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SMART SENSOR SOLUTIONS FOR MECHANICAL MEASUREMENTS AND DIAGNOSTICS

Application of many sensors located on a mechanical structure causes serious technical problems. One of the main problems is wiring of sensors which is time-consuming and may change the system output due to high structure loading and damping. To overcome this problem new smart sensor designs have been proposed. One of the most promising technologies in this field is wireless data transfer. In the paper requirements for the developed smart wireless sensor are specified.

The important part of a smart sensor is the transducer which transforms certain information from the physical world to user defined values – mostly the voltage. In the paper the application of industrial accelerometers was specified and descriptions of basic types of accelerometers are given. For smart sensor design two modern embedded accelerometers were specified and laboratory-tested.

Keywords : transducers, smart sensors, wireless networks

1. INTRODUCTION

Due to the rapid advance in the field of transducers, low power microprocessors and wireless technology, it is possible to design powerful smart sensors for mechanical measurements like: displacement, acceleration, force and pressure. Especially the wireless connection between sensors and the data acquisition unit is a very promising technique because of simplifying placement of sensors and heavy wire elimination. Implementation of the wireless technique in synchronous measurements mode must be applied with great care due to high time-consuming procedures required for establishing connection and further data transfer.

Currently manufactured accelerometers make it possible to design extremely small ‘smart sensors’ which are equipped with a minimum amount of components – sensor, microcontroller and communication chip.

The paper describes the requirements for smart acceleration sensor design and results of acceleration transducer measurements. Special care has been taken for measurements of transducer properties which are essential for further evaluation of measurements.

2. SMART SENSORS APPICATIONS FOR MECHANICAL MEASUREMENTS

Hardware solutions for sensing and computing are considered to be one of the key issues in structural health monitoring (SHM). One of the methods which seems to be very promising for damage detection and damage prediction is the impedance method [1]. This method requires small size actuators and many sensors located at a certain distance from actuators. The number of actuators and sensors located on monitored structures depends on their dimensions and on the required accuracy of damage location and prediction. In case of a large construction, the number of applied sensors can amount to thousand actuators and several thousand sensors.

Other method, which is useful for SHM purposes, is an operational modal analysis [2]. This method is widely used for many industrial applications such as diagnostics of space shuttles, airplanes and very large distributed installations in power plants, petrochemical factories, mines, bridges etc.

In any case, the analytical and operational advantages of modal processes have certain drawbacks, which include:

- requirement of a large number of sensors which need to be equipped with wired connections,
- limitation of the sensor mass such as to not “load” or “damp” the test structure,
- proper support and security of the interconnecting wires which, if not secured, will add “noise” modes to the test structure.

To achieve an acceptable, from the metrological and economical point of view, solution, the following requirements for hardware should be fulfilled:

- the sensing and actuation system should be fully integrated with the structure,
- the solution must remove extensive cabling,
- data from actuators and sensors must be collected synchronously,
- high level of signal processing must be performed by the sensor itself,
- harvesting of power energy from vibrating structures for self powering,
- easy and unlimited enlargement of data the collecting network.

The proposed general architecture of a smart sensor required by the SHM system is shown in Fig. 1.

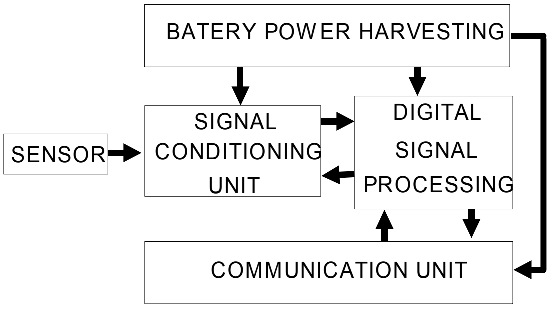

Fig. 1. General architecture of a smart sensor designed for SHM purposes.

As mentioned above smart sensors are connected and cooperate within the data acquisition network, so from this point of view the most important is the communication unit. More about other units of the presented solution can be found in [3]. Using a processing power at the sensor node, a high level of data compression can be applied to reduce the data flow in the network, thus reducing operational power and overall network bandwidth requirements. The protocol used for communication within the data acquisition network must be able to synchronize and exchange data between the sensor nodes and a central computer in real time.

In practical application of such sensors few basic modes are applicable:

- data transmission over the predefined amount of time,
- data acquisition into on-board memory in the predefined amount of time,
- data acquisition into on-board memory synchronous to a central clock signal.

The first mode is difficult to apply in case where several sensors transmit their data at the same time. In this case frequency hopping systems must be applied for data storage from different sensors. This mode is widely used for sensor verification or data acquisition from a single point at high sample time rates.

The second mode is applicable for SHM methods, only then proper time synchronisation between sensors is applied. This can be done before data acquisition by transmitting a time synchronisation message to all sensors in the network. The procedure of time synchronisation is similar to conventional network management like TT CAN [5]. During the data acquisition stage the collected data from different sensors must be equipped with a time stamp for further data synchronisation.

The last mode is difficult to achieve in high sample time acquisitions due to high time consuming procedures related with hardware and software overheads. This method is well suited in case of few sensors or long time measurements with low sample time. This method is widely applied in diagnostic applications where high sample rates are not important.

In case of last two described modes the data acquisition by a central unit is done after the measurement time in point-to-point mode where each sensor transmits its data to the main unit without interruption.

On the market few wireless solutions exist like: Bloetooth [6], ZigBee [7] and others, but for practical low power and high sample time smart sensors design purposes the advanced wireless solutions based on CC1000 wireless chip from Chipcon must be applied [8]. Application of such elements makes it possible to control protocol overhead and minimize the transfer and connection establishment time.

The family of Chipcon wireless chips allows to design extremely low power smart sensors because they work in 3V technology, have advanced power management and are easily integrated with low power microcontrollers. Due to high software overhead and high requirements for operational speed (few mega instructions per second at least) the modern RISC based microcontrollers are required. As an example, of such well suited, microcontroller for wireless application is the Atmel ATmega series [9]. ATmega microcontrollers are modern devices equipped with on board oscillators, working voltage of 3V, flash memory and additional on-board peripherals like: programmable gain ADC 10 bit 200 kHz converter, counter/capture unit, PWM generators, SPI and serial units. The microcontroller is available in small PLCC44 outline which makes it possible to design a complete smart sensor together with Chipcon wireless module in a dimension not exceeding a 15x15x15 mm cube.

In the following chapter the types and properties of accelerometers used in the described design are presented.

3. APPLICATION OF ACCELEROMETERS FOR MECHANICAL MEASUREMENTS

One of the most important transducers used for mechanical measurements are accelerometers that are designed to measure vibration and shock. Some applications in which accelerometers have demonstrated to be successful include [10, 11, 12]:

- machinery vibration analysis - measurement of increased vibration levels, detected by periodically monitoring rotating machinery vibration, are an indication of bearing or gear wear, imbalance, or broken mounts. Machinery like: motors, pumps, compressors, turbines, paper machine rolls, and fans, engaged in critical processes, is routinely monitored to predict failure, intelligently schedule maintenance, reduce downtime and avoid catastrophic interruption of production runs.
- balancing - performance and longevity of rotating machinery is improved when rotors, turbines and shafts are properly balanced. Measurement signals generated by accelerometers implemented into balancing machinery provide an indication of the severity of any imbalance. This measurement, in conjunction with a timing signal provided by a tachometer, allows for proper counterweight sizing and placement to bring the machinery into acceptable balance.
- vibration control - desired vibration, such as that induced for the purpose of environmental stress screening, must be precisely controlled. Accelerometers sense the generated vibration at the driving point of a vibration exciter or shaker. This sensor’s measurement signal is then fed into a vibration controller which adjusts the input parameters that drive the shaker.
- active vibration reduction - to enhance user comfort levels of sound and motion generated by such items as household appliances, aircraft and machinery, designers are now considering the use of active electronic techniques where passive methods, such as isolation, insulation, and damping have become insufficient or impractical. Accelerometers are used to sense the

disturbing vibration induced, structure-borne sound, or motion. The measurement signal is then manipulated, typically with digital signal processing, into one an opposing phase for use in driving an actuator or shaker to null the annoying vibration. This closed-loop control method proves useful in applications like helicopters, marine hulls, dishwashers and aircraft fuselages.

- structural testing - accelerometers measure the stimulus response and structural resonance characteristics of a wide variety of mechanical devices, from small computer disk drive components to massive bridges, buildings and civil structures. Such measurements allow designers to optimize product performance and life cycle by selecting construction materials with proper strength and stiffness characteristics. Vibration measurements can also provide an indication of stress, fatigue, damage, or defective assembly due to loose or missing fasteners, welds or joints on finished goods, or items undergoing maintenance assessment.
- modal analysis - accelerometers measure relative phase and amplitude of structural motion, allowing operating deflection shape determination, which offers a virtual study of the animated mode shapes. This computerized representation enables designers to optimize performance and user comfort for such items as automobiles, aircraft and satellites.
- seismic vibration - accelerometers detect motion of the ground, buildings, floors, foundations, bridges and other civil structures for purposes of earthquake detection, geological exploration, condition assessment monitoring and impact surveys of nearby activities such as mining, construction, or heavy vehicle transportation.
- shock - accelerometers measure the maximum impact acceleration levels experienced by such items as vehicles and crash dummies. Metal-to-metal impacts, pyroshock studies and shock exposure experienced by space vehicles and cargo during liftoff and stage separation are also measured and analyzed using shock accelerometers.
- motion and attitude detection and stabilization - accelerometers monitor motion and orientation of items that rely on precise positioning for proper operation. The measurement signal can be used to warn of excessive motion during upset conditions so that equipment is not operated when inadequate performance is certain. Measurement signals can also be used in a feedback-control-loop scenario to perform active motion reduction to maintain levels within acceptable limits. Apparatus requiring such attention to motion includes sensitive optical instruments, satellite antennas, lasers, surveillance cameras and semiconductor fabrication equipment.
- ride quality, response and simulation - accelerometers play a key role in vehicle design by measuring their response to on- and off-road conditions. Suspension performance, chassis and frame evaluations, engine-mount damping, drive-train NVH and ride comfort levels are among the many studies conducted. Proving ground tests, dynamometers, electro-dynamic shaker and hydraulic motion simulators are all methods of providing input stimulus to vehicle structures for which accelerometers are used to measure the resulting vibration, shock and motion of the vehicle and its components.

The basic use of a sensor is to convert information from the physical world to user measurable signals. Accelerometers measure the acceleration exerted upon them. Currently built sensors are extremely rugged, provide a wide dynamic range and are available in a variety of configurations to meet individual installation requirements.

There are numerous ways of measuring acceleration, all with different advantages and disadvantages, but the most important from an application point of view are: piezoelectric sensors and capacitive acceleration sensors [13].

Piezoelectric sensors measure acceleration as a strain in the crystal. The primary sensing element is a piezoelectric element constructed in such a way that when stressed by vibratory forces, a proportional electrical signal is produced. Some materials are found to be naturally piezoelectric. Quartz is a natural material commonly used in accelerometers and exhibits unmatched long term stability. Polycrystalline ceramic materials can be made to exhibit piezoelectric properties. Lead zirconate titinate (PZT) is a common material used in accelerometers after they have been "polarized." Due to their working principle piezoelectric accelerometers often have problems with measuring low frequency components (below 2-4 Hz).

Three basic structural designs are used in manufacturing industrial accelerometers. They are the flexural, compression and shear designs the schematic drawing of which is shown in Fig. 2.

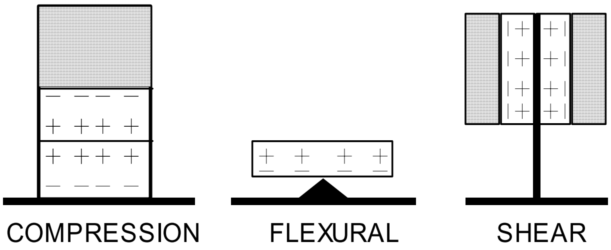

Fig. 2. Schematic drawing of compression, flexural and shear accelerometers.

All three designs contain the basic components of the piezoelectric element, seismic mass, base and housing.

In the flexural design the piezoelectric element is secured to the seismic mass in the form of a double cantilever beam. Flexural designs have lower resonant frequency and are generally not well-suited for machinery monitoring applications.

In the compression design the crystal, quartz or ceramic is sandwiched between the seismic mass and the base with an elastic pre-load bolt. Motion (vibration) into the base squeezes the crystal creating an output. Compression designs are much more suited than flexural designs for industrial machinery monitoring applications because of their high resonance and more durable design.

The shear design subjects the sensing element to a shear stress. The piezoelectric sensing element and seismic mass are secured to a center post/base standing upright via a retaining ring. This preload produces a stiff structure with good frequency response and greater mechanical integrity. As the sensitive axis is not in-line with the mounting surface, environmental conditions such as base strain and thermal transients do not produce false signals as in the other designs.

The second widely used type of accelerometer design is the differential capacitor accelerometer which comes in two subtypes and both are a downsized version of the force rebalancing accelerometer. When influenced by acceleration, a displaced spring-mass creates a proportional capacitance shift. The most advanced capacitive accelerometers are made in MEMS technology which combines in one the structure transducer and electronic circuit [14] – a typical example is an ADXL 202 from Analog Devices. The measuring part of such transducer is build as a mass held up by springs etched out of silicon. A part of the mass makes up the middle plate of three plates, thus creating two different capacitors. The shift in position of the mass alters the distance between the plates, In the first subtype of differential capacitor accelerometers the difference in capacitance produces a current that is converted to an output voltage by a control logic.

The second subtype of differential capacitor accelerometers uses a control voltage to force the moving plate into the middle position giving the same capacitance between the different plates at all times. From the voltage needed to position the plate, the acceleration can be calculated. This is done to avoid some nonlinearities in the first type of differential capacitor design which otherwise have to be compensated for in the control logic for the circuit.

Capacitive accelerometer design is preferable in applications, where low-level, low-frequency vibration must be measured. They give true DC frequency response capability.

SHM applications of accelerometers require low noise of the transducer, broad frequency bandwidth and high shock durability. The frequency response should be flat over the measuring range and the phase angle should be constant or linear.

One of the examples of modern accelerometers which can be applied for wireless sensors design are the ADXL 202 MEMS based accelerometer from Analog Devices [15] and PB3AXN from Oceana Sensor [16].

The ADXL 202 is equipped with a built-in digital interface which can be easily implemented with the microcontroller but then the system resolution and system bandwidth is limited. In this case also the time synchronization between sensors is difficult to achieve within two sample periods. The best solution is to measure the voltage at Xfilt and Yfilt outputs, this voltage is proportional to the measured acceleration. The output signal must be buffered by the voltage follower to prevent the influence of relatively low resistance output at those pins. The main advantage of ADXL 202 accelerometer is static acceleration measurement so the bandwidth of this transducer is wide (0 Hz to 5 kHz) [9].

The second accelerometer – PB3AXN unit employs field-proven, solid-state, piezoelectric sensing elements for durability and broadband performance. They exist in either charge-mode types, which achieve high operating temperatures or voltage-mode ICP types, with built-in signal conditioning microelectronics, for simplified operation and connectivity to data acquisition and vibration monitoring instrumentation. The bandwidth is 0.32 Hz to 10 kHz with the current consumption less then 1 mA [10].

The accelerometers described above were chosen for laboratory testing. The testing procedure and results are described in the next chapter.

4. ACCELEROMETER TESTING

The ADXL 202 and P3BXN accelerometers were laboratory tested. The general diagram of the laboratory rig is shown in Fig. 3.

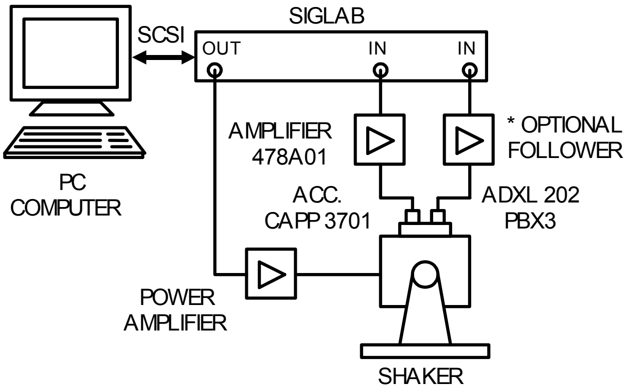

Fig. 3. Block diagram of laboratory rig used for accelerometers testing.

During the laboratory test the time response, transfer function between reference accelerometer and ADXL 202 and P3BXN and frequency characteristics were obtained. As a reference accelerometer the precision capacitive 3701 series accelerometer from PCB was chosen. The reference accelerometer has a bandwidth of 0 to 300 Hz within ± 5% range. All tests and measurements were done with the SigLab interface and Matlab environment. As the vibration source the standard shaker was chosen, this solution limits low frequency range to about 10 Hz. As the input signal the chirp signal with appropriate frequency range was chosen. Accelerometers were measured up to 200 Hz, which is sufficient for most of applications.

During the first test the ADXL 202 was measured. The results are shown in Fig. 4.

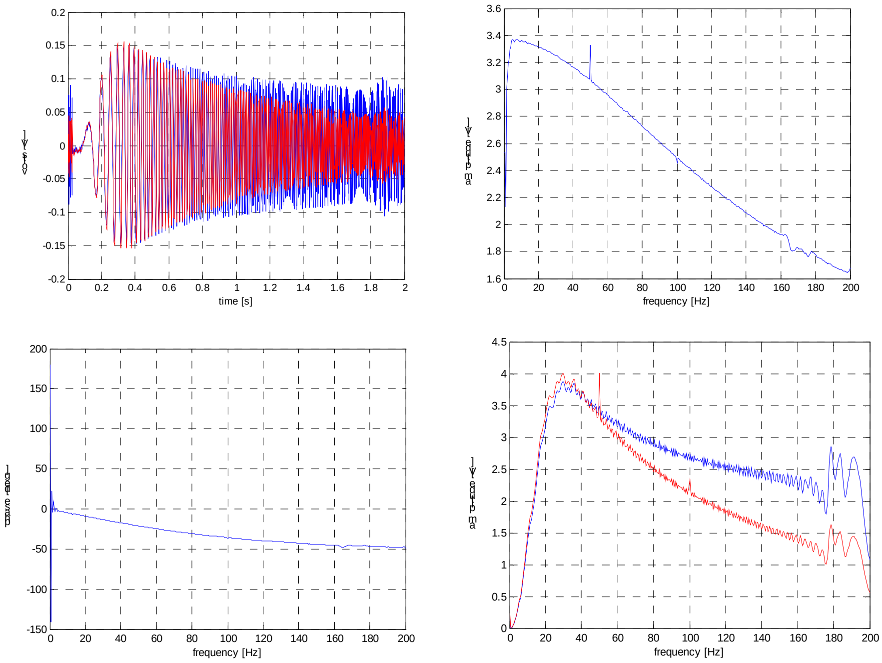

Fig. 4. Measurements results of ADXL 202 accelerometer – time response, transfer function, phase angle, frequency response.

The obtained results qualify the ADXL202 accelerometers as not suitable for precise measurements. Especially the signal amplitude decease over the frequency range is well visible and quite difficult to compensate. Results suggest that this accelerometer is best applied as a tilt sensor (DC measurements) or for simple monitoring applications after calibration. Measurements of the P3BXN accelerometer are shown in Fig. 5.

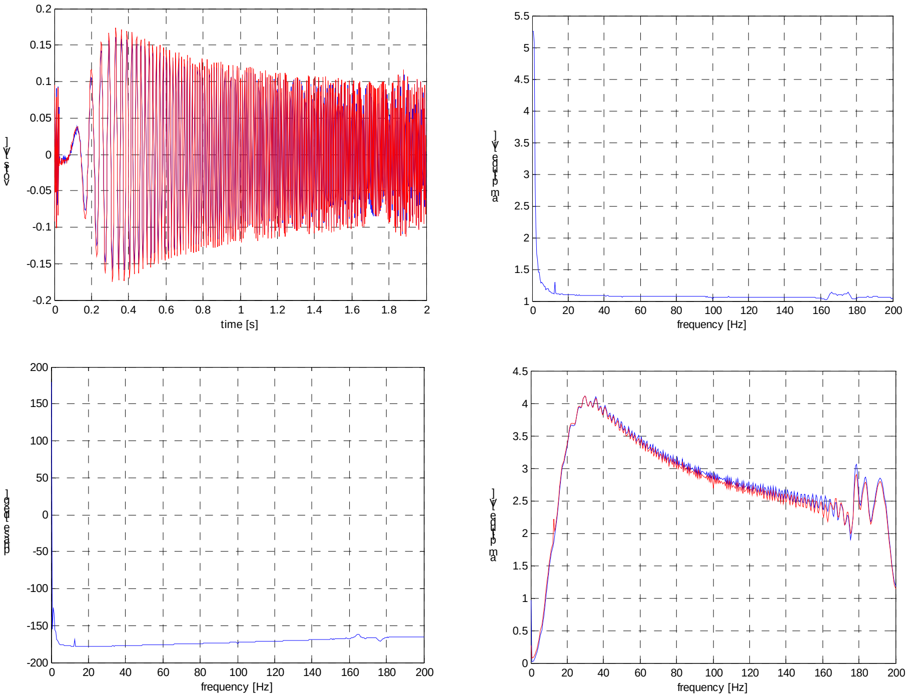

Fig. 5. Measurements results of ADXL 202 accelerometer – time response, transfer function, phase angle, frequency response.

Measurement results qualify the P3BXN accelerometer as best suitable for design in a wireless smart sensor. The constant signal amplitude and almost flat phase angle compared with high quality capacitive accelerometer guarantee good measurements over the defined bandwidth. The phase angle is equal to 180 degrees due to opposite accelerometers mounting. Also the frequency response between those two accelerometers is very similar. The P3BXN accelerometer was chosen as preferred transducer for smart sensor design because it has good measurement characteristics, works with minimum current consumption and has built-in electronics which simplifies integration with an ATmega microcontroller.

5. CONCLUSIONS

Over the past decade, measuring vibration parameters has become the most widely-used technology for mechanical system identification, testing and machinery monitoring. Industrial accelerometers have become the most important part in the identification and diagnostics but the application of many of them requires a solution which eliminates interconnecting wires.

Modern microelectronics currently gives to the designer almost ready wireless solutions. Modern wireless modules and low power microcontrollers allow designing small smart sensors. The key for proper measurements with such sensors is: a high quality transducer for proper measurements and optimization of wireless transmission due to high real time requirements.

In the paper a general description of modern wireless sensors was presented and the elements of such sensor were specified. A brief description of accelerometer applications and their basic design was also presented. At the end of article laboratory results for two different modern embedded accelerometers were presented and the accelerometer best suited for design of wireless sensor was chosen.

Further work must be carried out for complete wireless sensor assembly, hardware and software testing.

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NOWE ROZWIĄZANIA INTELIGENTNYCH CZUJNIKÓW POMIAROWYCH DO POMIARÓW WIELKOŚCI MECHANICZNYCH I DIAGNOSTYKI

Streszczenie

Współczesne systemy diagnostyczne i monitorujące wymagają zastosowania wielu czujników, co często wywołuje wiele problemów natury technicznej. Głównym problemem jest odpowiednie wykonanie okablowania zainstalowanych czujników w sposób, który nie wpłynąłby na zmianę parametrów konstrukcji i jednocześnie był optymalny z punktu widzenia charakterystyk połączeń elektrycznych. Montaż przewodów sygnałowych w wielu przypadkach jest również utrudniony, a sygnał jest narażony na wpływ zakłóceń o różnym charakterze.

Jednym z rozwiązań, które mogą uprościć i ułatwić instalację takich złożonych systemów diagnostycznych jest zastosowanie bezprzewodowej transmisji danych.

W artykule opisano strukturę i wymagania nowoczesnego bezprzewodowego czujnika drgań projektowanego w KRiDM AGH przeznaczonego do diagnostyki układów mechanicznych.

Jednym z kluczowych elementów projektowanego czujnika drgań jest akcelerometr. W artykule opisano dwa zaawansowane czujniki drgań ADXL202 i P3BXN, które zostały poddane szeregowi testów laboratoryjnych mających na celu określenie ich przydatności do budowy inteligentnego czujnika.

Załączone w artykule wyniki pomiarów są pomocne w zorientowaniu się o właściwościach metrologicznych prezentowanych czujników.