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New hardware solutions for Structural Health Monitoring

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Abstract

Nowadays, research concerning applications of Structural Health Monitoring has arisen a great interest. SHM methods are applied to condition monitoring of machines and structures, structural integrity assessment, damage detection and structural failure prevention. Measurement data acquired by the use of different sensors and data acquisition systems is essential for SHM. The most popular SHM algorithms require vibration measurements, which arise difficulties resulting from the analysis of signals from many sensors. In the paper the new developed hardware solutions for the SHM application are presented. In accordance with the defined requirements, the design of CAN based accelerometer module is shown.

Streszczenie

Współcześnie dużego znaczenia nabierają prace związane z praktyczną realizacją systemów do monitorowania stanu konstrukcji. Metody aktywnego monitorowania znajdują zastosowanie do badania maszyn i struktur mechanicznych, badań strukturalnych, detekcji zniszczenia, zapobiegania stanom awaryjnym. W systemach monitorujących najczęściej analizowane są drgania konstrukcji. Uzyskanie prawidłowych wyników zależy od sposobu akwizycji danych pomiarowych, co w przypadku analizy sygnałów z wielu czujników nie jest zadaniem prostym. W artykule opisano konstrukcję inteligentnego modułu akcelerometru zbudowanego z zastosowaniem układów MEMS i wyposażonego w interfejs magistrali CAN.

1. Introduction

Hardware solutions for sensing, actuation, power harvesting and computing are considered to be one of the key issues in structural health monitoring (SHM). There are several solutions which are based on smart materials, PZT materials, wireless data transmission and fibber optics applications. One of the method which seems to be very promising for damage detection and damage prediction is an impedance method [1]. This method requires a small size actuator and many sensors located in a certain distance from the actuators. Actuators generate a high frequency excitation while the sensors measure system responses. Each sensor computes on board impedance based on the measured vibration accelerations and information about current excitation amplitude and phase transmitted by the actuator. The number of actuators and sensors located on monitored structures depends on their dimensions and 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 the SHM purposes is an operational modal analysis. This method is widely used for many industrial applications such as diagnostics of space shuttles, high performance airplanes and very large distributed installations in power plants, petrochemical factories, mines, etc. In either case, the analytical and operational advantages of modal processes have certain drawbacks. Generally, these limitations include:

- requirement of a large number of sensors,
- limitations of sensor masses so as not to "load" or "damp" the test structure,
- support and security of the interconnecting wires which, if not secured, will add "noise" modes to the test structure.

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

- the sensing and actuation system should be fully integrated with structures,
- the solution must remove extensive cabling,
- data from actuators and sensors must be collected synchronously,
- high level of signal processing 'inside' sensor,
- harvesting of power energy from vibrating structures,
- easy and unlimited enlargement of data collecting network

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

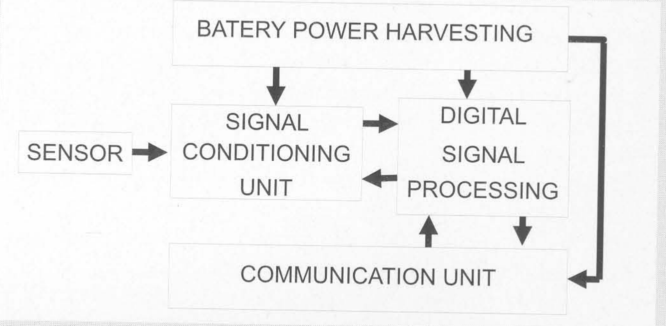

Figure 1. Schematic illustration of the single smart sensor for the SHM purposes

The presented smart sensor for the SHM consists of four main units:

- signal conditioning unit
- digital signal processing unit
- communication unit
- power unit

The signal conditioning unit transforms signals from applied sensors to form accepted by a digital signal processing unit, which controls the data acquisition and data analysis processes. The communication unit implements network based communication protocol mainly by the use of a radio data transmission technology. The power unit is responsible for power distribution, data saving and harvesting.

Smart sensors are connected and cooperate within the data acquisition network. Modern measurement solutions introduce distribution of the data processing, required by the SHM algorithms, down to the lowest level of the network. 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 some applications the specific data transmission protocol is used. For example in automotive industry the CAN based network is widely used. In such a case the smart sensors should have the same communication bus for easy integration in the monitored system. In the paper an overview of possible hardware solutions for SHM systems is presented. A CAN based smart sensor prototype for acceleration measurements that was developed in KRiDM and will be used for in-operation modal model identification is also presented.

2. Wireless technology

The SHM requires application of many sensors and actuators which can strongly influence obtained data, because:
- sensors and wires introduce an additional mass to structure and change a local stiffness of a structure,
- cables restrict a free movement of a system under test,
- signal and power cables generate a noise, because of tribo-electric effects associated with both high and low impedance transducers,
- cables can introduce other additive or multiplicative noise effects,
- complicate the cabling in case of a large system

Application of many sensors requires elimination of wire connections and replacing them with reliable wireless communication. The main advantage of the wireless technology applied to the SHM is a possibility to extend the measurement network to theoretically unlimited number of actuators and sensors.

There are some innovative wireless data transmission solutions which can be applied to SHM.

One of the existing solutions has been developed by Invcom, Inc. (MicroTAU) [2] for NASA space shuttle. The solution consists of three axis accelerometers and a radio wireless data transmitter which allows to transmit digital data to a central connection units. MicroTAU solution can be configured by the user for multiple operation modes. The main advantages of this solution are:
- automatic synchronization of multiple sensor data inputs with precision of 10μs,
- transfer of multiple sensor data from measurement points to a central data collection station (computer) without cables,
- improved data quality due to quantization of the analogue signal at the sensor and the resulting elimination of the cables.

The second example of a wireless sensor solution for SHM is IWIS [3] (Internal Wireless Instrumentation System). The system is currently installed at the International Space Station (ISS) to measure extremely small microgravity conditions. The system has very high resolution (0.5μg) and absolute accuracy (100μg). The automatic synchronization of multiple sensors with precision of 300ns is an operational advantage of the IWIS wireless system. The system is developed to collect the impulse responses of the system in order to track changes in dynamic characteristics resulting from docking new modules to ISS.

The next successful solution of a wireless sensor is the WAIS (Wireless Airborne Instrumentation System) which is used for the CH-53 helicopter HUMS (Health and Usage Monitoring System) [4]. The purpose of this system is to replace wires between various test sensors (up to 16 transducers). Benefits of this system are: reduced test installation time, increased signal quality and extended analogue sensor placement on rotor hubs or other extreme locations. The main unit of the system collects data and controls 2 Mbps binary data flow to the central computer. Modification of the WAIS system is applied to flight testing of aircraft [5]. This modified system (WATS - Wireless Airborne Test System) operates by transmitting data from a remote sensor to a System Interface Unit. The system operates in a real-time mode where data is synchronized to +/-10μs. The operating time from internal batteries is 24 hours of continues work.

MICA Mote described in [6] is a very promising and inexpensive solution of wireless sensor technology. The system is a development platform of wireless sensor technology because of its ready-made communication capabilities of the 8 bit ATMEGA microprocessor equpped with 10 bit A/D converter on the main board. The system is equipped with the ISM band 916 MHz radio transceiver with a range up to 400 m.

Based on the above system description some demands for future wireless sensor solutions for SHM application can be formulated:
- smart SHM sensor uses processor power at the sensor node level to reduce data flow in the network,
- sensor performs time to frequency transformation at individual sensor node to reduce band of data communication,
- signal processing should be dedicated to a given model parameter estimation to reduce amount of needed computation power (specified methods should be applied),
- wireless network control protocol should provide capability to store data if a communication between nodes is not possible,
- high quality synchronization between individual sensors channels should be maintained.

It is not simple to fulfil the above requirements and minimize size and weight of sensors, but ready solutions can arise new possibilities of the applications to SHM that would have previously not been possible. One of the most important limitations of the wide use of autonomous wireless sensor technology for SHM is the problem with power supply source.

3. Energy harvesting solutions

Application of new smart materials arises possibilities that a mechanism can be used for transferring vibration into electrical energy, which can be stored and further used for power sensors. Such a material that can be used for this purpose is a PZT material (Piezoelectric material). The PZT power generation can provide alternative to traditional power sources for SHM systems including sensors/actuators, MEMS device, telemetry, etc. The energy produced by the PZT can be stored in two different ways. The first way is to charge a capacitor in which energy is stored and can be immediately used for sensor supply [1]. The second method is based on charging a nickel metal hydride battery. The power generated by vibrating piezoelectric is shown to amount maximum to 2mW, and provide enough energy to charge a 40mAH cell battery during one hour [7]. Currently developed SHM wireless systems base on battery operated power sources but miniaturization and low power electronic elements allow them to operate for a long time during the data acquisition stage.

4. Smart sensor design for application to SHM in automotive industry

Analyzing smart sensor requirements, the basic functions of developed modules were defined as follows:
- microcontroller board with additional memory for data acquisition, field bus connector, extension connector,
- acceleration sensing module based on MEMS chip,
- optional RF module for external data triggering.

The block diagram of the designed smart sensor is shown in the Figure 2.

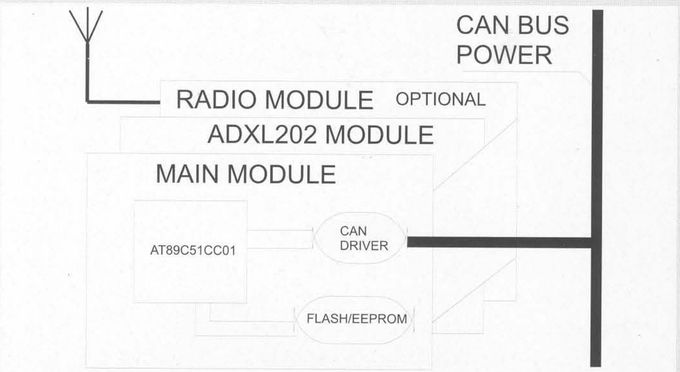

Figure 2. Block diagram of a designed smart sensor

As a 'heart' of the smart sensor an ATMEL 89C51CC01 microcontroller was chosen. From the hardware point of view the AT89C51CC01 is a M51 microcontroller compatible device with additional on board elements like: ADC, extended counter/capture PWM unit, CAN interface, power management feature. The microcontroller is RS232 in-circuit programmable. Since this feature reduces the software development time, it is very useful during software development. The core of the microcontroller can be run in X2 mode, which speeds up the program execution. The on- board CAN interface allows to connect microcontroller via additional driver to a standard CAN-bus.

The CAN-bus is a well know industry standard of a field bus. The CAN communication protocol allows to send the synchronization message over the network in resolution of 130 μs with 1Mb transfer rate [8]. This message can be used as a 'trigger' input for data acquisition in distributed sensors network. The network can be used also as a data transfer path for reading data from sensors to a main station for further processing. The developed sensor can be applied to vehicle body measurements because of an easy integration with CAN network that is widely used in automotive industry. [8]

For the purposes of application to SHM, the microcontroller module was equipped with an acceleration module based on the Analogue Devices ADXL MEMS accelerometer ADXL202. This modern sensor is a small transducer of variable capacity, where a silicon, electronic and mechanical structure is developed. Interesting features of this chip are: static and dynamic acceleration measurements in range of +/-2g, low signal-to-noise ratio, digital interface. Only few external elements allow designer to choose a carrier frequency and a sensor bandwidth. The digital interface gives possibility to connect sensor to microcontroller with only two digital lines and therefore reduce expensive analogue circuits. The full data of ADXL can be found in [9].

In the presented construction an optional radio board can be used as a radio controlled trigger in applications where placing of wire connections is difficult or a number of sensors exceeds a CAN network capacity.

The modules are power supplied from an external supply or from a battery. The power harvesting solution for a smart sensor has to be developed in future.

The mechanical design of modules allows to integrate them together in one package. The view of assembled modules is presented in the Figure 3.

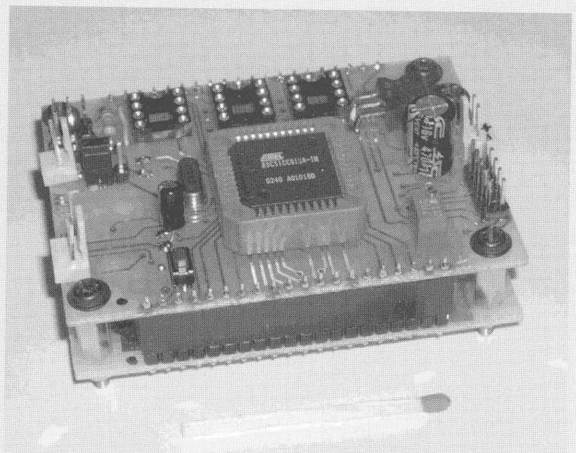

Figure 3. Assembled smart acceleration sensor

Presented module was laboratory tested by the use of a shaker. Acquired data was applied to sensor parameters verification and a model estimation. The estimated model was compared with the Simulink model of ADXL202 from Analogue Devices [10].

5. Test results

During laboratory experiments the module was accelerated by a shaker. The band limited white noise was used. Data was acquired with sampling time of 0.001s. The measured system input and output are shown in Figure 4. The measured output was scaled to analogue voltage in a range specified for ADXL202.

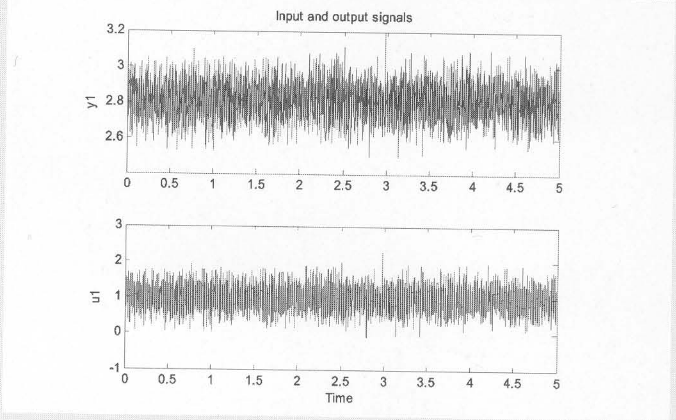

Figure 4. Plot of the excitation signal and a sensor response

The sensor bandwidth for applied external elements of ADXL was specified. The different system parameters due to an external ADXL element adjustment are shown in the Figure 5.

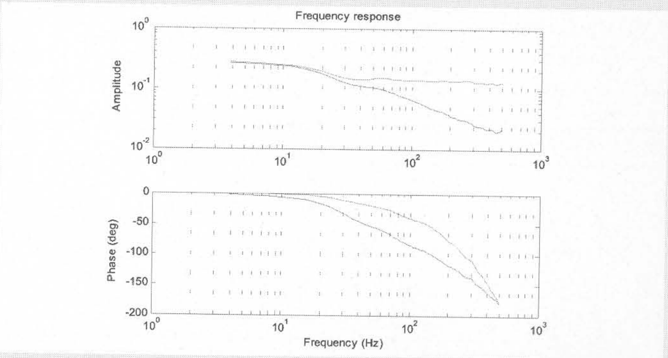

Figure 5. System bandwidth change due to external elements adjustment

On the basis of the acquired data the ARX model of ADXL202 was estimated by the use of the MATLAB System Identification Toolbox. The ARX441 model was chosen based on an optimal order selection procedure. The obtained model was tested with a real and simulated data. The Simulink block diagram used for comparison of the AD ADXL model and the estimated model is shown in the Figure 6.

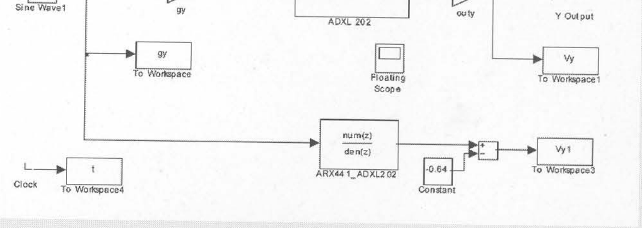

Figure 6. Simulink block diagram of ADXL202 model and estimated ARX441 model used for output comparison

The error between output signals of both models is shown in the Figure 7.

The presented characteristic shows a good compatibility of models.

During further laboratory tests parameters of the designed sensor will be specified.

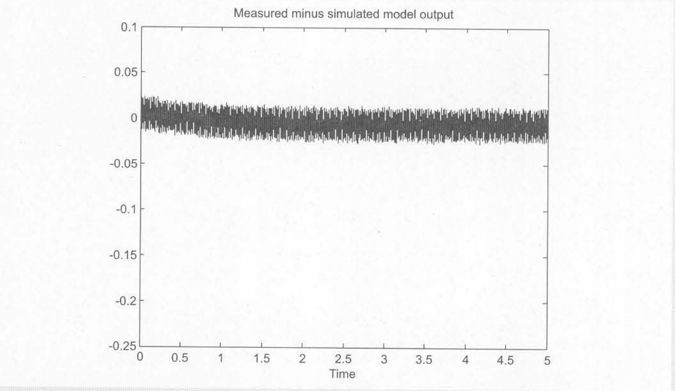

Figure 7. Error between Simulink ADXL202 and ARX441 model - for sine 50Hz

6. Conclusions

New measurement methods developed for SHM require employment of modern sensor designs to achieve optimal diagnostic results. The modern smart sensors use the wireless or fieldbus data transmission which eliminate system cabling. The design of wireless network is not simple and this subject is still under extensive development, some information about current progress in this field can be found in [11]. Beside the data triggering and receiving problems the power supply problem seems to be very important in order to minimize size and mass of smart sensors. In the paper the modular construction of a smart sensor for acceleration measurements is described. The design of the sensor is based on modern electronic elements, which reduce the design, implementation and testing time. The results of laboratory tests were shown and the ARX model was estimated. Simulations based on ADXL model from Analogue Devices show good agreement between booth models of the sensor. Further tests must be performed to obtain full smart sensor parameters. CAN based solution allows to design a fast responding smart sensors networks with high data throughput. The power harvesting solution for the developed sensor must be designed and tested in the future.

7. Literature

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Tytuł: Nowe rozwiązania inteligentnych czujników pomiarowych dla diagnostyki układów mechanicznych.

Artykuł recenzowany