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Turbine Inlet Gas Temperature Measurement System Using a Fluidic Temperature Sensor

William L. Webb*
Pratt & Whitney, West Palm Beach, Fla.
and
Paul J. Reukauf†
NASA Flight Research Center, Edwards, Calif.

A fluidic turbine inlet gas temperature measurement and control system was developed for use on a Pratt & Whitney Aircraft J58 engine. This paper includes the criteria used for material selection, system design, and system performance. It was found that the fluidic temperature sensor had the durability for flight test under the conditions existing in the YF-12 airplane. As a result of turbine inlet gas temperature fluctuations, over-all engine-control system performance cannot be adequately evaluated without a multiple gas sampling system.

I. Introduction

THE size and weight of a gas turbine are strongly affected by the maximum allowable turbine inlet gas temperature (TIGT). The maximum temperature is limited by the metallurgical properties of the turbine. Once an engine has been qualified and enters service, the effect of increased temperature is to decrease engine life and the effect of lower temperature is to increase thrust specific fuel consumption. Parametrically, the effect of temperature on engine life is as shown in Fig. 1. Thrust specific fuel consumption increases are on the order of 3%/100°F for modern engines. These relationships generate a requirement for a direct measurement of TIGT.

Turbine inlet gas temperature in the 2000°F to 2500°F range can be measured with noble metal thermocouples. However, because of low mechanical strength, thermocouple sensing junctions must be relatively large to achieve the life required in turbine engines, some models of which have overhaul cycles in excess of 10,000 hr. Since a thermocouple is a thermoelectric device, its response to temperature change is directly related to the size of the sensing junction. This phenomenon is illustrated in Fig. 2.

A fluidic temperature sensor can be used to measure TIGT. Fluidic sensors demonstrated the ability to operate at a 4000°F sensed temperature for short periods and provided rapid transient response. Fluidic sensors have a demonstrated extended life potential at 2200°F sensed temperature. Pratt & Whitney Aircraft, with Honeywell, Inc., as the subcontractor, has built a fluidic TIGT measurement and control system which will be flight tested on a YF-12 airplane at the NASA Flight Research Center, Edwards, Calif. References 1 and 2 provide development and capability information for fluidic temperature sensors upon which this program is based.

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*Senior Assistant Project Engineer, Control Engineering Department, Florida Research and Development Center.
†Aerospace Engineer.

II. Fluidic Temperature Sensor Operation

The fluidic temperature sensor operates as a sustained acoustic oscillation with the frequency of oscillation an exponential function of the gas temperature. The transient response of a fluidic temperature sensor is comprised of two components. The first is a very rapid response and represents the time required to fill the oscillator cavity with a "new" sample of gas. The second is a slow response and represents the time required to bring the "wetted" sensor area up to the sensed gas temperature. The first response is a function of the oscillator cavity volume, the flow area into and out of the cavity, and the pressure ratio across the sensor. Typical flushing times are on the order of 0.002 to 0.01 sec. The second response is a function of the sensor mass that must be brought up to temperature and is on the order of 8 to 15 sec for refined immersed sensors. A more thorough description of this phenomenon is included in Ref. 3 and is shown pictorially in Fig. 3.

The uniqueness of this two-level response can be used to advantage in a high-response temperature measurement system. Since the heat transfer rate of a given metal body can be predicted by standard heat transfer equations and since the initial response has been shown to represent a percentage of the total temperature change, an electrical equivalent of the second response can be constructed and added to the initial response to approximate the final value of input temperature. This "added" input can then be removed at a rate equivalent to the heat transfer into

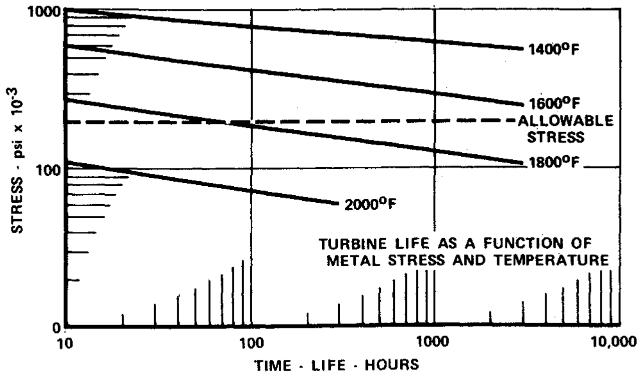


Fig. 1 Turbine life temperature relationship.

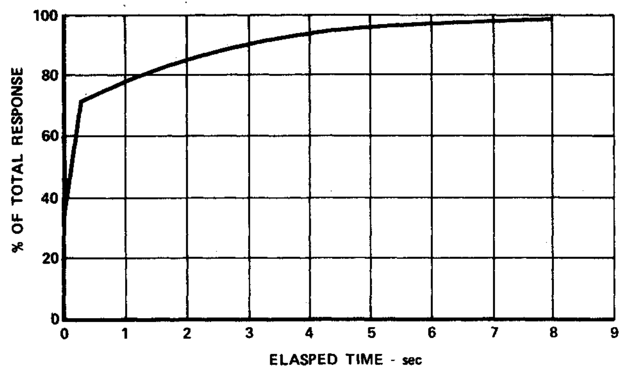


Fig. 3 Fluidic sensor transient response.

or out of the sensor body thereby maintaining a constant indicated temperature. A second variable affecting the rate of heat transfer between the sensed gas temperature and the sensor walls is gas density which can be approximately determined using pressure and temperature.

III. Development Program

The goals to be met when designing the TIGT measurement and control system were as follows:

1) Measure gas stream temperature with steady-state accuracy of ±40°F for the temperature range of 1500°F to 2200°F and pressure from 35 psia to 125 psia.

2) Measure within 5% of the steady-state temperature value 0.1 sec after a step change, 1% of the final value within 3 sec and be within the steady-state tolerance after 15 sec from the disturbance when the step change is equal to or less than 200°F. When the step change is greater than 200°F it shall be within 1% of the final value after 7 sec.

3) Complete the equivalent of a preliminary flight rating test to assure suitability for 50 hr operation in a YF-12A airplane.

4) Mate with the existing J58 engine exhaust gas temperature vernier control to form a TIGT control loop.

5) Provide the capability to allow selection of Exhaust Gas Temperature (EGT) or TIGT control by external command.

6) Meet the performance goals with electronics environmental temperature of −65°F to 160°F, vibration of 13½ *g's* and pressure of ½ to 25 psia.

7) Meet the performance goals with engine-mounted components environmental temperature conditions of −65°F to 1250°F, vibration of 13½ *g's* and pressure of ½ to 25 psia.

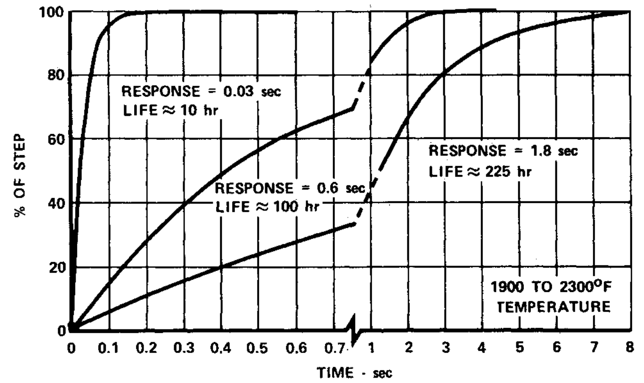


Fig. 2 Ideal response of thermocouple.

The resulting system consists of 1) a hot gas sampling probe, 2) a fluidic temperature sensor, 3) a piezoelectric frequency sensor, 4) a pressure sensor, 5) an electronic interface/selector, and 6) an electronic exhaust gas temperature vernier control (see Fig. 11).

The system operates by inducing gas flow through the hot gas sampling probe and fluidic sensor. The sensor reacts to the temperature of the gas by setting up a sustained pressure oscillation. The piezoelectric crystal is excited by the pressure wave and generates a voltage of equal frequency that is transmitted to the electronic interface/selector. The interface/selector transmits and converts the frequency signal to provide outputs of 1) direct sensor frequency, 2) a fast response 0–5 v indication, and 3) a slower response 20 to 40 mv control signal. The pressure sensor generates an electrical signal representing sensed gas pressure which is transmitted to the interface/selector and is used to bias the transient response.

IV. Materials Selection

Careful selection of the materials used for constructing the hot gas sampling probe and fluidic sensor was required to meet life requirements in the hostile environment. The results of materials investigations reported in Ref. 2 guided the sampling probe material selection.

Gas Sampling Probe

The criteria for selection of the probe material was to operate for 60 hours in a 2300°F oxidizing environment at 0.3 to 0.45 Mach and 225 psia with 9 *g* vibrational load.

B-66 columbium with a silicide coating met all the requirements and was available through commercial channels. Several materials met many of the requirements but had some deficiency or shortcomings, listed as follows.

Columbium Alloy WC3015: medium oxidation resistance and no available coating process.

Silicon Carbide: poor oxidation resistance between 1800°–2100°F.

Beryllide of Tantalum: poor low temperature ductility.

Tantalum Alloy T-222 with coating: poor oxidation resistance if coating fails.

Beryllium Oxide: low tensile strength, toxic, and hydrates between 1800°–2100°F.

Aluminum Oxide: brittle and poor thermal shock resistance.

Molybdenum Silicide: poor thermal shock resistance.

Silicon Nitride: hydrates at ambient temperature.

Boron Carbide: low thermal shock resistance and incomplete development.

TD Cobalt Alloy: incomplete development and nonavailable.

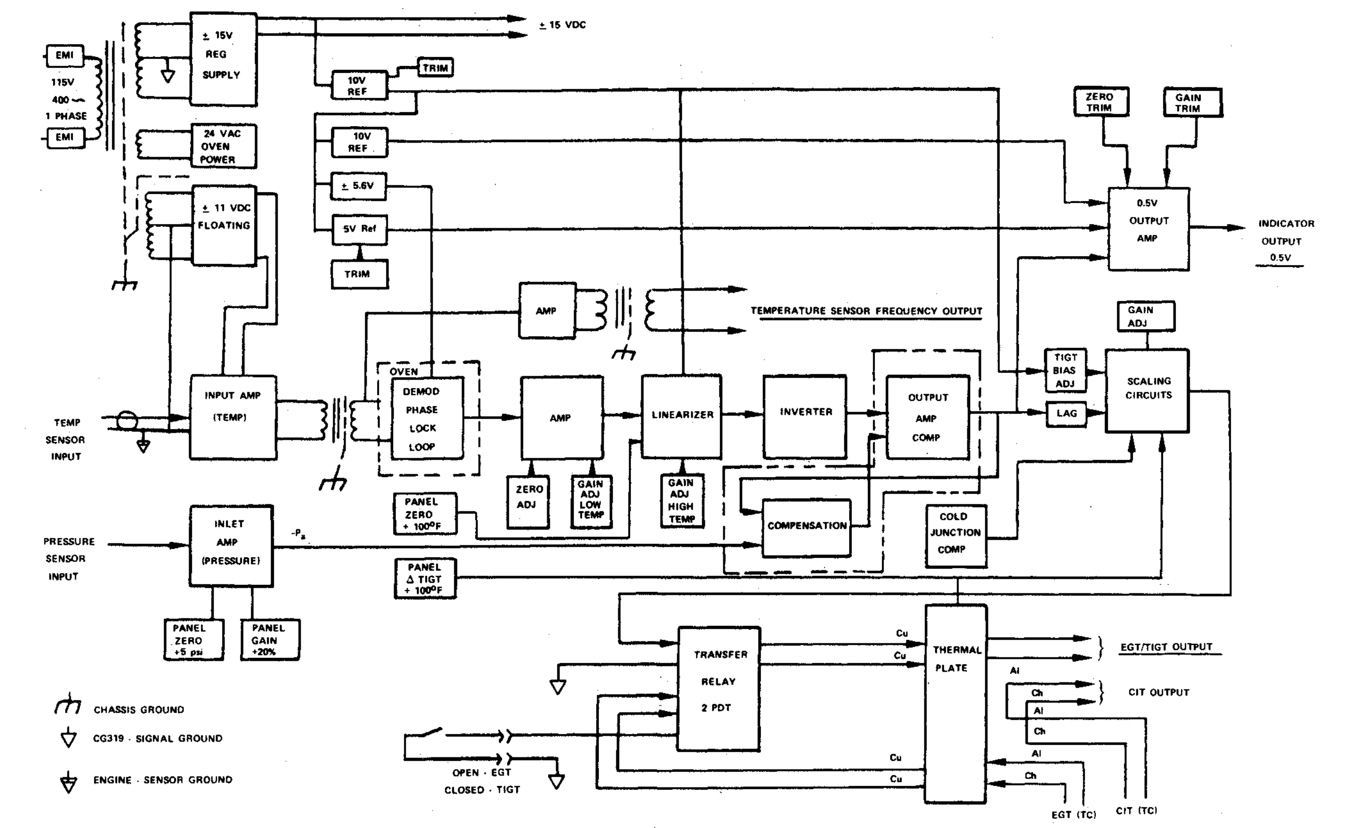


Fig. 4 Block diagram, TIGT Interface/Selection.

Welding of B-66 is an uncertain process and past experience indicated that some scrappage would occur. However, this deficiency was offset by the favorable experience gained at P&WA™ in experimental programs using this material and therefore it was selected as the hot gas sampling probe material.

Fluidic Sensor

The criteria for the fluidic sensor material selection was as follows:

1) Vibration as specified in MIL-STD-810B, Fig. 514-2, Curve H with 13½ *g's* substituted for 10 *g's*.

2) Sensed temperature level to 2200°F with ambient temperature 1250°F.

3) Oxidation resistance to give 50-hr life capability at maximum temperature operating condition.

4) Material compatibility with the probe material (B66).

5) Geometric configuration compatible with a 0.350-in. i.d. probe.

The materials considered and applicable comments are as follows.

KT Silicon Carbide: poor thermal shock resistance, excessive brittleness and special design for assembly required.

Diborides: requires metal support for strength and special features for mounting transducer.

Chrome 90: excessive brittleness.

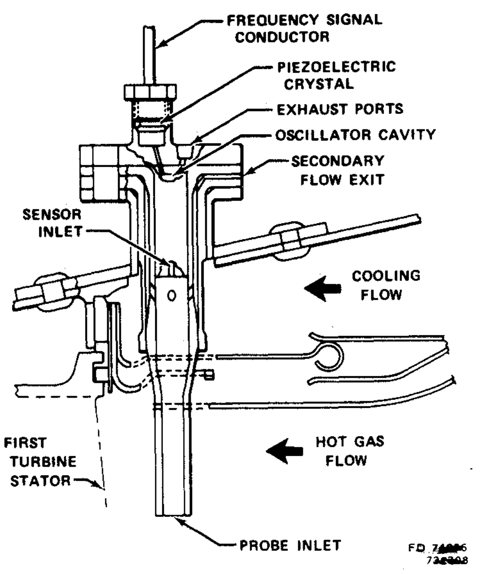


Fig. 5 TIGT probe and sensor installation.

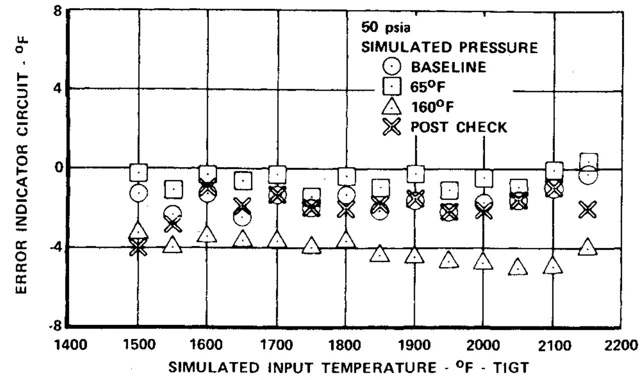


Fig. 6 Environmental tests TIGT Interface/Selector.

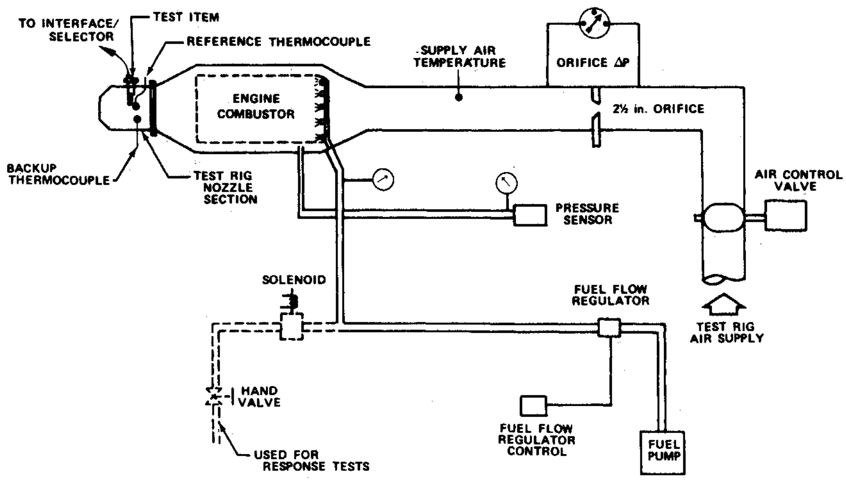


Fig. 7 TIGT measurement system bench test setup.

Hastelloy Alloy X and Alloy S: high oxidation causing low life at 2200°F.

TDNiCr: excessive oxidation around bond joints at 2200°F.

TDNiCR Al: selected on the basis of 1) acceptable oxidation resistance, 2) tensile strength, 3) sensor/probe assembly requirements, 4) machineability, 5) fabricability, and 6) rough stock availability.

V. System Design

The requirement to provide a steady-state control signal and simultaneously provide a very rapid indicating signal led to the selection of a dual output interface design. One output (20 to 40 mv) is scaled to be compatible with the existing J58 EGT Vernier Control. The other output is the 0 to 5 v signal used for high-response TIGT measurement. In response to a coordinated request, a third output of sensor frequency was added. A block diagram of the resulting electronics is shown in Fig. 4. The sensed temperature (frequency) is amplified, demodulated in a phase lock loop, amplified again, linearized and inverted before entering the output amplifier. Transient response compensation to indicated temperature is also added in the output amplification process.

The electronics also include a selector switch that allows EGT control when open and TIGT control when closed.

The design and installation features of the probe and sensor are shown in Fig. 5. The probe is designed to extract a sample of hot gas and deliver it to the fluidic sensor with less than 10°F loss. The hot gas enters the static pressure type pickup of the probe where there is a change in direction. The sample travels up the tube to the fluidic sensor. Shortly before entering the sensor, some of the boundary layer flow is extracted through four 0.050 in. diam holes and passed through an annular flow area between the probe and isolation sleeve to the ambient air. The mainstream flow enters the sensor through the rectangular inlet slot, passes through the oscillation chamber and also is dumped to ambient through exhaust ports. The purpose of the sleeve outside the probe is to isolate the "hot" probe outside surface from the engine cooling air flow passing around the outside diameter of the combustion chamber. The piezoelectric crystal and signal conductor assembly features are also shown in Fig. 5.

VI. Component Tests

The interface selector was subjected to vibration and environmental temperature test in accordance with the requirements met by similar systems in the YF-12 airplane. The unit performance during and after environmental temperature tests is shown in Fig. 6. The data shown are the deviation from a pretest calibration for each separate test condition and represent the effect of environmental temperature on component performance.

The hot gas sampling probe was subjected to and successfully completed a 50-hr test in a 2300°F environment while being vibrated at the natural frequency with input loading 50% more than engine data indicated would be present.

The TIGT sensor was also subjected to vibration tests and additionally was operated at maximum conditions of expected operation (2200°F and 125 psia) for 50 hr. The pre- and post-test performance comparison indicated the sensor constructed of TDNiCr Al would meet the system life and operational requirements.

VII. System Tests

Performance tests were conducted on the TIGT measurement system to determine what improvements or changes were required to meet the operational goals. A schematic of the bench test setup used for the system tests is presented in Fig. 7.

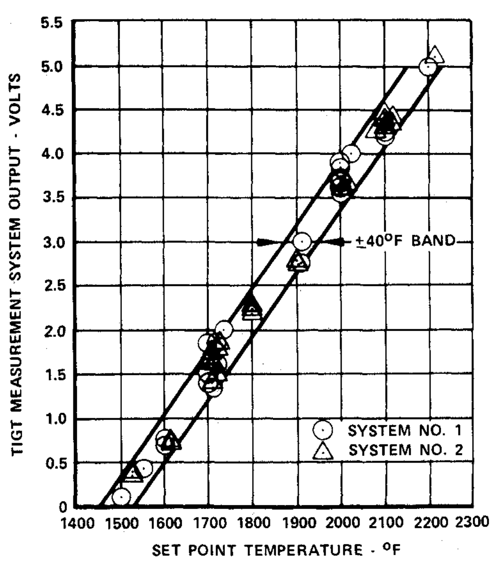


Fig. 8 TIGT measurement system performance.

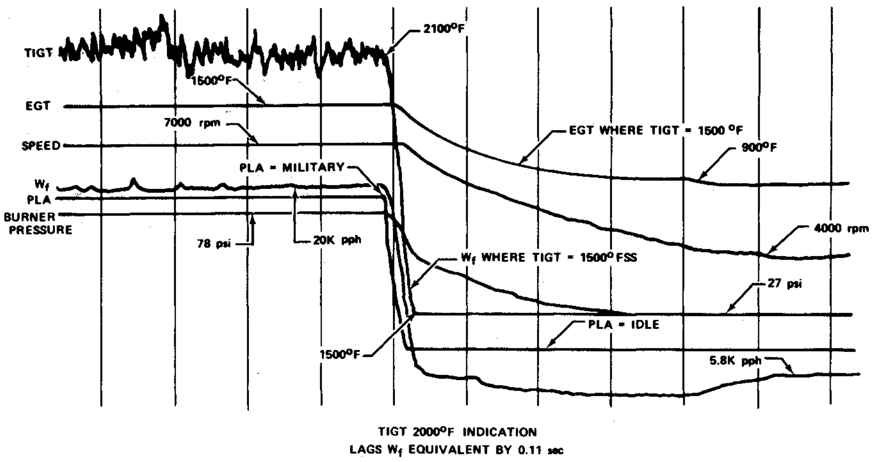


Fig. 9 TIGT measurement system response to a snap decrease of engine power.

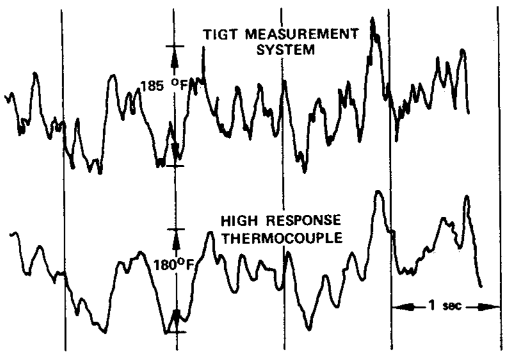
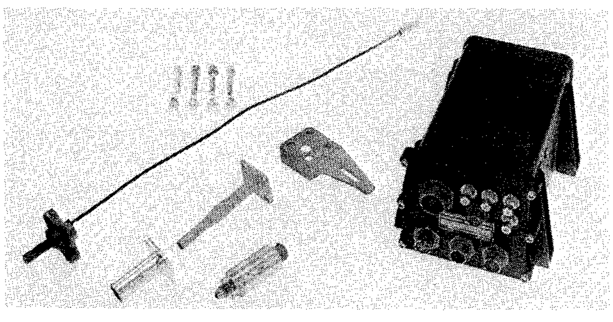


Fig. 10 TIGT system response to combustion noise.

Two experimental TIGT measurement systems were subjected to performance tests with gas temperature ranging from 1500°F to 2200°F and pressure from 25 psia to 80 psia. A plot of these data referenced to a ±40°F accuracy band is presented in Fig. 8. The data represent 87 nonselected points with two outside the steady-state performance goal.

Response of the TIGT measurement system to a snap throttle decrease is presented in Fig. 9. The response is measured against indicated power lever angle and burner fuel flow. The TIGT indication lags fuel flow by 0.11 sec and leads the EGT indication by about 3.5 sec.

Creation of a step change in a real system is impossible since control dynamics and combustion delays combine to add finite time delays to what may have started out as a step. However, any combustion system does exhibit a certain amount of noise that approaches the physical limit of temperature ramp rates and can be used to indicate the response of a dynamic temperature measurement. A plot of TIGT measurement system response to TIGT "noise" is shown in Fig. 10. The thermocouple used as the reference was a high response (0.04 sec time constant) Platinum-87% Platinum/13% Rhodium unit. Examination of the two traces shows the TIGT measurement system to indicate temperature peaks at the same time as the high-re-



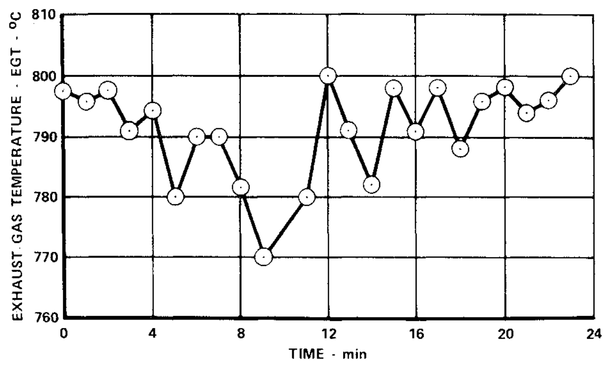


Fig. 12 Observed EGT while on TIGT control.

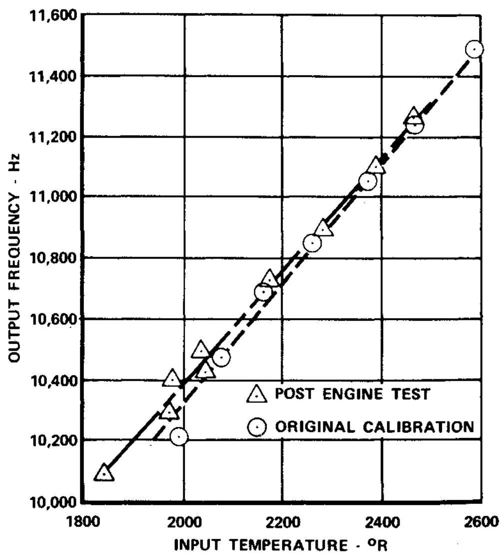


Fig. 13 TIGT sensor SN x 3 calibration, 75.5 hr engine time.

sponse thermocouple and also indicate the same peak-to-peak temperature changes, thereby demonstrating acceptable response to small temperature changes.

VIII. Engine Tests

The TIGT system shown in Fig. 11 was installed on a J58 engine for flight suitability tests. Preliminary checks were made with a thermocouple installed in place of the fluidic sensor. The data taken during this test indicated that TIGT varied 67°C at the TIGT sampling location when EGT was constant. Therefore, it was anticipated that when on TIGT control there would be some EGT wander. Figure 12 is a plot of the system performance while on TIGT control. The range of EGT as shown in Fig. 13 was 30°C which is about ½ the earlier observed drift. This can be explained to some degree in that the EGT thermocouples have about a 2 sec time constant and the millivolt output of the interface selector also has a lag equal to about 2 sec. These two combine with the slow trim rate of the EGT vernier control to "clip" peaks that occur in the observed TIGT.

A post-test calibration was conducted on the system after 75 hr engine test time. The results of the sensor calibration are shown in Fig. 13. The postengine test calibration is slightly higher in frequency than the preengine test results. This is the direction of deterioration for a fluidic temperature sensor.

The hot gas sampling probe had accumulated 106 hr at the end of the engine test. A visual inspection of the probe revealed that the silicide coating was oxidized and flaky in places but there was no indication of base metal deterioration.

IX. Conclusions

1) The fluidic temperature sensor designed to measure the turbine inlet gas temperature of the J58 engine has been developed and qualified for flight tests in a YF-12 aircraft.

2) The transient response and steady-state accuracy of the TIGT measurement system meet the YF-12 flight test requirements.

3) Because of TIGT fluctuations at a single station, over-all engine control system performance cannot be adequately evaluated without a multiple TIGT sampling system.

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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Unsteady Vortex Flow Past an Inflating, Decelerating Wedge

K. R. Reddy*

University of Sydney, Sydney, Australia

Nomenclature

b = half breadth of the wedge
C_p = pressure coefficient
K = constant defined by Eq. (4)
L = length of the rigging lines
n = α/π
p = pressure
q = velocity magnitude
s = distance measured along the surface
t = time
U = reference velocity
W = $\phi + i\psi$
x,y = coordinate axes
Z = $x + iy$
α = half apex angle of wedge
Γ = vortex strength
δ = slope of the rigging lines with the symmetry axis of the wedge
ζ = $\xi + i\eta$ an independent complex variable related analytically to W
ξ,η = coordinate axes
θ = direction of velocity vector
ρ = density
σ = $\log U/q + i\Theta$
ϕ = velocity potential
ψ = stream-function

Introduction

THE inflation of a parachute from the line stretch condition to the fully inflated configuration is a complicated problem. Extensive studies have been made by Heinrich, Melzig, French, and others. However, their methods are primarily based on filling-time approach, where conveniently chosen inflow and outflow parameters completely determine the opening rates. More recently Roberts,[1] Wolf,[2] and Reddy[3] emphasized the importance of the aerodynamics of the unsteady flow in the canopy area.

In this Note, the parachute is approximated as a two-dimensional wedge as shown in Fig. 1. The problem of unsteady flow of an ideal fluid past an inflating, decelerating wedge is considered. The particular flow model shown in Fig. 2 is essentially one containing a wake flow with vortex sheet buried in and coinciding with the physical location of the canopy. As a first step an integral equation is developed which connects the rate of opening with the strength of the vortex sheet. Then, a second-order differential equation in time is obtained by equating the moment about the apex due to aerodynamic pressure acting

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Index category: Nonsteady Aerodynamics.

*Research Student, Dept. of Mechanical Engineering.