternate use of two absolute pressure transducers along with two temperature transducers (to achieve a more accurate modeling equation) too sophisticated. The tradition of simple single variable models using few highly accurate transducers to achieve moderate system accuracy is so well founded in the measurement and control industries that until recently only manufacturers of low volume, high accuracy, high cost transducers existed. The low cost LX Series devices are first and foremost integrated circuits (that happen to be transducers as well) rather than conventional transducers (that happen to utilize integrated circuits). In electronics in general, and specifically within the integrated circuits business, adding functions is easy . . . but measuring to a tight spec is difficult.

In most closed flow applications the variables of interest are functions of absolute pressure, differential pressure, and temperature, with respect to time and location. If the system modeler desires a certain tolerance on this complex function he may either gather single variable data at multiple locations or multivariable data at few locations.

In either case, auto-referencing techniques can greatly improve system accuracy.

Approaches to Flowmetering

SenSym

SSAN-7

TRADITIONAL PRESSURE TRANSDUCER FLOWMETERS

The simplest form of pressure transducer flowmeter is called a Pitot Tube. It measures the difference between stagnation pressure and static pressure at a point and in a specific direction within a fluid stream. Static pressure (P_O) is the pressure measured perpendicular to the flow velocity so as to be free of kinetic effects. Stagnation pressure (P_{OO}) is the pressure measured facing directly into the flow velocity so that the measured fluid is brought to rest against the pressure port. Thus the stagnation pressure is the sum of static pressure and the total effects of kinetic energy. In an adiabatic stream, stagnation pressure is a measure of total system energy and can be assumed constant at any point in the stream. *Figure 1* shows a Pitot Tube. Equation 1 defines stagnation pressure.

$$P_{OO} = P_O + \rho\frac{v^2}{2g} \qquad (1)$$

where: P_{OO} = Stagnation pressure [#/in^2]
P_O = Static pressure [#/in^2]
ρ = Fluid density [#/in^3]
v = Stream velocity [in/sec]
g = Gravitational constant [in/sec^2]

The Pitot Tube's differential pressure (ΔP) input to the pressure transducer is given by equation 2.

$$\Delta P = P_{OO} - P_O = \rho\frac{v^2}{2g} \qquad (2)$$

Pitot Tubes are used almost exclusively in fluid streams that are much larger in cross section than the tube itself. For example, Pitot Tubes are often used for air speed determination in the open atmosphere and in large ventilation ducts. In most closed fluid stream systems, such as flow in pipes, the fluid velocities of interest are too small for measurement with a Pitot Tube. That is, the velocity of the fluid moving through the full inside diameter of the enclosing pipe is too small to give rise to a large enough differential pressure for accurate measurement. Fortunately, most systems also can tolerate more flow impedance than required by a Pitot Tube. An obstruction in the stream that amplifies the fluid velocity is just what is needed. Consider a Venturi section of pipe as shown in *Figure 2*. Consider area one (A_1) to be the cross section intersected by pressure tap one (P_1) and area two (A_2) to be the cross section intersected by pressure tap two (P_2). Consider also that for a low flow velocity through a short section, fluids are incompressible (ρ = constant). This means that the volumetric flow rate (Q) through area one and area two are equal as is expressed by equation 3.

$$Q = A_1v_1 = A_2v_2 \qquad (3)$$

In addition, consider the flow to be adiabatic through the short section, such that stagnation pressures at area one and area two are equal as is expressed by equation 4.

$$P_{OO} = P_1 + \rho\frac{v_1^2}{2g} = P_2 + \rho\frac{v_2^2}{2g} \qquad (4)$$

The differential pressure input to the pressure transducer ($\Delta P = P_1 - P_2$) is derived by substituting equation 3 into equation 4 and is given by equation 5.

$$\Delta P = \frac{\rho}{2g}\left(\frac{Q}{A_1A_2}\right)^2 (A_1^2 - A_2^2) \qquad (5)$$

A sharp edged orifice of equivalent area ratio (A_2/A_1) to a Venturi section has the disadvantages of higher flow impedance, some compressibility, and some heat loss. It has the advantages of lower cost and great standardization. Though not obvious, if the area two pressure tap is placed immediately downstream of the orifice, equation 5 very closely approximates the differential pressure input to the pressure transducer shown in *Figure 3.*

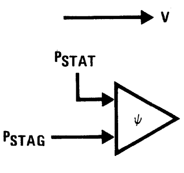

FIGURE 1. Pitot Tube

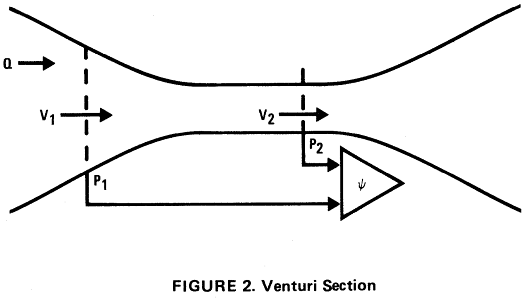

FIGURE 2. Venturi Section

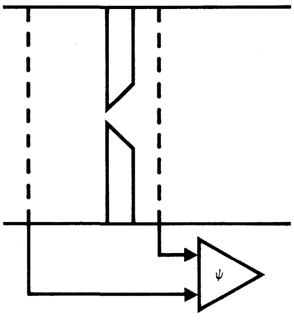

FIGURE 3. Sharp Edged Orifice

THE SQUARE LAW PROBLEM

Equation 5 clearly indicates that flowmetering methods based upon the creation of a calibrated obstruction in the flow stream involve a square law relationship. That is, the output which is simply proportional to differential pressure (ΔP) is in turn proportional to the square of the flow rate (Q). Many schemes have been devised for linearizing the output signal relationship to flow rate in the electronic domain. This involves creating a square root relationship between the output voltage from the pressure transducer and its conditioning electronics (V_p) and the differential pressure across the calibrated obstruction (ΔP). That is, if (V_p) is made proportional to the square root of (ΔP), and (ΔP) is proportional to the square of (Q); then (V_p) is proportional to (Q). An analog circuit approach to square rooting makes use of the logarithmic relationship that exists between the voltage drop across a diode junction and the current through it. Over a limited range of values, the ratio of a number's natural log to its square root is nearly constant. Section 8 gives details of this method. Digital approaches to such linearization are far more powerful because no specific algebraic relationship is required. That is, any single-valued relationship can be linearized by digital techniques. One such approach digitizes the transducer output and feeds that value into a read-only-memory (ROM). The ROM simply does a code conversion that yields an output code representing the flow rate corresponding with that pressure. The problem with that approach is that a gigantic ROM is required for reasonable flow rate resolution. Another digital approach trades conversion speed for ROM size (and thus resolution) by having the ROM store deltas. In this case only the increments between successive differential pressure values $(\delta \Delta P)$ corresponding to the increments of flow rate (δQ) to be resolved are stored. This technique has been used in the construction of accurate aneroid altimeters. Section 8 gives details of this digital approach to linearization useful with inexpensive techniques of analog to digital conversion and output display (see Section 7).

Unfortunately, circuit techniques of linearization do not linearize inaccuracies. To examine this revelation, allow some simplifying (albeit erroneous) assumptions to be corrected later. First, assume that calibrated obstruction and the fluidic phenomena that give rise to the square law relationship between (ΔP) and (Q) are error free. Second, assume that the pressure transducer's inaccuracy is common-mode or pressure independent. This means the error can be expressed as a constant uncertainty in units of pressure regardless of what pressure is applied. Third, assume that all circuitry within and outboard of the pressure transducer to yield (V_p) contributes no error. Fourth, assume that the required flowmeter's inaccuracy is common-mode or flow rate independent. This means it is desired that the error in (V_p) as a function of (Q) can be expressed as a constant uncertainty in units of flow rate regardless of what flow rate is applied. Since all inaccuracy is assumed to be due to the pressure transducer, it would be well to examine the effect of the inaccuracy on the output signal, both as a function of (ΔP) and as a function of (Q). *Figure 4* shows the pressure transducer output characteristic, (V_p) vs (ΔP), with a highly exaggerated common-mode inaccuracy indicated as an error band. *Figure 5* shows the flow rate vs pressure square law relationship. *Figure 6* shows the flowmeter output characteristic with the

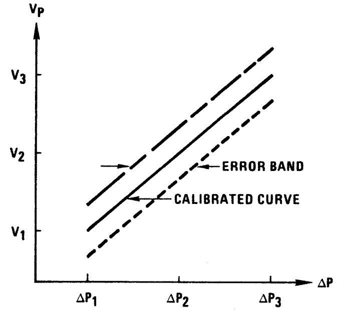

FIGURE 4. Pressure Transducer Output With Exaggerated Common-Mode Inaccuracy

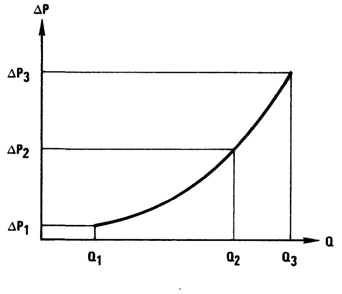

FIGURE 5. Flow Rate Pressure Square Law Relationship

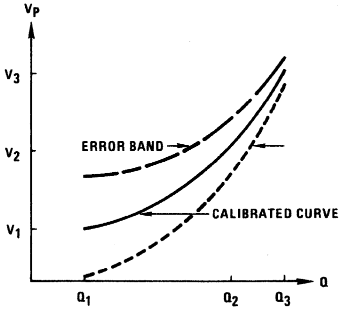

FIGURE 6. Flowmeter Output With Exaggerated Pressure Transducer Common-Mode Inaccuracy

pressure transducer error band superimposed. Since an increment pressure change corresponds with a very large flow rate change at the low end of the flow rate range, the output inaccuracy is also very large at the low end. At the high end of the flow rate range an increment of pressure change corresponds with a small flow rate change, yielding a small output inaccuracy. When electronic signal shaping is used for linearization, the basic cause of inaccuracy is unaltered. *Figure 7* shows the result of electronic linearization with respect to accuracy. Clearly, the inaccuracy is not common-mode per our assumed requirement. Electronic linearization is generally useful and will be useful to the approach described later in this text. . .but it has little or no effect on square law inaccuracy.

FLOWMETER ACCURACY REQUIREMENTS

The simplifying assumption that the optimum flowmeter inaccuracy is common-mode (flow rate independent), though sometimes true, is not generally the case. To better understand flowmeter accuracy requirements, it is necessary to understand how a flowmeter is applied. Most often, the process of interest involves moving one or more fluids from one location to another. Depending upon how important the fluid state variables are to the process, there may or may not be interest in measuring and controlling the exact flow rate during the fluid transfer. If such measurement is of primary importance, then common-mode accuracy is of primary importance. But, almost always, the most important requirement is accurate knowledge of how much total fluid has transferred at any time. Consider a process wherein the fluid flow rate can vary over a wide range and where the variable of interest is instantaneous accumulated volume. Examples of such a process are residential gas and water metering, fuel metering, pumping gasoline, pipeline control, irrigation, etc. In this case, the requirement is for a certain accuracy of accumulated volume whether all the fluid transfer occurred at low or high flow rate. Unlike the common-mode assumption where the required accuracy could be expressed as a constant percent of flow rate range, the required accuracy in this case can be expressed as a constant percent of flow rate value throughout the flow rate range (not including zero flow). *Figure 8* shows the desired shape of inaccuracy of a linearized flowmeter output for optimum flow totalization. The electronic accumulation function via integrating the flow rate output signal is simply a digital counting job, and is assumed to be error free. Comparison of *Figure 8* with *Figure 7* shows the real square law problem. The flowmeter needs best accuracy at the lowest flow rates, and is forgiving at the highest flow rates. The square law problem causes the flowmeter to have maximum error at the lowest flow rates and best performance at the highest flow rates. In short, accuracy is out of phase.

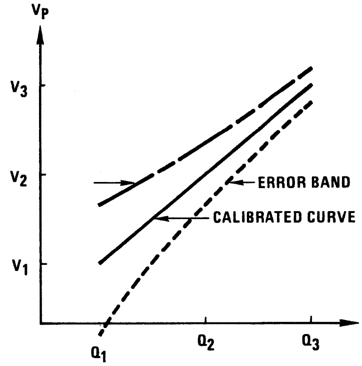

FIGURE 7. Electronically Linearized Flowmeter Output With Exaggerated Inaccuracy

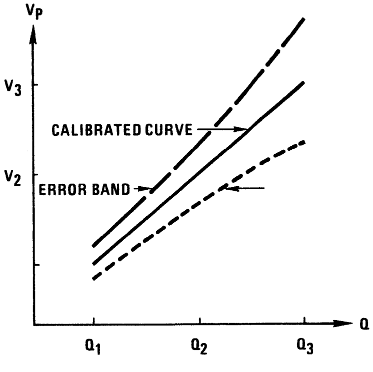

FIGURE 8. Linearized Flowmeter Output With Exaggerated Desirable Inaccuracy

A NEW APPROACH TO FLOWMETERING—THE FLEXURAL IRIS ORIFICE

Certainly the best way to remove the inaccuracy problem associated with the square law relationship between the differential pressure across an orifice and the flow rate through the orifice is to alter that algorithm right at its source. . .at the orifice. In addition to showing that (ΔP) is proportional to (Q^2), equation 5 indicates that (ΔP) is a function of areas (A_1) and (A_2). Most usually, the pipe cross sectional area (A_1) is much larger than the orifice area (A_2). For this case equation 5 can be simplified to equation 6.

$$\Delta P = \frac{\rho}{2g}\left(\frac{Q}{A_2}\right)^2 \tag{6}$$

The trick, then, is to make (A2) a variable function of (Q) such that (ΔP) is proportional to (Q^n); where (n) is much less than two (2). This can be accomplished using a virtually no-moving-part modification of a simple orifice that operates as a flexural iris.* Suppose the orifice of *Figure 3* were composed of cantilever beam sections rather than a single rigid plate. *Figure 9* shows such a flexural iris orifice with four cantilever beam sections. Also depicted is an exaggerated flexure of one cantilever element due to dynamic pressure. Appendix I gives an analysis of the dynamic pressure gradient acting upon such a cantilever, the beam flexure, and the resulting orifice area as expressed in equation 7.

$$A = \left[b_o + 2\left\{ L - \frac{h}{\Delta P}\left(\frac{E}{2}\right)\left(\frac{h}{L}\right)^2 \left(\frac{b_o + L}{3b_o + 2L}\right) \text{sine}\, \Delta P \left(\frac{2}{E}\right)\left(\frac{L}{h}\right)^3 \left(\frac{3b_o + 2L}{b_o + L}\right) \right\} \right]^2 \tag{7}$$

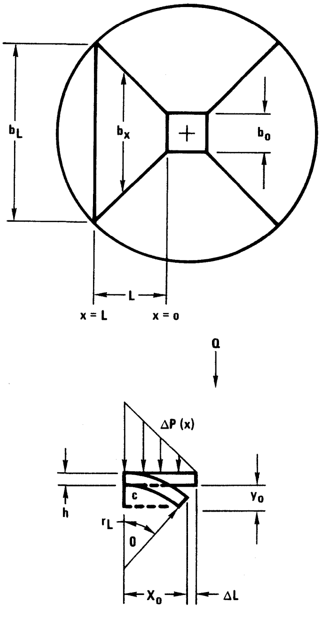

FIGURE 9. Flexural Iris Orifice

Consider a specific flexural iris orifice of easy to achieve dimensions and properties given in Table I, designed to fit within a 1-inch inside diameter pipe. Equation 8 is the result of substituting the values of Table I into equation 7 and converting units such that (ΔP) is expressed in atmospheres (atm) and the angle whose sine is represented is expressed in degrees.

$$A = \left[0.708 - \left(\frac{1.067}{\Delta P}\right) \text{sine}\, 36.43\Delta P\right]^2 \tag{8}$$

TABLE I. Flexural Iris Orifice Example Design Values

b_o	0.030 inches
b_L	0.707 inches
L	0.339 inches
h	0.005 inches
E	3×10^7 psi

Equation 9 is the result of substituting a value of density typical of gasoline and many oils into equation 6 as well as converting units such that (Q) is expressed in gallons per minute (gpm) and (ΔP) is expressed in atmospheres.

$$Q = 182\sqrt{\Delta P}\ A;\ \rho = 0.7\ \rho_{water} \tag{9}$$

It will quickly become obvious that the dimensions chosen, though easy to achieve and otherwise appropriate, were not arbitrary. It happens that a flow rate of one (gpm) through the flexural iris yields a pressure drop of one (atm). This allows easy comparison of simple pressure to flow rate relationships that represent various conditions with that of the flexural iris. Equation 10 gives the relationship for an ordinary orifice of fixed area which yields the square law accuracy problem.

$$Q = \sqrt{\Delta P}\ ;\ A = \text{const.} \tag{10}$$

Equation 11 gives the relationship for a hypothetical structure of variable area which yields uniformly distributed accuracy.

$$Q = \Delta P;\ A\ \alpha \sqrt{\Delta P} \tag{11}$$

Equation 12 gives the relationship for a hypothetical structure of variable area which yields the ideal flowmeter accuracy distribution.

$$Q = (\Delta P)^2;\ A\ \alpha\ (\Delta P)^{3/2} \tag{12}$$

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*National Patent No. 4006634.

Table II tabulates the results of equations 8 through 12 for various values of (ΔP). Since the flowmeter output signal before linearization is proportional to the differential pressure, a plot of Table II values expressed as (V_p) vs (Q) immediately reveals the effects of the flexural iris. *Figure 10* is the plot of Table II values. Clearly, the flexural iris output shown in *Figure 10* most closely approximates the output for ideal accuracy. The value of the digital techniques of linearization rather than a square root analog is also apparent from *Figure 10.* This consideration points up a preferred embodiment of the flexural iris for volume production of flowmeters. That is, it is far more important to have an output characteristic that is very reproducible in production than one that closely approximates some analytic expression.

One technique that favors flexural iris reproducibility is the stamping or molding of both the cantilever spring sections of the iris and spring constraints together in one piece. *Figure 11* is a sketch of a stamped flexural iris with cylindrical (jar-lid style) integral constraint.

AUTO-REFERENCING

During discussion of the square law problem, it was assumed that the major inaccuracies were common-mode. Continuing that assumption, auto-referencing yields the optimum accuracy for the lowest cost (see Section 7).

TABLE II. Pressure/Flow Rate Relationship for Various Structures

ΔP[atm]	FLEXURAL IRIS		FIXED AREA	VARIABLE AREA	
	$A[10^{-4}$ inches$^2]$	Q[gpm]	$Q = \sqrt{\Delta P}$ [gpm]	$Q = \Delta P$[gpm]	$Q = (\Delta P)^2$ [gpm]
0.1	8	0.05	0.32	0.1	0.01
0.2	9	0.07	0.45	0.2	0.04
0.3	10	0.10	0.55	0.3	0.09
0.4	12	0.14	0.63	0.4	0.16
0.5	15	0.20	0.71	0.5	0.25
0.6	19	0.27	0.77	0.6	0.36
0.7	25	0.38	0.84	0.7	0.49
0.8	32	0.52	0.89	0.8	0.64
0.9	43	0.73	0.95	0.9	0.81
1.0	55	1.00	1.00	1.0	1.00

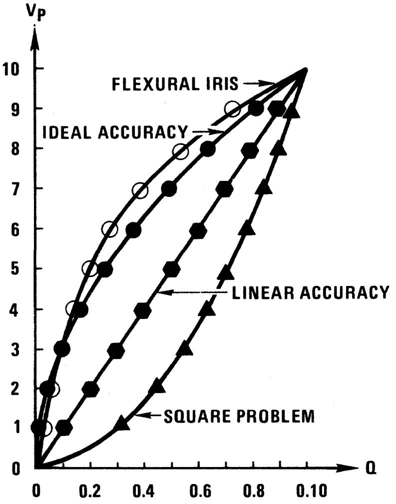


FIGURE 10. Flowmeter Output Signals for Various Configurations

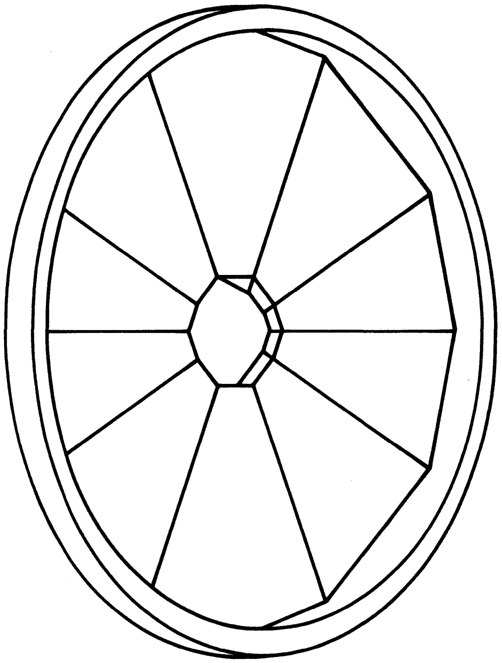


FIGURE 11. Stamped Flexural Iris With Integral Cantilevered Spring Sections And Jar-Lid Constraint

THE NEW FLOWMETER

The new flowmeter is not all new. The most advantageous features of the traditional flowmeter approach have been kept intact. The device remains essentially a dynamically responsive, low volumetric displacement, no-moving-parts system. A sharp edged orifice is replaced by a flexural iris orifice. Some errors normally handled by expensive transducers coupled with meticulously tweeked linear circuitry are instead handled by a solenoid valve coupled with well proven digital circuits using inexpensive standard solid state components. The craft of tool-and-die makers, delicately and expensively balanced within a many socket-head-capscrewed coat of armor, is replaced by an elegantly simple hybrid IC performing as a pressure transducer. The composite flowmeter system given by *Figure 12* is the new flowmeter.

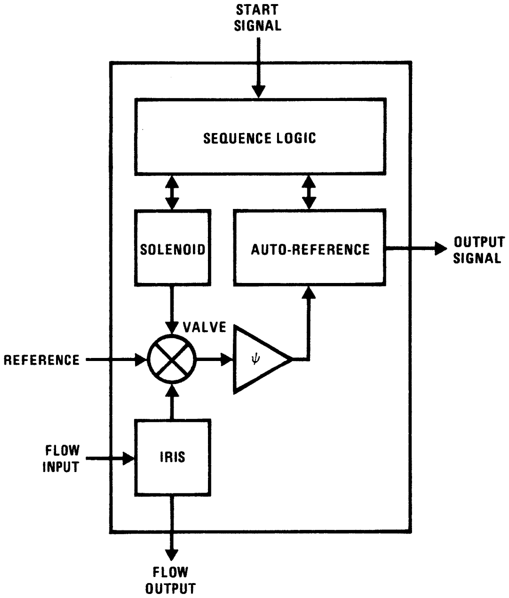


FIGURE 12. Composite Flowmeter

APPENDIX I

Analysis of Trapezoidal Cantilever Dynamic Pressure Gradient, the Resulting Flexure and Orifice Area:

The trapezoidal cantilever width of *Figure 9* is given by:

$$b_x = b_o + x$$

The dynamic head (ΔP), is given by equation 6:

$$\Delta P = \frac{\rho}{2g} \left(\frac{Q}{A_2}\right)^2$$

$$A_2 = b_o{}^2$$

$$\therefore \Delta P = \frac{\rho}{2g} \left(\frac{Q}{b_o{}^2}\right)^2$$

The full (ΔP) occurs at ($x = L$), whereas ($\Delta P = o$) at ($x = 0$). Since the flow rate radial profile in a pipe is essentially parabolic, the radial pressure gradient is roughly linear:

$$\Delta P_x = \left(\frac{x}{L}\right) \Delta P$$

Therefore the beam loading (F):

$$dF_x = \Delta P_x \, dA_z = \Delta P_x b_x dx$$

$$F_x = \int_o^x \Delta P_x b_x dx = \frac{\Delta P}{L} \left[b_o \int_o^x x dx + \int_o^x x^2 dx\right]$$

$$F_x = \frac{\Delta P}{L} \left[\frac{b_o x^2}{2} + \frac{x^3}{3}\right]$$

The beam moment (M):

$$M_x = x F_x$$

The beam stiffness (D):

$$D_x = \frac{Eh^3}{12} b_x \text{ ; } E = \text{Young's Modulus}$$

The beam radius of curvature (r):

$$r_x = \frac{D_x}{M_x}$$

$$\therefore r_L = \frac{1}{\Delta P} \left(\frac{Eh^3}{2L^2}\right) \left(\frac{b_o + L}{3b_o + 2L}\right)$$

The angle of curvature (ϕ):

$$\phi = \frac{L}{r_L}$$

The axially projected beam length (x_o):

$$x_o = r_L \sin \phi$$

The change in projected beam length (ΔL):

$$\Delta L = L - x_o$$

The orifice area (A):

$$A = (b_o + 2\Delta L)^2$$

$$\therefore A = \left[b_o + 2\left(L - r_L \text{ sine } \frac{L}{r_L}\right)\right]^2$$

substituting the entire expression of (r_L):

$$A = \left[b_o + 2 \left\{L - \frac{h}{\Delta P} \left(\frac{E}{2}\right) \left(\frac{h}{L}\right)^2 \left(\frac{b_o + L}{3b_o + 2L}\right) \text{ sine } \Delta P \left(\frac{2}{E}\right) \left(\frac{L}{h}\right)^3 \left(\frac{3b_o + 2L}{b_o + L}\right)\right\}\right]^2$$

Scaling Transducer Output Voltage

SenSym

SSAN-8

INTRODUCTION

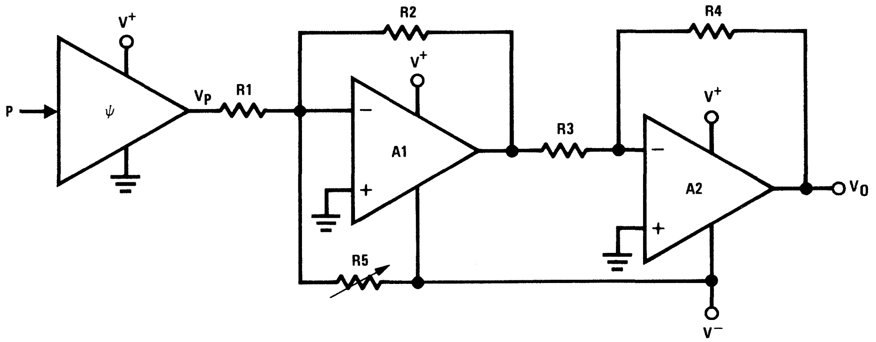
Most of Sensym's signal-conditioned pressure transducers have standardized curves where an output of 2.5 V represents the minimum pressure input and an output of 12.5 V represents the maximum pressure input. This is true throughout the range of zero to 5000 psi. Rescaling for specific applications is often required.

Since the most common requirement calls for zero volts out when pressure input is zero that case will be dealt with in detail. The assumption will be made that the user has access to plus and minus supplies (relative to ground). Most op amps will not operate linearly near their supply voltages; thus a single ended supply system (0 to 15V for example) will introduce errors near zero.

The circuit shown in *Figure 1* will allow the user to level shift the transducer output and adjust the gain as desired.

By using two operational amplifiers in the standard inverting configuration, gain and offset can be adjusted independently. Amplifier A1 is always set for unity gain (R1 = R2) and R5 is adjusted to set the offset voltage (usually zero volts). Amplifier A2 will control the gain without changing the offset.

To illustrate the versatility of the circuit, two devices will be compared. The LX1603G is a single ended pressure transducer while the LX1604G is a double ended type. Table I shows their output voltage vs pressure input characteristics. In addition, Table I shows the resulting voltages after shifting to zero volts out for zero pressure in.



$$V_O = V_P\left(\frac{R2}{R1}\cdot\frac{R4}{R3}\right) - \left(V- \cdot \frac{R2}{R5}\right)$$

If R1 = R2 and R3 = R4, then $\Delta V_P = \Delta V_O$.

FIGURE 1

TABLE I

INPUT PRESSURE (PSIG)		OUTPUT VOLTAGE		
LX1603G	LX1604G	STANDARD TRANSDUCER	MODIFIED LX1603G	MODIFIED LX1604G
0	−15	2.5	0	−5.0
15	0	7.5	5.0	0
30	+15	12.5	10	+5.0

Example 1

If the desired output of an LX1603A is 0V for 0 psia and 10V for 15 psia, R1–R4 = 10k, $V^+ = 15V$ and $V^- = -15V$. Equation 1 indicates the proper determination of R5.

$$R5 = \frac{R2 \cdot V^-}{Vp\ (0\ psia)} = \frac{10k \cdot 15}{2.5} = 60k \qquad (1)$$

Example 2

If the desired output for an LX1604G is −5V for −15 psig, 0V for 0 psig and 5V for 15 psig, R1–R4 = 10k, $V^+ = 15V$ and $V^- = -15V$. Equation 2 indicates the proper determination of R5.

$$R5 = \frac{R2 \cdot V^-}{Vp\ (0\ psig)} = \frac{10k \cdot 15}{7.5} = 20k \qquad (2)$$

If a gain other than unity is desired, R4 can be adjusted and not affect the offset. Equation 3 indicates the independence of R4 for gain setting.

$$R4 = A \cdot R3 \text{ and } R1 = R2 = R3, \qquad (3)$$

where A is desired gain.

It is possible to design a single op amp circuit to dependently adjust offset and gain. However, the dual op amp approach shown above eliminates trial and error tweaking with minor cost addition.

Solid-State Barometers

SenSym

SSAN-9

As an example of how you can scale a transducer's output to suit your needs, consider a do-it-yourself barometer. Either an LX1801AZ or an LX1802AN is a candidate. Let's take a standard LX1802AN with a 2.5 V to 12.5 V output swing (for 10–20 psia) and externally scale the output. *Figure 1* shows you the necessary circuit and its equation. Let R1 = R2 = R3 = 10 kΩ. Let's derive appropriate values of R4 and R5 to provide output voltages in common barometric units.

Consider output in millibars (mb). At 11 psia, we wish the output to be 7.584V, corresponding to 758.41 mb. The normal output would be 3.5 ±0.5V. Suppose the particular transducer chosen had the mean output of 3.5V. Then the output at 11 psia need be increased by 4.084V. Equation 1 shows the selection of R5.

$$R5 = \left(\frac{6.9}{\Delta V_O}\right) R2 = \frac{6.9\ R2}{4.084} = 16.895\ \mathrm{k\Omega}$$

Similarly, at 19 psia, we wish the output to be 13.1V, corresponding to 1309.98 mb. Suppose the particular transducer chosen exhibits the perfect nominal output for 19 psia, 11.5V. Thus, the transducer span between 11 psia and 19 psia is 8V. The desired span is 5.516V, corresponding to 551.6 mb (1309.98 mb – 758.41 mb). Equation 2 shows the selection of R4.

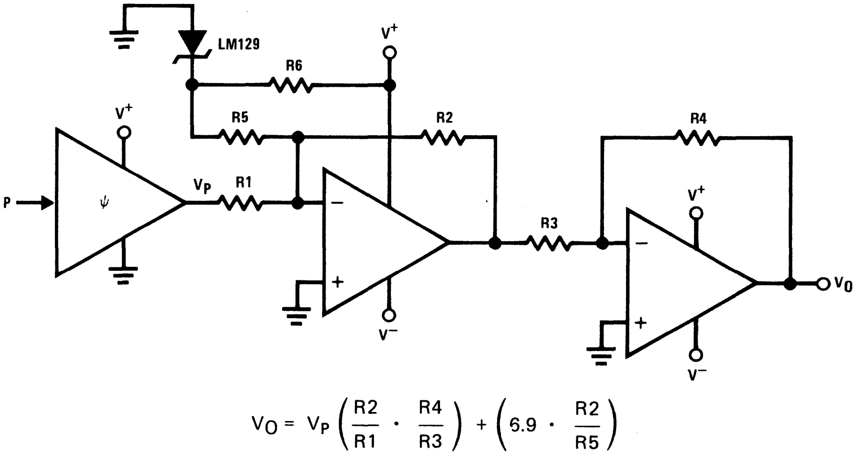
$$R4 = \left(\frac{\text{Desired Span}}{\text{Span}}\right) R3 = \frac{5.516}{8} \cdot 10 = 6.895\ \mathrm{k\Omega}$$

In like fashion, the values of R4 and R5 can be calculated for output in units of mm Hg. Table I tabulates values of R4 and R5 for outputs in mb and mm Hg.

We have been considering ideal transducers. But a production LX1801AZ could have ±500 mV offset error. Resistor tweaking may be necessary to correct for such an error. In fact, probably the best way to build the barometer is to use 15 kΩ, 5% resistors with 5 kΩ series pots, measure actual slope and offset for your circuit, then—you guessed it—diddle.

TABLE I. LX1701A

Vp	psia	mb	R4	R5	mm Hg	R4	R5
3.5V	11	758.41		16.895 kΩ	568.87		31.526 kΩ
11.5V	19	1309.98	6.895 kΩ		982.59	5.171 kΩ	



$$V_O = V_P\left(\frac{R2}{R1} \cdot \frac{R4}{R3}\right) + \left(6.9 \cdot \frac{R2}{R5}\right)$$

where $V^+ = 15$ V and $V^- = -15$V

FIGURE 1

Pressurized-Cable Fault Detection and Location – Example of Frequency Output

SenSym

SSAN-10

The underground and surface cables used in wire transmission of data are often pressurized. The pressurization protects the cable against its environment. Any leakage, or a break in the external layer, exposes the cable's interior to possibly destructive environmental conditions. Thus it is necessary to detect a leak as quickly as possible and to localize it with a maximum of precision. *Figure 1* shows a basic pressurized-cable control system that uses mechanical transducers (designated as "M" in the figure).

A long-distance transmission cable usually has a certain number of conductors designated for control and supervisory purposes (six are shown in *Figure 1*). Such wires are placed in pairs so as to form (three) independent loops—B1, B2 and B3— of a known resistivity per mile for a given wire diameter. Further, in each cable joint there is a mechanical pressure transducer. When the pressure drops below the transducer's threshold level, contact "C" closes.

Now, let's assume that ℓ is the distance between two consecutive transducers, in miles, and r is the loop wire resistance in ohms per mile. When a fault condition exists the n^{th} device is activated and the corresponding contact closes, the formed loop represents a resistance $R = nr\ell$, which shunts one branch of a Wheatstone bridge. This lets us compute the approximate distance to the leakage. The use of three independent loops and three bridges increases the accuracy of the measurement.

HYBRID IC TRANSDUCERS IN THE CABLE

The system just described is relatively simple but suffers from a number of faults. First of all its accuracy leaves much to be desired. Then, the information received at the terminal indicates that the pressure of the n^{th} joint dropped below a fixed level, but doesn't provide an actual value. Further, a mechanical transducer's characteristics change with time (springs and membrane). And, last but not least, such a system is expensive.

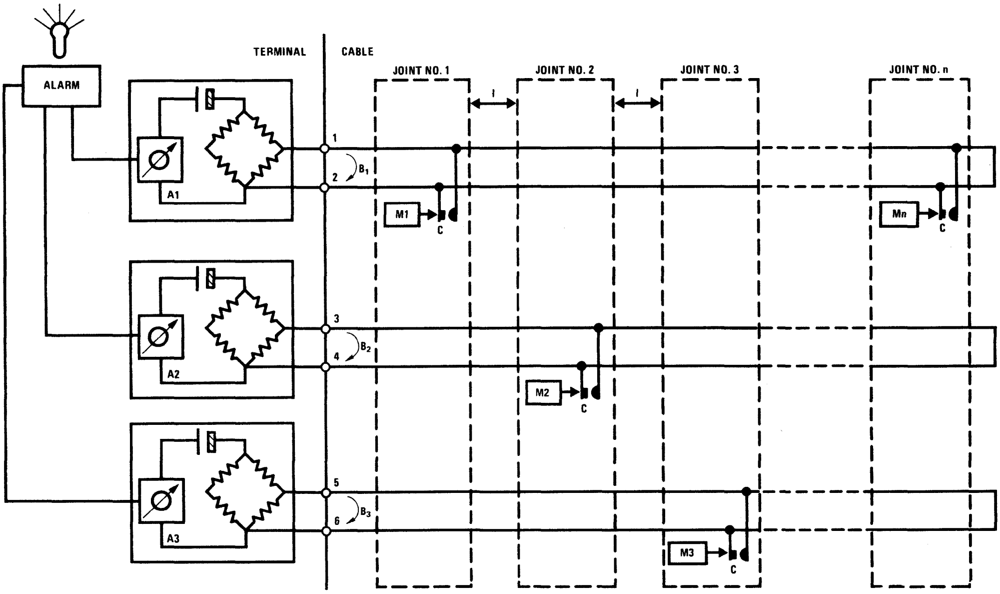


FIGURE 1. A Traditional Pressure Control System Using Mechanical Transducers

The use of IC pressure transducers improves system performance and saves money at the same time. Such a fully electronic cable control system is shown in *Figure 2*. The system comprises a main power supply; a digitally programmable generator capable of generating *n* different frequencies and having a digital display (FREQUENCY DISPLAY); a received-signal detector with display (PRESSURE DISPLAY) and alarm circuitry; and a number of transducers located at the joints.

HOW IT WORKS: THE CABLE

Referring to *Figure 3*, the main dc supply feeds the cable equipment through wires 1 and 2; the voltage at point Z is always at least 18V. (The resistance R1 compensates for the wire resistivity and is chosen separately for each joint.)

LM567 is a tone decoder capable of detecting its own characteristic frequency, which is different for each joint. When such a frequency is present at the input, the decoder output goes low and, translated in level, saturates Q1. Q1 then furnishes current to the local 15 V power regulator, the pressure transducer (LX1803AZ)* and the voltage controlled oscillator (LM566).

The VCO input is so biased that for a nominal cable pressure (usually, 1.5 atm), the VCO output frequency is set around an arbitrarily-chosen value convenient to transmission efficiency. The linear voltage changes of the transducer's output (proportional to a measured pressure) cause linear frequency variations on the VCO output.

HOW IT WORKS: THE TERMINAL

A digitally-programmed generator cyclically transmits the interrogating frequencies f_1 to f_n. These frequencies correspond to the characteristic frequencies of the decoders on the line. The number of the interrogated device (1 to n) that corresponds to the number of the frequency being sent out is displayed on FREQUENCY DISPLAY. When the appropriate frequency is detected by one of the cable decoders, the corresponding VCO sends back fm-encoded pressure data. This data signal is counted (decoded), memorized and the received pressure value is displayed on the PRESSURE DISPLAY. A microprocessor provides a simple cost-effective method of managing the system. New data can be compared with previous data allowing for an "early-warning" detection system—a fault can be detected before any damage can occur.

During the whole interrogation cycle, only one transducer is energized at any given time. The supply current of an energized joint's circuitry is 35 mA (typ.), while the standby current of each non-interrogated joint is about 6 mA.

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*LX1603A may also be used.

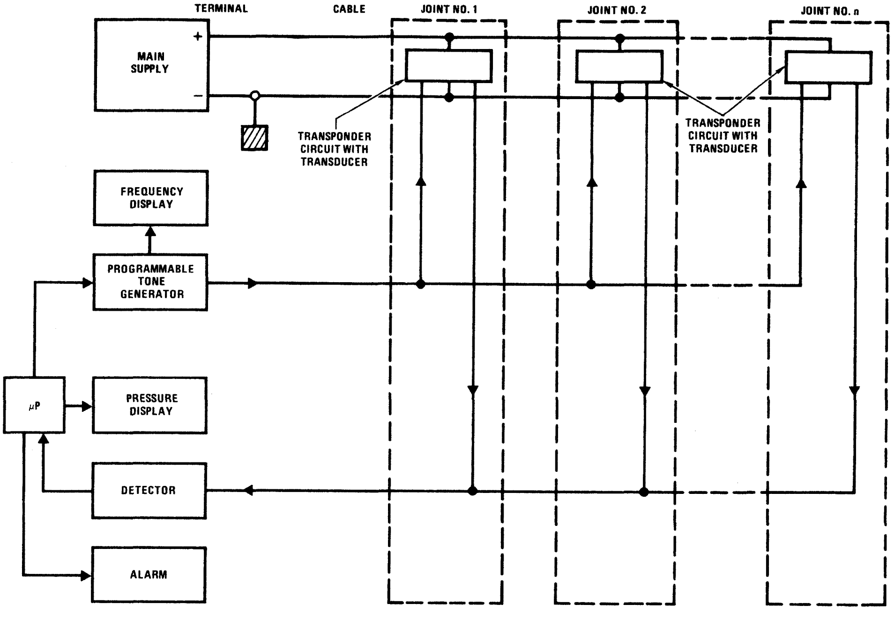


FIGURE 2. Block Diagram of an Electric Pressure-Control System that uses IC Pressure Transducers

WHAT THE ELECTRONIC SYSTEM OFFERS

First of all, the expected, overall linearity of the electronic system is better than four percent.

Compared to a traditional mechanical system, the electronic system using IC pressure transducers offers: higher precision and an actual pressure value, which is necessary for pressure gradient evaluation along the cable to localize the leak; the possibility of a permanent pressure display via BCD outputs to a printer; and a cost savings, by decreasing the number of necessary wires (from six to four) through phantom feeding.

The principles of this system can be used, with some modifications, for remote pressure control in other applications such as liquid and gas flow, and, in the future, pressurized waveguides.

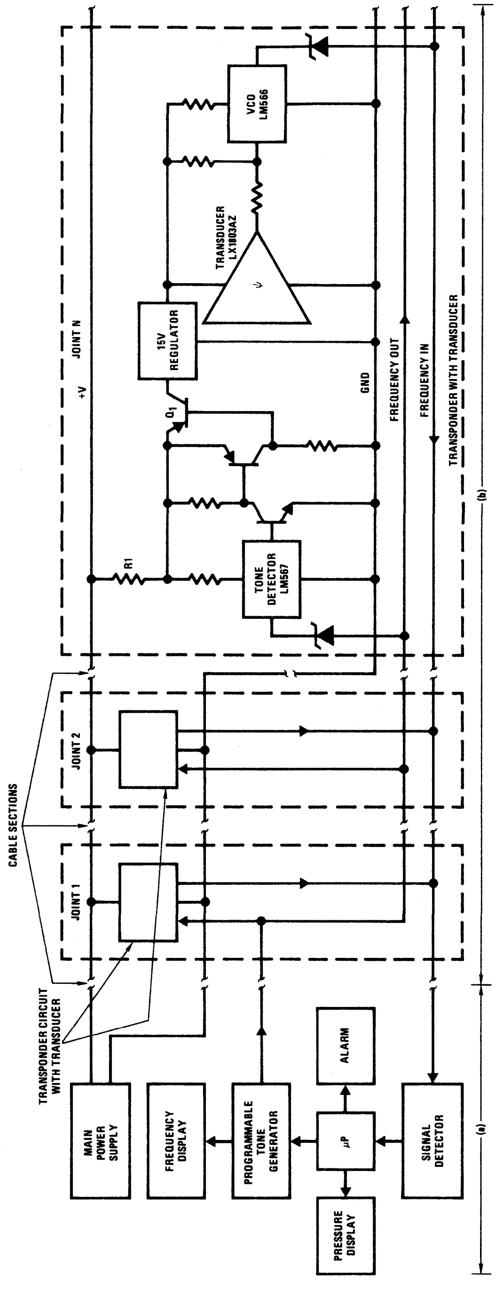


FIGURE 3. The Components of the Pressurized System

Flow Velocity Measurement — Example of Analog Shaping Conditioning

SenSym

SSAN-11

The pressure developed by a flowing fluid is a direct function of the square of the flow velocity. Therefore, to use an LX series pressure transducer for the determination of a fluid's flow velocity it is necessary to extract the square root of the transducer's analog voltage output: $V_T = f(P_{IN})$; $P_{IN} = f(v^2)$; so, $(V_T)^{1/2} = f(v)$.

One way to accomplish square rooting is to make use of the logarithmic relationship that exists between the voltage drop across a diode junction and the current through it. We can use a diode's voltage/current relationship because, over a limited range of values, the ratio of the natural log of a number to its square root is approximately constant. Table I shows this relationship in terms of values of N that are numerically equal to the 2.5 V to 12.5 V output voltage span of Sensym's LX series of pressure transducers.

TABLE I

N	$N^{1/2}/\ln(N)$	1.37 X ln(N) (Const. Mult.)	% Deviation From True $N^{1/2}$
2.5	1.73	1.26	−20.6
3	1.58	1.51	−13.0
4	1.44	1.90	−5.00
5	1.39	2.20	−1.43
6	1.37	2.46	+0.24
7	1.36	2.67	+0.76
8	1.36	2.85	+0.71
9	1.37	3.01	+0.33
10	1.37	3.16	−0.22
11	1.38	3.29	−0.96
12	1.39	3.40	−1.73
12.5	1.40	3.46	−2.12

The implementation of the concept, however, is a bit more complex than simply forcing a current through a diode, measuring the junction voltage drop and scaling it in an amplifier. But an amplifier that works on that principle and does the job is shown in *Figure 1*; it uses a pair of matched, diode-connected transistors as the logarithmic elements. The transfer function of the circuit is complex, but the output voltage variation is of the form $V_{OUT} = A\ln(V_T/B)$, where A and B are constants.

Figure 2 shows the amplifier's performance in terms of the deviation of the output voltage (V_{OUT}) from a true square root of the input voltage ($V_T^{1/2}$). Varying the value of the resistor, R, shifts the curve along the percentage axis. This value may be set as required to suit any particular application.

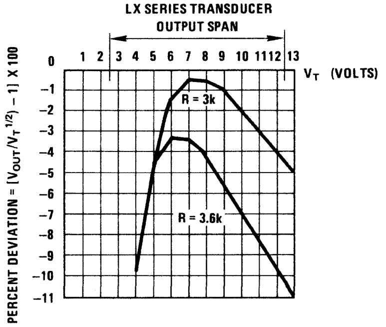


FIGURE 2. Square-Rooting Error Performance of the Amplifier

Better curve fitting can be achieved by using an LH0094 in place of the circuit of *Figure 1*.

Greater accuracy can be achieved using the dual slope integration technique described later in this section.

Still greater accuracy can be achieved using the flexural iris approach described in Section 6.

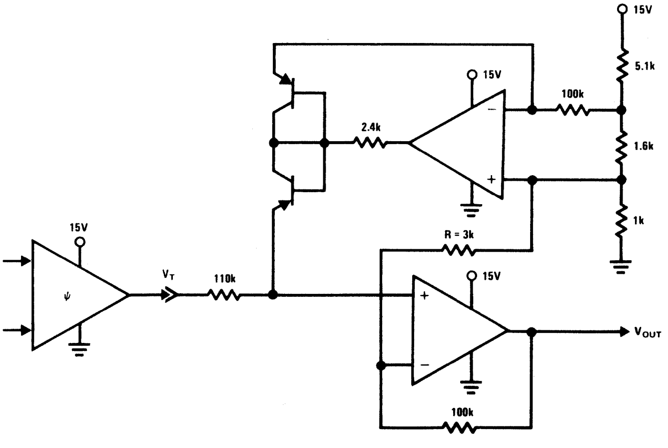


FIGURE 1. Square-Rooting Amplifier for Flow Velocity Measurements

Solid-State Altimeter for Transponder Applications— Example of Digital

SenSym

SSAN-12

INTRODUCTION

An inexpensive, all solid state altimeter, which operates from −1000 feet to +50,000 feet is described. It is intended as an example of digital signal conditioning and not as a method for the manufacture of altimeters to meet FAA requirements.

BLOCK DIAGRAM

Figure 1 is the block diagram of a digital altimeter intended for use with altitude reporting transponders. The LX1802AN absolute pressure transducer is used to sense barometric pressure.

The integrator and comparator form the analog portion of a dual slope A to D converter. The 512 x 4 ROM is used to linearize altitude and pressure. The nine bit counter is part of the dual slope A to D and at the end of a conversion it contains the altitude value in the form of a binary number. Binary is used here to make the most efficient use of the ROM. The four bit scaling counter is used in conjunction with the ROM to linearize altitude and pressure.

The LED display logic presents the altitude reading in decimal form. It uses a three decade counter with a −1,000 foot preset that runs in parallel with the nine bit altitude counter. This is simpler than trying to do a binary to BCD conversion from the altitude counter. The altitude reporting code logic is similar to the LED logic in that it runs in parallel with the binary counter rather than doing a conversion from it.

PRESSURE TRANSDUCER

The most critical part of the altimeter is the transducer. The first question that comes up is how can we use a transducer whose specifications say its maximum error

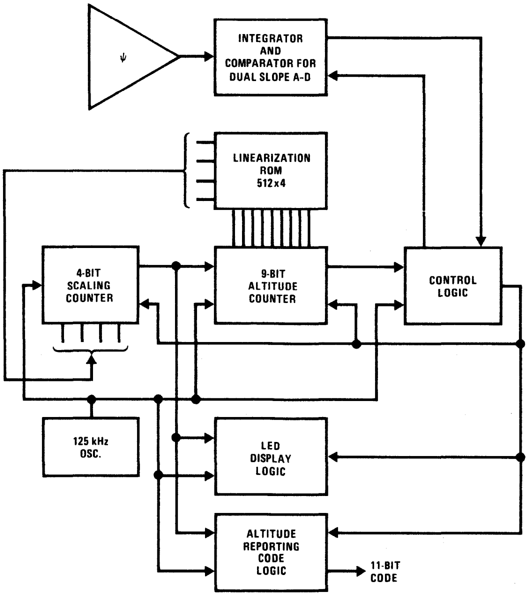


FIGURE 1. Block Diagram For Transponder Altimeter

can be as much as 2.5% of its span to do a job that calls for an accuracy of approximately 0.05% of span?

To answer that question we must examine a number of things. First the data sheet gives the specs that *all* devices will meet. If a system is designed around a 2.5% transducer, then no system calibration or transducer selection is necessary to ensure operation over temperature. All transducers would be interchangeable. However, if we are willing to trim each system to compensate for transducer variations, then the question becomes one of sensitivity, linearity and repeatability.

An individual transducer is easily sensitive enough since very minute pressure changes will cause corresponding changes in the output voltage. The linearity of an individual unit may not be perfect. However, we can compensate for transducer nonlinearities by the appropriate coding of the ROM that is being used to linearize pressure and altitude. It probably is not necessary to generate a special ROM for each transducer since many transducers exhibit very similar non-linearities. For this reason a few ROM patterns could probably compensate all transducers by simply matching a transducer with a certain class of non-linearity to its corresponding ROM.

So, we can summarize what we must do to be able to use the LX1802AN in an altimeter. First, we must be willing to trim each altimeter when we build it. And second, we must use auto-referencing if we are to approach accepted altimetric standards.

LINEARIZATION OF PRESSURE AND ALTITUDE

As you are probably aware, air pressure does not vary linearly with altitude. *Figure 2* is the curve of pressure versus altitude over our range of interest.

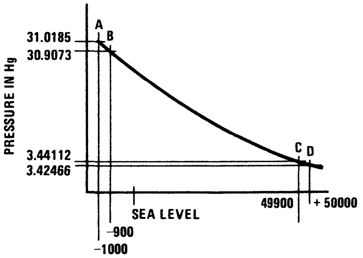


FIGURE 2. Pressure vs Altitude

There are a number of ways to linearize the curve using analog or digital techniques. For example, feeding a voltage proportional to pressure into a diode function generator would give us a voltage out that was proportional to altitude. We could digitize that voltage and we would have a digital value proportional to altitude.

Alternatively, we could digitize the pressure voltage directly and feed that value into a ROM. The ROM would simply do a code conversion, giving us an output in the appropriate code which represented the altitude corresponding to that pressure. This approach, though simple, requires a very large ROM. The number of bits in the ROM is given by the equation:

$$N = 2^M \times B$$

where M is number of output bits in the A to D converter, and B is the number of bits in the output code (in the case of the altitude reporting code, eleven). For this altimeter, an eleven bit A to D would be adequate; therefore, the ROM would have 2^{11} or 22,528 bits.

Another digital approach trades speed of conversion for ROM size. In this case the ROM stores only deltas, the incremental pressure differences between successive altitudes. The conversion is done sequentially using two counters. This technique is used in this altimeter and it will be fully described below. But before we do, let's discuss some general problems involved in linearizing curves using digital techniques. Some of the questions that come up are: How many bits should my A to D converter have? How big a ROM do I need?

The number of bits of the A to D is determined by two things. First, into how many increments do we want to divide our range of interest? In the case of the altimeter, we are interested in 510 increments of 100 feet each over the range of −1,000 feet to +50,000 feet of altitude.

Second, how drastic is the slope change? If the slope didn't change at all (if the curve were linear) a 9-bit A to D would be adequate for our job. The increasing slope with decreasing altitude forces the A to D to need more bits. The approximate number of bits required is given by:

$$A = RI/2$$

where R is the ratio of maximum slope to minimum slope, and I is the number of bits to encode the number of increments dividing our range of interest. This equation is valid for smooth or lumpy curves as long as the sign of the slope never changes. Also, this equation is valid regardless of which digital linearizing technique is used. Only the desired resolution and slope change determine the A to D requirements.

The simplest way to calculate the required resolution of the A to D is to first compute the incremental change, at the minimum slope, of the parameter we desire. Then divide the full range of the input parameter by this incremental change, to give us the number of increments the A to D must resolve.

For example, in the pressure versus altitude curve the maximum slope occurs at −1,000 feet and the minimum at +50,000 feet. Since we are interested in altitude increments of 100 feet, we would compute the incremental change in pressure between 50,000 feet and

49,900 feet. We would then divide this incremental pressure change into the pressure change over the full range of −1,000 to +50,000 feet. Using the numbers in Table I we have:

$$\text{Number of Increments} = \frac{P_{(-1,000)} - P_{(50,000)}}{P_{(49,900)} - P_{(50,000)}}$$

$$= \frac{31.0185 - 3.42466}{3.44112 - 3.42466}$$

$$= 1676.4180 \text{ increments}$$

Therefore, we would need at least an 11-bit analog to digital converter to resolve one part in 1676.

ALTITUDE (FEET)	EQUIVALENT PRESSURE (INCHES OF MERCURY)
−1,000	31.0185
−900	30.9073
0	29.9213
500	29.3846
1,000	28.8557
1,500	28.3345
2,000	27.8210
3,000	26.8167
4,000	25.8418
6,000	23.9782
8,000	22.2250
10,000	20.5770
12,000	19.0294
14,000	17.5774
16,000	16.2164
18,000	14.9421
20,000	13.7501
22,000	12.6363
25,000	11.1035
30,000	8.88544
35,000	7.04062
40,000	5.53802
45,000	4.35488
49,900	3.44112 (EST)
50,000	3.42466

TABLE I

The same factors affect ROM size. In the straight code conversion, the number of bits in the output code also affects ROM size. See the equation $N = 2^M \times B$ earlier in this section. In the case of the technique of storing only deltas, the ROM size is approximately determined by the equation:

$$N = R2^I$$

where N is the number of bits in the ROM, R is the *number of bits* needed to encode the ratio of max to min slope into binary, and I is the number of range bits as before. The organization of the ROM is 2^I locations by R bits wide.

Returning to the actual linearization technique used in the altimeter we can describe it simply by asking the following question: "If I have described a basic pressure increment and if I know that I am at a certain altitude of interest, how many basic pressure increments must pass before I know that I am at my next altitude of interest?"

In our altimeter, we use a dual slope A-D technique with a ROM to cause the conversion to be non-linear with pressure but linear with altitude. The R's and C's and the clock frequency are selected such that one clock period represents a pressure change equivalent to an altitude change of 100 feet at 50,000 feet.

Effectively, the converter starts at −1,000 feet and starts accumulating pressure increments until its accumualted pressure matches that of the pressure transducer. The total number of clock pulses to occur is equal to the number of pressure increments between −1,000 feet and the altitude being digitized. The ROM says, "if you are at −1,000 feet, accumulate six pressure increments before incrementing the altitude counter to −900 feet and so on."

This process continues with the ROM changing the number of pressure increments accumulated between successive altitudes. Ultimately the nine-bit binary counter has in it the binary representation of the altitude to the nearest 100 feet.

This technique is not restricted to use with a dual slope A-D, but can also be used if pressure information is already available in digital form. In that case the pressure information would be loaded into a down counter and counted down to zero, while the altitude counter and ROM count up from zero to the desired altitude value.

DUAL SLOPE ANALOG TO DIGITAL CONVERTER

In our altimeter we will have to take atmospheric pressure, which is analog information, and convert it to digital form for transmission to a ground station. We used a dual slope analog to digital conversion technique to do that job. We chose this technique because it is simple and cheap and we can tolerate the long conversion times typical of this approach.

Figure 3 shows the block diagram and basic timing of a dual slope A-D. Capacitor C1 is charged to some initial voltage V_{START} and I_{REF} is off. I_{IN}, which is variable and proportional to the voltage to be digitized, is allowed to charge C1 for time T1. T1 is constant. At the end of T1, I_{IN} is switched off and I_{REF} which is a constant, is switched on, discharging C1 back to V_{START} in time T2. T2 then, is proportional to the unknown input voltage. Times T1 and T2 are both measured by counting the oscillator and, therefore, at the end of T2, the counter contains a number proportional to the input voltage.

Figure 4 shows the actual circuitry employed in the altimeter to do the analog portion of the dual slope A-D.

V_{START} is set by R3 and R4. The setting is not critical as long as it is somewhere toward the lower end of the LM108 linear region. (An LM108 will not pull all the way down to the lower supply.)

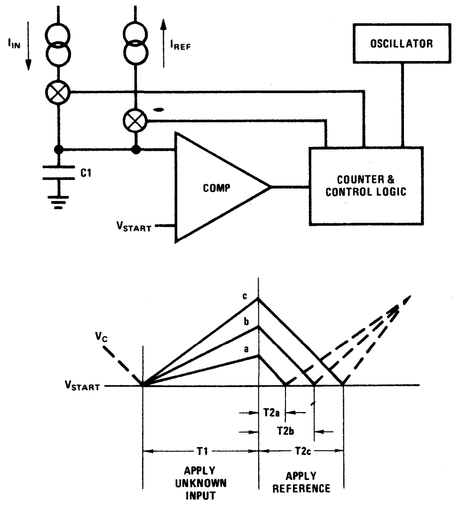


FIGURE 3. Dual Slope A-D

R2 is the zero adjust for the altimeter. R2 is adjusted until V_1 is equal to the transducer output voltage with an input pressure equal to −1,000 feet of altitude.

R1 is the full scale adjust. With R2 set, I_{IN} max is equal to V_1 minus the transducer output voltage at a pressure equivalent to 50,000 feet of altitude, divided by R1. I_{REF} is equal to 15V minus V_1 divided by some portion of R1.

When we apply full scale voltage, we are on curve C in *Figure 3.* In a typical A-D, times T1 and T2c would be equal for that condition. In our altimeter, however, T1 and T2 are not equal at 50,000 feet, or at any other altitude for that matter. To simplify some of the logic we chose T1 to be 2048 clock periods. T2 max becomes 1676 clock periods because of our linearization technique. Therefore, the ratio of I_{IN} max to I_{REF} is 1676 to 2048 with I_{REF} larger.

For others who will use this technique there is one thing that is not obvious from *Figures 3 and 4*. Many dual slope techniques use an initializing circuit of some sort to ensure that the capacitor starts from a known voltage each time.

If the capacitor were to accumulate some residual charge the final conversion would be incorrect. The critical time is at the end of T2 when the comparator is tripped. Unless I_{REF} is turned off immediately, it will continue to charge C1, applying an offset voltage that will affect the next conversion. If this happens with each conversion, succeeding conversions become more inaccurate.

The way around the problem is to be certain that I_{REF} is switched off and I_{IN} switched on at the next clock pulse after the comparator switches *(Figure 5).* This ensures that the residual voltage will always be one bit or less.

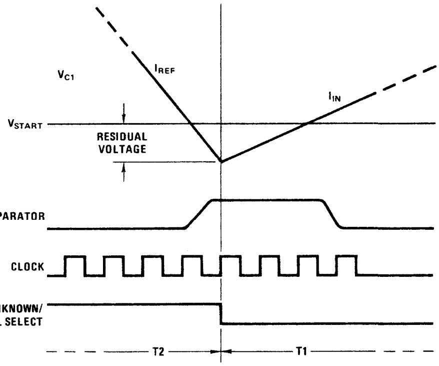


FIGURE 5

Even with the excellent function shaping afforded by dual slope integration and accuracy improvements resulting from use of the syringe—auto-referencing technique (see Section 7), it is doubtful that standard commercial grade pressure transducers can provide system accuracy and reliability required by FAA.

However, less stringent altimeter requirements for mountain climbers, drones, gliders, balloons, altitude rate indication and meteorological mensuration . . . are all good candidates for these techniques.

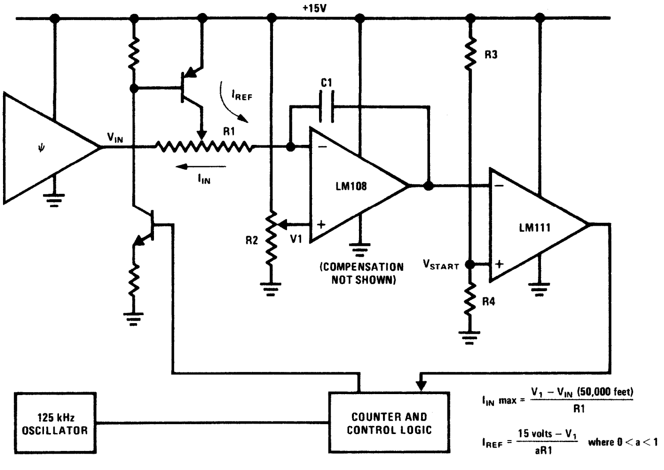


FIGURE 4. Analog Circuitry For Dual Slope A-D

Switch Control

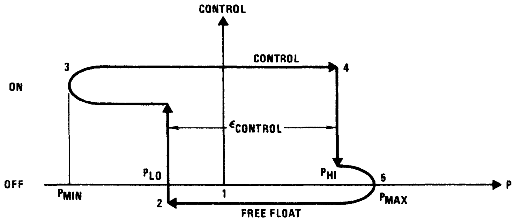
SenSym

SSAN-13

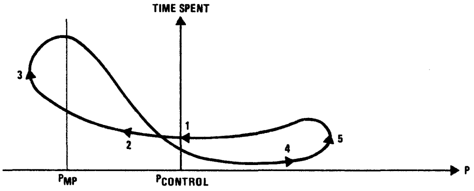
SINGLE-SWITCH CONTROL

Most control systems using pressure transducers employ a single control element, such as a valve or pump, that is either ON or OFF. Examples include the pressure in a boiler, liquid level in a container, and air flow in environmental control systems. In these single-switch systems, the control cycle can be represented as shown in *Figure 1a.* Beginning with the switch OFF and the pressure at $P_{CONTROL}$ (Point 1), the pressure decreases until the control element is activated at P_{LO} (Point 2). The momentum of the system carries the pressure to P_{MIN} (Point 3) where the control element finally succeeds in turning the system around. The control element drives the pressure to P_{HI} (Point 4) which turns off the control element, and the momentum imparted to the system carries it to P_{MAX} (Point 5), after which the system is free floating until it reaches P_{LOW} again.

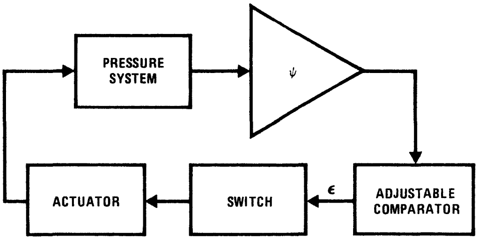
Because of the momentum of the system and the generally different forcing functions acting in the ON and OFF states, the rate of pressure change varies throughout the control cycle. The inverse of this rate can tell us the time spent or the probability of finding the system in any pressure interval within the control range. This is shown in *Figure 1b* for a weak control element, (system momentum large compared to effect of control element, i.e., small fan in large, long room). In this situation, the most probable pressure, P_{MP}, is offset from the average pressure, $P_{CONTROL}$. Although this effect is of little consequence in many applications, it is important in comfort control since the system seems to "always" be below its proper setting.



a. Control Cycle



b. Time-Spent



c. Block Diagram

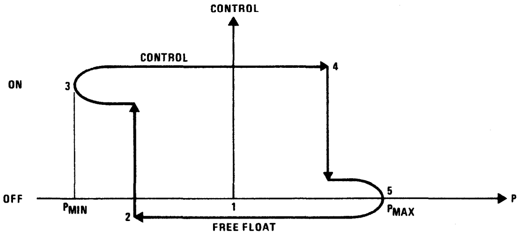
FIGURE 1. Single-Switch System, Weak Control

If the control element is made stronger or the system weakened (bigger fan in smaller room), as shown in *Figure 2*, another peak in pressure probability, $P_{MP\ HI}$, develops at the high pressure end. When the control element force is twice that of the system the pressure change rate is the same for the ON and OFF states, and the time-spent plot is symmetrical about $P_{CONTROL}$. The system then spends much of its time near P_{HI} and P_{LO}, thus seeming to "always" be too high or too low and "never" at $P_{CONTROL}$. If the uncontrolled system rate is further reduced (or the control element strengthened), the result is a cycle that is skewed to the high pressure side, a mirror image of the case shown in *Figure 1.*

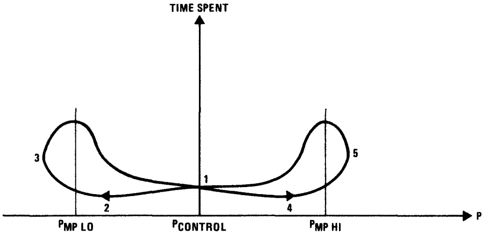
DUAL-SWITCH CONTROL—SINGLE-SIDED

To compensate overshoot in a single-sided system, a second switch can be added to activate another control element acting in the same direction (opposing system momentum). This element could be a valve, pump, alarm or another fan in the aforementioned large room. An example is shown in *Figure 3.*.

Once again at $P_{CONTROL}$ (Point 1), the system pressure is decreasing and all control elements are OFF. At Point 2, the first control element turns ON, (i.e., first fan), slowing the rate of pressure decrease. At Point 3, the second control element turns ON (i.e., second fan), further slowing pressure decrease and reducing system overshoot such that Point 4 represents minimum system pressure. With control elements 1 and 2 activated, the system pressure increases quickly to Point 5, where one control element is shut down. At Point 6, the second control element is turned OFF, allowing return to Point 1.

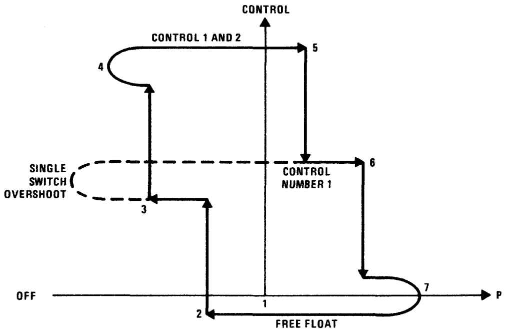


a. Control Cycle

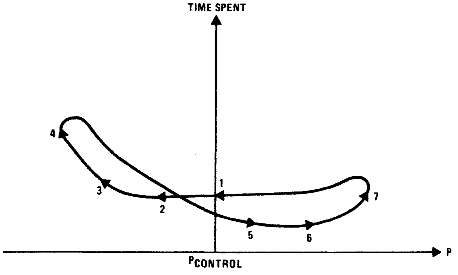


b. Time-Spent

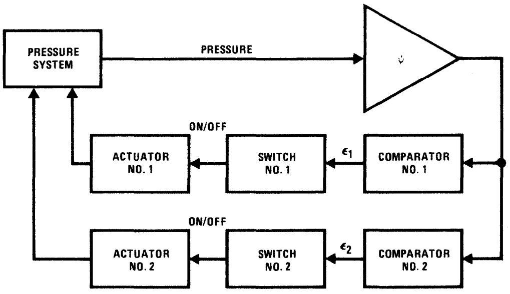
FIGURE 2. Symmetric Control Function



a. Control Cycle



b. Time-Spent



c. Block Diagram

FIGURE 3. Dual-Switch Control—Single-Sided

SINGLE-SWITCH CONTROL—DUAL-SIDED

In single-sided control, the system needs a tendency to move in one direction without controlling influence. In dual-sided control, the control elements drive the system in both directions. That is, if one control element increases pressure, the other must decrease pressure. This would equate to opening (ON) and closing (OFF) a door at end of our large, long room while turning the fan at the other end OFF and ON. This approach is shown in *Figures 4, 5 and 6*.

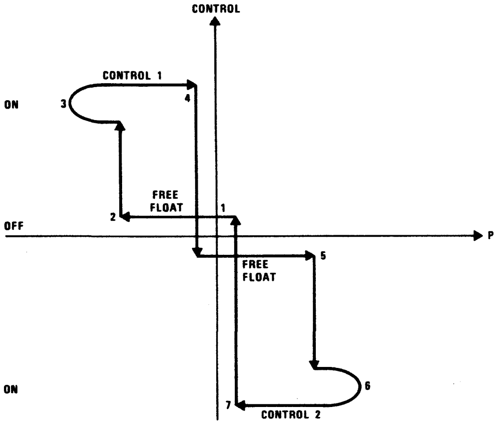
Figure 4 shows a properly designed control for a system with little undriven tendency to move. The control elements have roughly equal effect in driving the system. The system is free floating at $P_{CONTROL}$ and spends much of its time there ($P_{CONTROL} \approx P_{MP}$). Points 1 through 4 of *Figure 4a* operate exactly as discussed for *Figure 1a*. The system then free floats to Point 5. The identical process now occurs for the control element that decreases pressure.

If the control elements are too strong for the system momentum, and wide pressure limits are desired (perhaps to provide low switching rate), an "undercontrolled" system may result. In this situation *(Figure 5)*, too much time is spent in free float. The system seems to "hunt" for $P_{CONTROL}$.

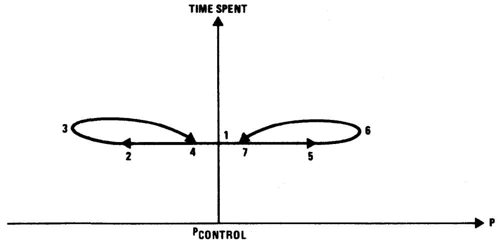
If the control elements are weak relative to system momentum, and narrow pressure limits are required, an "overcontrolled" system may result. In this situation *(Figure 6)*, too little time is spent in free float. More important, minimum time is spent at $P_{CONTROL}$ because the system is driven through $P_{CONTROL}$ from both directions. The system seems most stable at its pressure limits.

MULTIPLE-SWITCH CONTROL

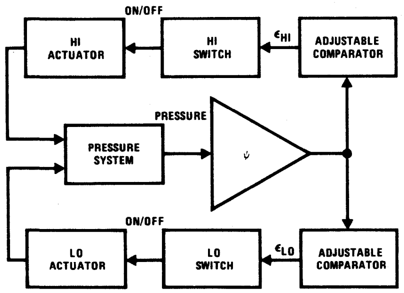
As with the single-switch controller, an additional switch can be added on each side of the dual-sided controller to achieve tighter tolerances around $P_{CONTROL}$. The control properties of each loop would then be equivalent to the single-sided dual-switch loop shown in *Figure 3.* Of course, further improvement can be obtained by adding still more switch loops until a "continuous" control function is approached. This is indeed the trend is modern large comfort control systems (see Section 7).



a. Control Cycle

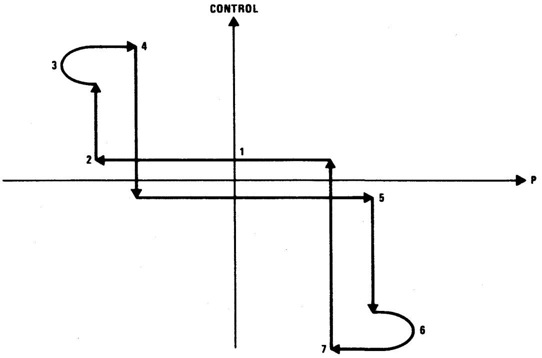


b. Time-Spent

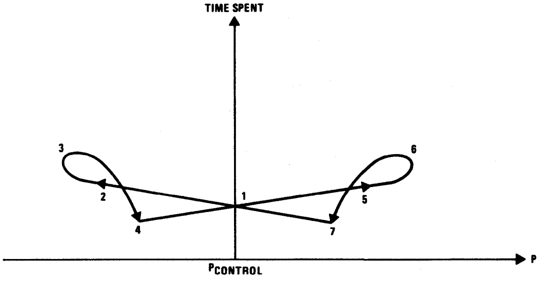


c. Block Diagram

FIGURE 4. Dual Control System, Properly Designed

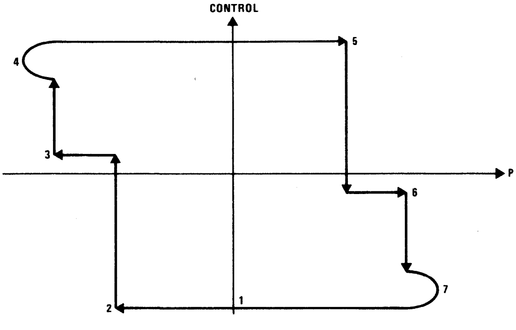


a. Control Cycle

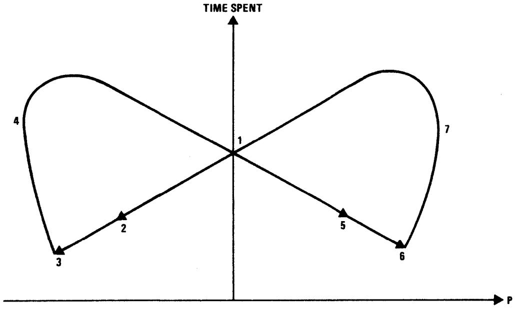


b. Time-Spent

FIGURE 5. Undercontrol



a. Control Cycle



b. Time-Spent

FIGURE 6. Overcontrol

SWITCHING ACCURACY AND AUTO-REFERENCING

In the previous discussion, the pressure switch was assumed to be error free, but in practice there will be some error in the switching points P_{LO} and P_{HI}, resulting from errors in the pressure transducer. The primary effect of these errors, as shown in *Figure 7,* is to extend the possible pressure excursion, P_{MIN} to P_{MAX}, by the total error, $P_{ERROR\,HI} + P_{ERROR\,LO}$. Although the errors in IC pressure transducers are normally small as compared with the required $\epsilon_{CONTROL}$ in a single-switch system, the use of a single transducer for multiple-switch control may result in errors that are a significant part of the control range. In such cases, auto-referencing can be used to improve its accuracy (Section 3, Accuracy; Section 7, Auto-Referencing), as illustrated by the system shown in *Figure 8*. In this system, $P_{CONTROL}$ is set by a pressure line to the differential pressure transducer. This places the output of the transducer at V_{REF} when the system is at $P_{CONTROL\,DES}$ which allows simple auto-referencing by momentarily connecting $P_{CONTROL}$ to the pressure system with a valve. It also simplifies detection of the switch pressures, P_{HI} and P_{LO}, and minimizes the errors, $P_{ERROR\,HI}$ and $P_{ERROR\,LO}$. For control systems where the accuracy of the transducer is adequate, such as in many single-switch controllers, the auto-reference circuit and valve will not be required.

Most commonly, the system pressure limits (ϵ_{SYSTEM}), overshoot ($\epsilon_{OVERSHOOT}$) and pressure to be controlled ($P_{CONTROL\,DES}$) are known. The designer need choose values for each switch circuit ($P_{HI\,DES}$, $P_{LO\,DES}$ and $\epsilon_{CONTROL\,DES}$) consistent with the errors contributed by the pressure transducer (P_{ERROR}). Inspection of *Figure 7* yields the following relationships:

$$P_{LO\,DES} = P_{CONTROL\,DES} - 1/2\,\epsilon_{SYSTEM} + \epsilon_{OVERSHOOT\,LO} + P_{ERROR\,LO}$$

$$P_{HI\,DES} = P_{CONTROL\,DES} + 1/2\,\epsilon_{SYSTEM} - \epsilon_{OVERSHOOT\,HI} - P_{ERROR\,HI}$$

For symmetric systems, the relationships reduce to:

$$P_{LO\,DES} = P_{CONTROL\,DES} - 1/2\,\epsilon_{CONTROL} + P_{ERROR\,LO}$$

$$P_{HI\,DES} = P_{CONTROL\,DES} + 1/2\,\epsilon_{CONTROL} - P_{ERROR\,HI}$$

The transducer errors expand to:

$$P_{ERROR\,LO} = P_{ERROR\,COMMON\text{-}MODE}\,(P_{REF}) + P_{ERROR\,NORMAL\,MODE}\,(P_{REF} - P_{LO})$$

$$P_{ERROR\,HI} = P_{ERROR\,COMMON\text{-}MODE}\,(P_{REF}) + P_{ERROR\,NORMAL\,MODE}\,(P_{HI} - P_{REF})$$

For $P_{REF} = P_{CONTROL\,DES}$:

$$P_{ERROR\,LO} = P_{ERROR\,HI} = P_{ERROR\,COMMON\text{-}MODE}\,(P_{CONTROL\,DES}) + P_{ERROR\,NORMAL\,MODE}\,(\epsilon_{CONTROL\,DES})$$

Section 3, Accuracy and Specifications, gives specific examples of how to calculate P_{ERROR} with and without auto-referencing.

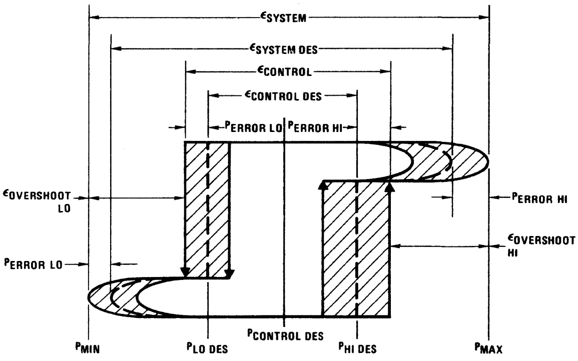


FIGURE 7. Switching Errors in Single-Switch Control Cycle

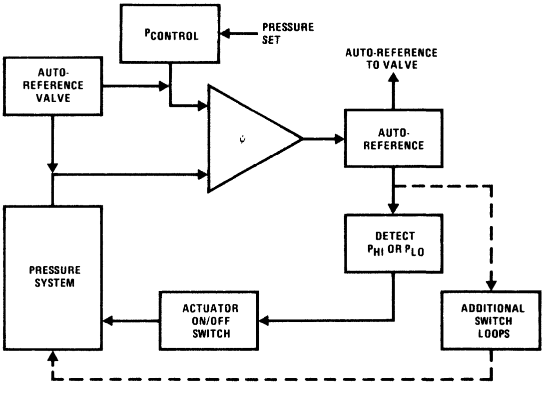


FIGURE 8. Pressure-Controlled Single-Switch Control Element With a Differential Pressure Transducer

Acoustic Applications of Pressure Transducers

SenSym

SSAN-14

The IC pressure transducer can be used as an acoustic sensor in microphones, hydrophones, sound level meters, musical instrument pickups, audiometers, and other sound detection applications. The IC transducer has a wide frequency response (from DC to 50 kHz) and a built-in operational amplifier that provides a high level signal output for audio range (DC to 30 kHz) pressure variations. Because the transducer diaphragm's natural frequency is outside the audio range (~50 kHz), it doesn't generate audio-range harmonics from input sound waves. This totally eliminates tricky microphone squealing even in heavy feedback situations. The IC pressure transducer's high accuracy, which can be further improved by auto-referencing, qualifies it for use in precision audio instruments.

ACOUSTIC INTERFACING

With the pressure port tube in place, the IC transducer has a directional acoustic pickup pattern that can be broadened by reducing the length of the tube. If the tube is removed, the pickup pattern is similar to a high quality cardioid microphone. The transducer can be used as is for musical instrument pickups *(Figure 1)* or for close-up directional microphones, but may require tube modification for other types of microphones.

> **Important:** The port must be protected by an acoustically compliant material to prevent breath moisture from reaching the transducer circuit in any microphone, wind instrument, or other application where someone could blow into the port.

For stand-off microphones, additional gain can be obtained by use of reflective sound collectors. Use a paraboloid reflector for directional pickup, as shown in *Figure 2,* or a hyperboloid for wide angle pickup, as shown in *Figure 3.* In either case, the pressure port should be shortened to accept the wide angles within the acoustic optical system.

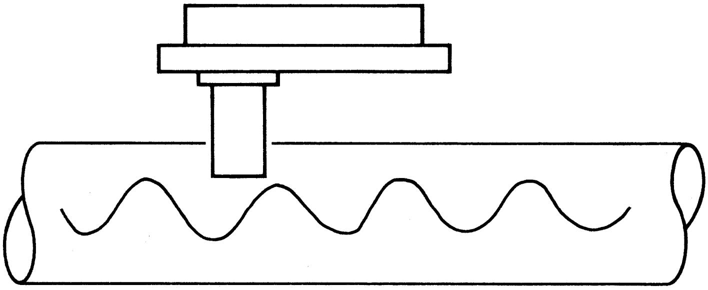


FIGURE 1. Instrument Sound Pickup

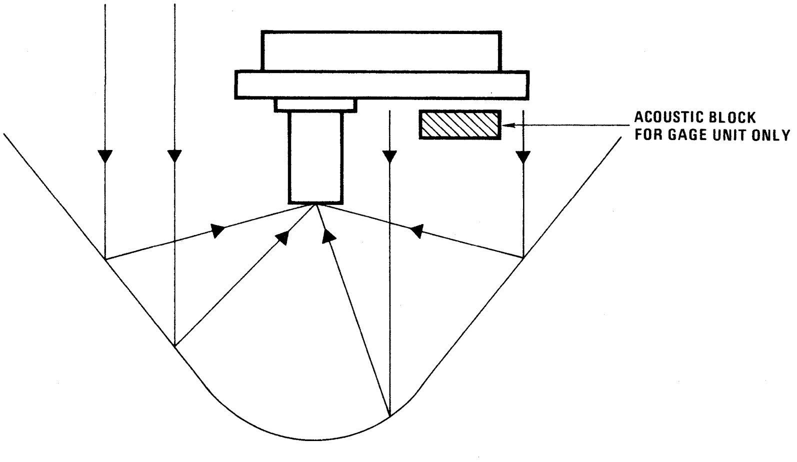


FIGURE 2. Directional Paraboloid "Mike"

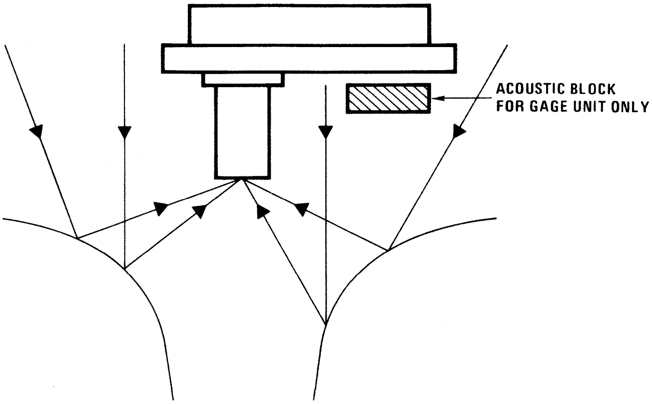


FIGURE 3. Wide Angle Hyperboloid "Mike"

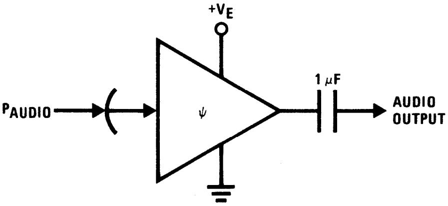


FIGURE 4. Transducer as a Solid-State Microphone

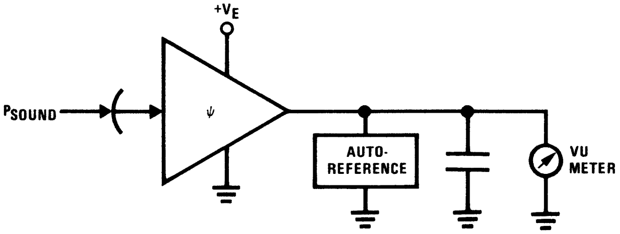


FIGURE 5. Transducer as a Sound Pressure Level Meter

ACOUSTIC TRANSDUCER SELECTION

For acoustic measurements, the most sensitive gage pressure transducer is normally selected. The sound pressure waves are usually small, requiring high sensitivity, and the gage inlet balances out atmospheric pressure. Since sound pressure waves go both positive and negative around the mean atmospheric pressure, the ±5 psig range of the LX1801GN is ideal for the following applications. The LX1801AN can also be used since its response is centered at 15 psi (atmospheric pressure), and it has the advantage of not requiring an acoustic block for the gage inlet.

Audio Pickups: For microphones and other audio pickups, the transducer only requires excitation voltage V_E and a 1 μF series capacitor to function effectively as a sound sensor *(Figure 4)*. The sound can be coupled in by any appropriate means as discussed above and by following the general principles used for all acoustic pickups.

Sound Pressure Level Meter: Conventional sound pressure level (SPL) meters normally use a microphone pickup. The resulting signal is amplified, rectified and used to drive a meter readout. Since the IC transducer's signal is already amplified, it eliminates much of the SPL meter circuitry *(Figure 5)*. But to be accurate, the SPL meter must be precisely coupled with the sound pressure level input, which should be discussed with Sensym's pressure transducer applications engineers. If an accuracy better than 3% of amplitude is required, either restricted temperature range or normal mode auto-referencing should be used.

Hydraphones: In underwater sound pickup applications, an absolute pressure transducer is used. As discussed in the Installation section, a very simple hermetic enclosure can be used to protect the transducer. Here again the model LX1601A transducer can be used, as shown in *Figure 6.*

Audiometer/Tympanometer: The audiometer/tympanometer combines the capabilities of the IC pressure transducer for precise sensing of both audio pressure variations and static pressure. As shown in *Figure 7,* this instrument uses an audio generator to teat the response of the human ear. The audiometer function relies on patient response and hence is only required to measure the AC amplitude (and frequency, if desired) of the audio signal entering the ear via the ear plug. The tympanometer measures the compliance of the ear drum without patient cooperation by comparing AC amplitude with DC level shift resulting from back pressure between the ear plug and the ear drum. Both normal mode and common-mode auto-referencing can be used to increase measurement accuracy.

Sphygmomanometer: Like the audiometer/tympanometer, this instrument makes use of both AC and DC pressure detection level measurements. It measures the absolute blood pressure levels for the systolic and diastolic points while monitoring the phase of the heartbeat cycle for more accurate location of the "true" systolic point, the point where the apparent heartbeat at the point of measurement undergoes a change in phase.

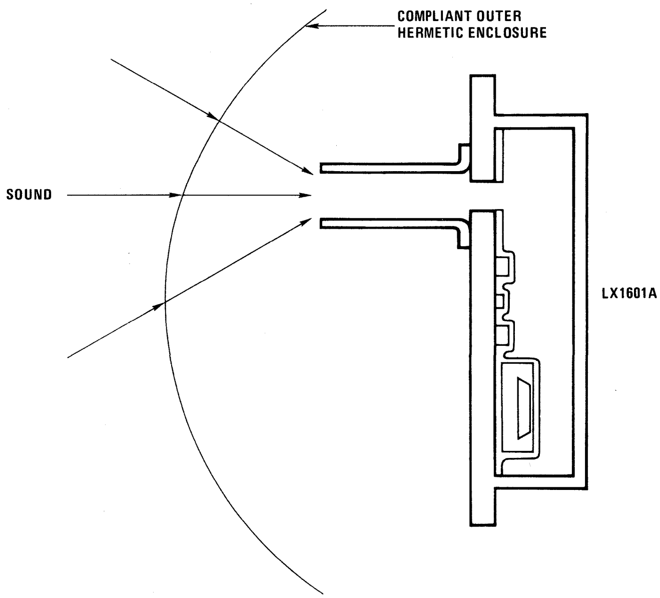


FIGURE 6. Conceptual Diagram of Transducer Hydraphone

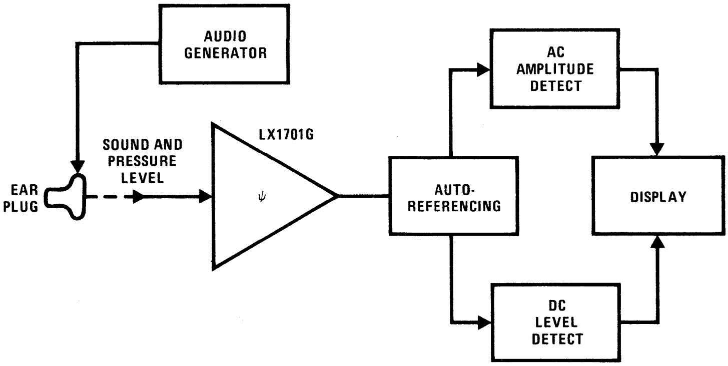


FIGURE 7. Audiometer/Tympanometer

FROM FAT TO CRISP AS EASILY AS BURNING BACON

It seems that professional musicians—horn players, in particular—have a problem. On stage and in the recording studio, they are forced to "play to the mike". These pros are not free to spin, dip, swoop and otherwise trip through all sorts of Body English as they feel the urge, for fear that the sound system will lose the full quality of the instrument's tone. And so the dream of this group is to have an omnidirectional sound system capable of detecting the most subtle nuances of their particular sound, regardless of how many dimensions of freedom the musician feels he must move through.

And of this group, woodwind players have yet another, secret dream. Since there have been pros around to hear it, woodwind players have greened with envy at the quality of a brass' attack. ("Attack" is a musical term descriptive of a tone's risetime.) A saxophone player simply tingles all over at the mere thought of having his instrument come on like a trumpet, for example.

To solve this heretofore insoluble problem for mankind in general—and for professional musicians in particular—National Semiconductor unleashed the full genius of its transducer applications engineers, who attacked the attack problem (with gusto) and promptly solved it. We modestly present the basic concepts here.

In brass instruments, the musician's mouth and throat are part of the instrument's air column. As such, the input air pressure is an important determinant of pitch, volume and the tonal quality of the sound. But in woodwinds, the musician's mouth and throat are not part of the air column; they are part of the reed. And as such, the input air pressure is associated with pitch only, and not, basically, with the final quality of the sound. Thus the need of woodwind players for an external method to manipulate the tonal quality of their instruments.

Figure 8 shows a fundamental, sound system for woodwind instruments—the musician's concept of the perfect microphone. It consists of an IC pressure transducer coupled tightly to the instrument's mouthpiece, serving both as a microphone and as a sound pressure meter.

If the AC signal is modulated by the DC signal, the output of the sound system is quite similar to that of an instrument with square-law attack. The woodwind has now already acquired the attack quality of a brass; it's still up to the musician as to how the attack is to be used.

The system using microprocessor-controlled modulation gives an instrument of selectable bell size, a tonal quality that varies from "fat" (full and rich) to "crisp" (sharp and clear-edged), and something that no echo chamber could ever achieve—selectable delay.

A clarinet, for example, can be given the attack of a trombone with the bell of a sousaphone, and yet retain the clarinet's characteristic playing facility. In short, we have brought the woodwinds out of their Dark Ages.

(P.S. to brass players: don't let the woodwind players know, but if you guys decide to try this system on your instruments . . . all we can say is that the results would be complex, difficult to guess at, but good!)

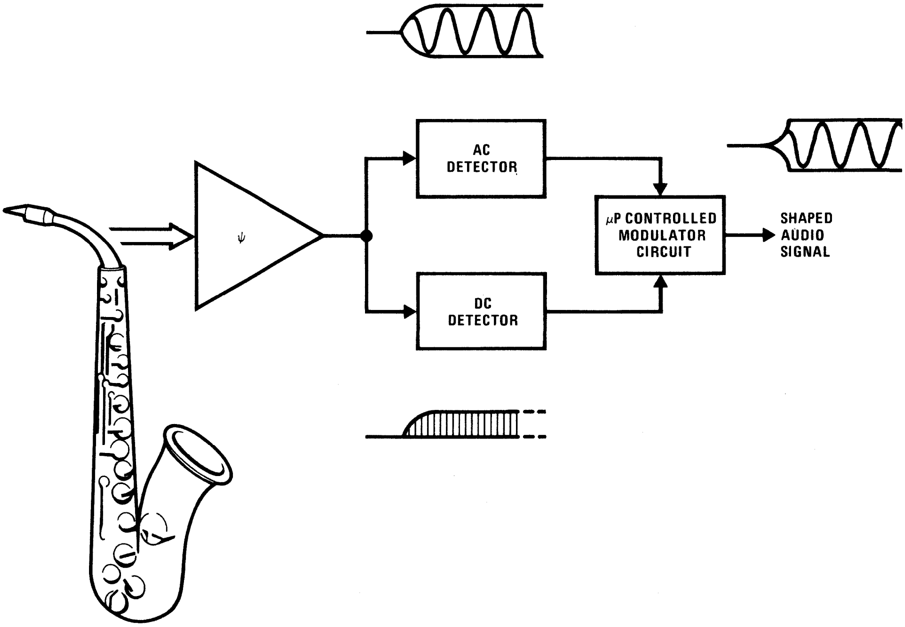


FIGURE 8. The Woodwind Player's Dream

Grease-Filling a Pressure Transducer

SenSym

SSAN-15

Introduction

Many applications require that the electronics associated with the transducer be isolated from the working environment. One of the most common media from which the electronics must be kept separate is water (i.e. tap water, sea water, irrigation water, etc.). It is typically in those applications where water is the media that grease-filling the transducer is the best isolation technique.

This application note has been written for those users who, in order to keep costs down, choose to do their own media isolation.

Equipment and Supplies

The following equipment and supplies are necessary:

- an inert grease; high grade gear or bearing grease, or equivalent
- a pressurized air source
- a vacuum pump capable of drawing greater than 25″ of vacuum
- an automotive grease gun
- a pressure transducer
- a grease-fill fixture (as shown in *Figure 1*)

Set-Up Procedure

Follow these steps to prepare for a grease fill:

1. Assemble the grease-fill fixture (see *Figure 1*)
2. Close all valves on the fill fixture.
3. Set air pressure to 80–100 psi.
4. Establish a vacuum. (Vacuum should be as high as possible using a conventional vacuum pump, 25–29″ Hg.)
5. Load the grease gun.

Remember to always use caution when working with pressure!

Fill Procedure Cautions

Please read the following section carefully before proceeding to grease-fill any device.

- Grease must be blown out of the fixture prior to each fill. If this is not done grease will plug the line, preventing a vacuum from being pulled at the transducer.
- If an overpressure relief valve is not used on the fixture, extreme care must be taken to avoid overpressuring the transducer. The grease gun can generate over 1000 psi and rupture a low pressure transducer diaphragm.
- If grease is pumped while valves #1 and #3 are open; grease will intrude into the vacuum lines, causing blockage.
- If air remains in the transducer, under the grease plug, the pressure frequency response will be reduced and thermal overshoot will occur. (See *Figures 2 & 3.*)
- In order to conserve grease, the distance between valve #1 and the transducer port should be as short as possible.

Grease-Fill Procedure

To fill the transducer with grease, follow these steps. (See *Figure 1.*)

1. Open valve #1 to the air lines.
2. Before connecting the unit to be filled to the fill fixture, hold a towel around the transducer port of the fill fixture and open valve #2 from the pressure supply. Leave valve #2 open until the air flows evenly. Close valve #2.

   Note: The towel is for catching any expelled grease left from the last fill operation.
3. Attach the pressure transducer to the fixture sensor port. Use teflon tape to insure a good seal.

   Note: If you are filling a device other than one with an 1/8″ NPT fitting, a different fixture must be used in order to get a proper seal.
4. Open valve #3 from the vacuum for approximately one minute, then close valve #3.
5. Close valve #1, then open valve #4 to the grease gun.
6. Use the grease gun to pump in the grease; continue until resistance is felt.
7. Close valve #4, then remove the transducer from the fixture. Clean excess grease off the transducer.
8. Repeat steps 1–7 for each device to be filled.

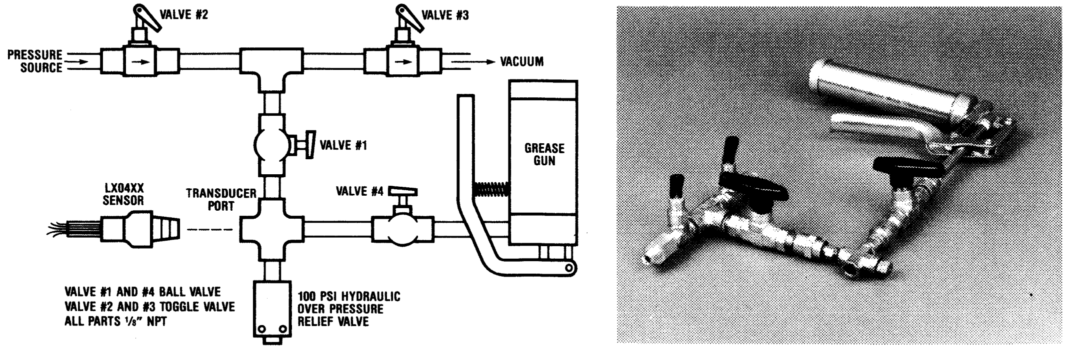


Figure 1. Grease-Fill Fixture for Pressure Transducer

Testing Procedures

There are two basic tests which can be performed to be certain that the grease-fill worked properly.

1. Pressurize the unit and measure the response time. If there is a large bubble of air trapped within the unit, the response time will be much slower. (See *Figure 2.*)
2. Heat the unit and measure its voltage output at a constant pressure. If you use a thermal step input to heat the unit, trapped air will cause an overshoot. (See *Figure 3.*)

Application Cautions

Grease-filling is not the answer to all isolation problems. Please take careful note of the following:

- **Do not use for oxygen isolation!** In general, grease-filling is *not* a good technique to use for gases.
- Select grease that is not soluble or reactive with the working medium.
- A high flow of the medium near the sensor may cause grease to "wash out" of the unit.
- The grease selected must maintain reasonable viscosity at working and storage temperature.

Alternate Isolation Techniques

There are a number of possible methods for achieving isolation. One of the simplest methods is to use a backward gauge device (GB series). Within certain limitations, this can be an excellent solution. The fluid in use must be such that the small hole that leads to the silicon diaphragm remains unplugged, and a dry ambient must be used. However, this device cannot be used to measure absolute pressure.

Using an add-on gauge protector, like those made by Bellofram Corporation, is another method. These, however, tend to be bulky and expensive. A less expensive solution is to use a silicon-based coating. Unfortunately, no silicon-based coating has been developed which will withstand high pressure cycling, and the coating must be applied at the factory, again running up costs.

For applications requiring high-pressure operation and low cost, grease-filling the transducer is the best option. Unlike silicon coating, grease-filled devices can withstand high pressure cycling and the user can save costs by doing the grease-fill himself. Which isolation technique is best depends on the particular application requirements and constraints.

Summary

If the preceeding instructions and cautions are followed carefully, you should be able to properly grease-isolate the pressure transducer. Grease isolation can be a very useful and low-cost method for protecting a transducer's electronics from the working environment in a number of applications. As noted, however, grease-filling will not solve all isolation problems.

If you have any questions about grease-filling and your particular application needs, or if additional information is needed on the grease-filling procedure, please contact the factory.

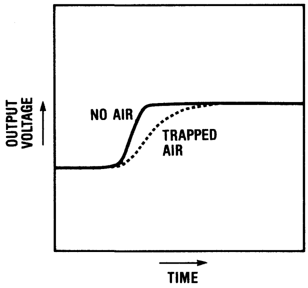


Figure 2. Grease-Filled Sensor Pressure Step Response

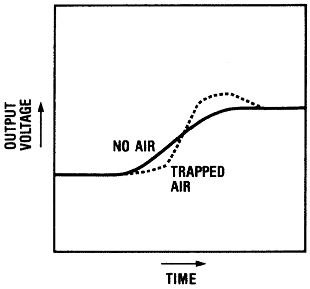
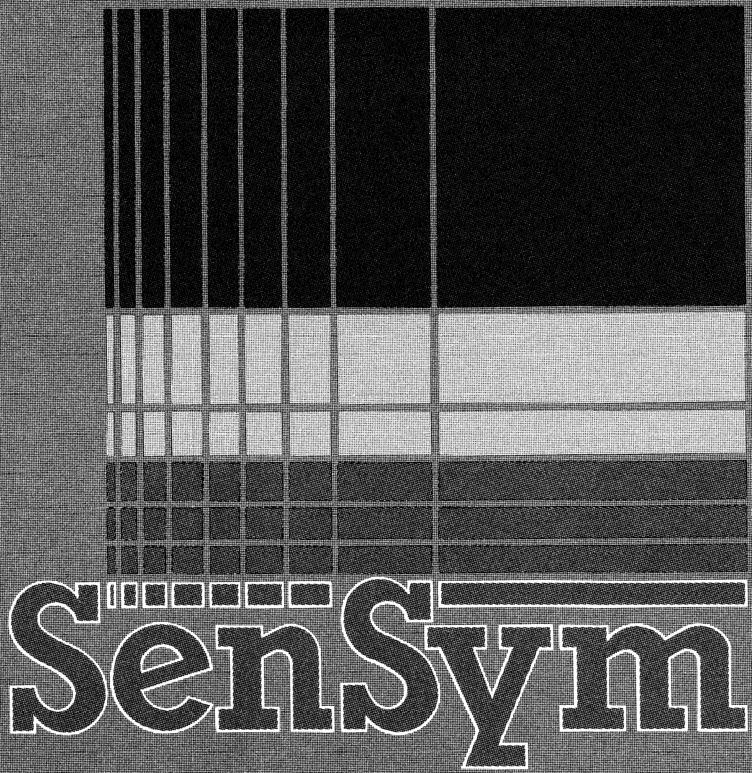


Figure 3. Grease-Filled Sensor Temperature Step Response

Section 10 Appendices



Definition of Terms

SenSym

GENERAL TRANSDUCER TERMS

Absolute Pressure: Pressure measured relative to a perfect vacuum. Usually expressed in pounds per square inch absolute (psia).

Absolute Pressure Transducer: A device containing a vaccum reference such that it measures absolute pressure either of the local ambient or of a pressure source piped to its input.

Differential Pressure: The pressure difference measured between two pressure sources. Usually expressed in pounds per square inch differential (psid). When one source is a perfect vacuum, the pressure difference is called *absolute pressure*. When one source is the local ambient, the pressure is called *gage pressure*.

Differential Pressure Transducer: A device that measures the differential pressure between two pressure sources piped to its inputs.

Gage Pressure: Differential pressure between the local ambient and another pressure source.

Gage Pressure Transducer: A differential pressure transducer with the local ambient as one source and the pressure piped to its input as the other source.

Barometric Pressure Transducer: An absolute pressure transducer measuring the local ambient pressure.

Altimetric Pressure Transducer: A barometric pressure transducer used to determine altitude from the pressure-altitude profile.

Vacuum: A perfect vacuum is the absence of gaseous fluid.

Vacuum Range: The range of absolute pressures between a perfect vacuum (0 psia) and one standard atmosphere (14.697 psia).

Vacuum Transducer: A transducer scaled for pressure measurement in the vacuum range. This is usually an absolute transducer, but sometimes a gage transducer.

TRANSDUCER PARAMETERS

Range: The specified endpoint pressures of the transducer operating pressure range usually expressed in psia, psid, or psig (e.g., 10 to 20 psia).

Span: The arithmetic difference in transducer output signal measured at the specified minimum and maximum operating pressures. Span is usually expressed in volts (V).

Sensitivity: The ratio of output signal voltage change to the corresponding input pressure change. Sensitivity is determined by computing the ratio of span to the specified input pressure range (slope of the *best straight line*). It is usually expressed in volts per psi (V/psi).

Reference Temperature: The temperature used as reference in measuring transducter errors in 25°C ± 3°C for Sensym transducers.

Reference Pressure: The pressure used as a reference in measuring transducer errors. Reference pressure is the lowest operating pressure. This is 0 psi for most transducers in Sensym's line.

Offset Voltage: The transducer output signal obtained when the reference pressure is applied, usually expressed in volts (V).

Over-Pressure — Maximum: The maximum *normal mode* (measured) pressure that can be applied without changing the transducer's performance or accuracy beyond the specified limits. This would be applied to either port of a differential transducer. This is also called PROOF PRESSURE.

Common-Mode Pressure — Maximum: The maximum pressure that can be applied to both ports of a differential transducer without changing its performance or accuracy beyond the specified limits.

Seal Pressure: The maximum pressure that can be safely applied to a gage or differential transducer and still ensure no leakage of the pressurized fluid to the surroundings.

Burst Pressure: The maximum pressure that can safely be applied to an absolute transducer and still ensure no leakage of the pressurized fluid to the surroundings.

GENERAL ERROR TERMS

Best Straight Line (BSL): The best straight line chosen such that the true transducer response curve contains three points of equal maximum deviation.

Error Band: The deviation of transducer response from its *BSL with force reference*, defined by lines on either side of its BSL and including the maximum deviation measured for a *given normal mode* or *common mode* error.

Temperature Coefficient (TC): The *error band* resulting from maximum deviation of a transducer output parameter (such as *offset* or *span*) as temperature is varied from 25°C ± 3°C to any other temperature within the specified range. It is usually measured in V/°C and divided by *sensitivity* to express the magnitude of the *error bank* in psi/°C.

Repeatability: The *error band* expressing the ability of the transducer to reproduce an output signal parameter (such as offset or span), at specified pressures and temperature, after exposure to any other pressure and temperature within the specified range. It is usually measured in volts and divided by *sensitivity* to obtain the magnitude of the *error band*, expressed in psi.

Stability: The *error band* expressing the ability of a transducer to maintain the value of an output parameter (such as offset or span) with constant temperature and pressure inputs. The maximum deviation is usually measured in volts and divided by *sensitivity* to obtain the magnitude of the *error band*, expressed in psi.

Interchangeability: The *error band* defined by the maximum signal deviation obtained when a transducer is replaced by any other transducer of the same type with equivalent pressure inputs and temperature ranges. It is usually expressed in psi.

Normal Mode Error: An error that is a function of (and usually assumed to be proportional to) the major input variable (input pressure). For Sensym transducers, all *span errors* are normal mode errors.

Common-Mode Error: An error that is independent of the major input variable (input pressure). For Sensym transducers, all *offset errors* are common-mode errors.

Auto-Referencing: A technique for eliminating errors by sampling one or more reference pressures, then correcting the output signal function.

OFFSET ERROR TERMS (COMMON-MODE)

Offset Error: The *common-mode error band* defined by the maximum deviation of *offset voltage* from its specified value. It may include calibration, temperature coefficient, repeatability and stability errors.

Offset Calibration: The *error band* defined by the maximum error in calibrating the *offset voltage.*

Offset Temperature Coefficient: The *error band* defined by the maximum deviation in *offset voltage* as the temperature is varied from 25°C to any other temperature within the specified range. The deviation is measured in volts, divided by the temperature excursion then divided by *sensitivity* to express the magnitude of the *error band* in psi.

Offset Repeatability: The *error band* expressing the ability of the transducer to reproduce the *offset voltage*, measured at 25°C, after exposure to any other temperature and pressure within the specified range. The deviation is measured in volts then divided by *sensitivity* to obtain the magnitude of the *error band* in psi.

Offset Stability: The *error band* expresing the ability of the transducer to maintain the offset voltage with constant pressure and temperature.

SPAN ERROR TERMS (NORMAL MODE)

Span Error: The *normal mode error band* defined by the maximum deviation of *span* from its specified value. It may include sensitivity calibration temperature, coefficient, linearity, hysteresis, repeatability and stability deviations.

Sensitivity Calibration: The *error band* defined by the maximum error in calibrating *sensitivity.*

Span Temperature Coefficient: The error band defined by the maximum deviation of the *span* as the temperature is varied from 25°C to any other temperature within the specified range. It is obtained by measuring output voltage change as pressure is varied from *reference* to maximum, dividing by the temperature excursion then by sensitivity to express the magnitude of the *error band* in psi.

Linearity: The maximum deviation of measured output at constant temperature (25°C) from "best straight line" through three points (offset pressure, full-scale pressure, and one-half full-scale pressure).

$$\%\text{ of full-scale error} = \left\{ V_{\frac{1}{2}\text{ full-scale}} - \frac{V_{\text{full-scale}} - V_{\text{offset}}}{\text{full-scale pressure}} \times \left(\tfrac{1}{2}\text{ full-scale pressure}\right) + V_{\text{offset}} \right\} \div 2 \quad \times 100\%$$

where:

V = measured value for each device

Hysteresis: The *error band* defined by the maximum deviation in output signal obtained when a specific pressure point is approached first with increasing pressure, then with decreasing pressure or vice versa.

Span Repeatability: The *error band* expressing the ability of a transducer to reproduce its *span*, measured at 25°C, after exposure to any other pressure and temperature within the specified range. The maximum deviation of *span* voltage is measured for a given number of pressure and temperature excursions, then divided by *sensitivity* to express the *error band* in psi.

Span Stability: The *error band* expressing the ability of the transducer to maintain the *span* voltage with pressure varied from minimum to maximum and temperature held constant. The maximum measured deviation in *span* voltage is divided by *sensitivity* to express the *error band* in psi.

OVERALL ACCURACY

Overall Accuracy — Calibrated: The combined *error band* relative to the *BSL with forced reference* unique to one specific transducer. It excludes offset and sensitivity calibration errors. It includes all other offset and span errors: temperature coefficient, repeatability, stability, linearity and hysteresis.

Overall Accuracy — Interchangeable: The combined *error band* relative to an ideal transducer response characteristic. It excludes stability errors because stability error is already included in specified calibration error. It includes all other offset and span errors: calibration, temperature coefficient, repeatability, linearity and hysteresis.

Most Probable Error: The *error band* obtained by computing the square root of the sum of the squares of all applicable errors specified for the transducer.

Worst-Case Error: The *error band* obtained by simple addition of all applicable errors specified for the transducer.

Pressure Unit Conversion Constants

(Most Commonly Used — Per International Conventions)

	PSI(1)	in. H_2O(2)	in. Hg(3)	K Pascal	mili Bar	cm H_2O(4)	mm Hg(5)
PSI(1)	1.000	27.680	2.036	6.8947	68.947	70.308	51.715
in. H_2O(2)	3.6127×10^{-2}	1.000	7.3554×10^{-2}	0.2491	2.491	2.5400	1.8683
in. Hg(3)	0.4912	13.596	1.000	3.3864	33.864	34.532	25.400
K Pascal	0.14504	4.0147	0.2953	1.000	10.000	10.1973	7.5006
mili Bar	0.01450	0.40147	0.02953	0.100	1.000	1.01973	0.75006
cm H_2O(4)	1.4223×10^{-2}	0.3937	2.8958×10^{-2}	0.09806	0.9806	1.000	0.7355
mm Hg(5)	1.9337×10^{-2}	0.53525	3.9370×10^{-2}	0.13332	1.3332	1.3595	1.000

NOTES:

1. PSI — pounds per square inch
2. at 39°F
3. at 32°F
4. at 4°C
5. at 0°C