Tadeusz UHL
AKADEMIA GÓRNICZO-HUTNICZA, KATEDRA ROBOTYKI I MECHATRONIKI

Structural Health Monitoring (SHM) – a new interdisciplinary approach to damage detection in mechanical structures

Prof. dr hab. inż. Tadeusz UHL

He is a head of Robotics and Machine Dynamics Department at Mining & Metallurgy Academy in Kraków. His research includes issues of structures dynamics, especially their modal analysis. His interests also include systems of active reduction of vibrations, control systems and wide range of mechatronics issues. He is the author of 17 books and hundreds of articles concerning those issues.

e-mail: tuhl@agh.edu.pl

Abstract

This work discusses a new interdisciplinary approach to structural health monitoring of mechanical structures. The goal of the paper is an overview of new discipline, which is subject to rapid development now. New methods and SHM procedures are briefly presented. The methods are divided into two groups: local methods and global methods. Advantages and disadvantages of the methods are discussed.

Keywords: Structural Health Monitoring, damage detection, monitoring systems, damage localization, interdisciplinary approach to SHM.

SHM- interdyscyplinarne podejście do wykrywania uszkodzeń konstrukcji

Streszczenie

W pracy przedstawiono interdyscyplinarne podejście do problemu monitorowania stanu i wykrywania uszkodzeń konstrukcji. Przedstawiono przegląd problematyki związanej z ta nową intensywnie rozwijaną na świecie dyscypliną. Opisano nowe metody stosowane w SHM, dokonano ich podziału na metody globalne i metody lokalne. Przedyskutowano zalety i wady każdej z grup metod. Artykuł jest pierwszym z serii artykułów z zakresu SHM, kolejne będą prezentowały szczegóły poszczególnych metod oraz przedstawiały ich zastosowania.

Słowa kluczowe: Monitorowanie konstrukcji, diagnostyka stanu konstrukcji, wykrywanie uszkodzeń, lokalizacja uszkodzeń, podejście interdyscyplinarne do monitorowania stanu konstrukcji.

1. Introduction

Structural Health Monitoring involves integrating sensors and actuators, possibly of smart materials, data transmission and computational power within a structure in order to detect, localize, assess and predict damages which can pose causes of structure malfunction at present or in the future [1, 2]. Typical SHM system is associated with on-line damage identification in structural systems most often applied in aircraft [3] and civil engineering structures [4]. The SHM systems utilize NDT methods, which are commonly carried out off-line and locally in zones of expected damage. But SHM methods should provide real time monitoring of the whole structure.

Damages in SHM area are defined as material properties or geometry changes of the structure which can affect current or future performance of the system. SHM is a next step in evolution of diagnostics of operating structure which originated historically from damage detection if damage occurred through condition monitoring, which was based on global assessment of structure condition during operation, to SHM which should detect material or geometry changes that occurred at early stage of their beginning [5]. SHM is interdisciplinary area which integrates such basic sciences as materials science, mechanics, electronics and computer science, and is strongly related to structures and their life cycle (Fig. 1). Design of SHM system depends on the type of damage which can occur, type of materials applied and physical phenomena employed for damage detection. Complexity of SHM system design is caused by a local nature of typical material damages and may not significantly influence system response measured commonly during operation e.g. low frequency vibration. Another feature that makes SHM data from damaged system difficult to acquire is a very limited accessibility of the system. It requires an in-depth study of local structure behavior with the application of analytical and simulation tools which are widely used for understanding damaged structure behavior and related signals characteristics. To design SHM system multi-physics and multi-scale simulation are requested. The design process consists of several steps, the most challenging are: selecting phenomenon which is sensitive enough to damages which are to be detected, defining required sensing system with self-validation capability, selecting data acquisition and processing architecture, defining feature extraction and information reduction procedures, formulating and implementing damage detection, its localization and size assessment procedure.

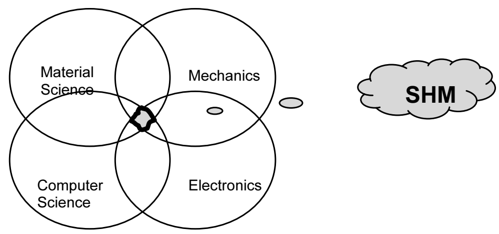

Fig. 1. Interdisciplinary nature of SHM
Rys. 1. Interdyscyplinarna natura SHM

Design methods are dedicated to a given structure, given materials and given physical phenomena employed for health monitoring.

SHM technology helps to achieve better operational safety and has economic impact on decreasing maintenance and operating costs because allows predicting possible damage long before its appearance and in consequence gives operators enough time to plan service and maintenance action.

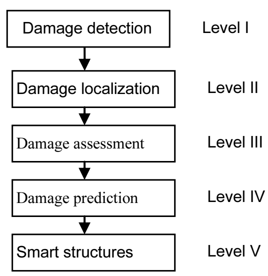

Fig. 2. Main levels of SHM procedure
Rys. 2. Główne poziomy procedury SHM

SHM systems tasks [1] can be classified as a process consisting of the following levels (Fig. 2); level I: damage detection, level II damage localization, level III assessment of damage size, level IV remaining life prediction and level V Smart Structures with Self-Evaluating, Self-Healing or Control Capabilities. The last level of SHM system is applied only to new structures, but up to now only in laboratory applications.

There are several very close disciplines which include SHM; CM – condition monitoring [5], NDE- non-destructive evaluation [3], SPC – statistical process control [5], DP – damage prognosis [5], MP – Maintenance Planning [6], e.g. RCM – Reliability Centered Maintenance. CM is very similar to SHM but is dedicated to rotating and reciprocating machinery. Main differences are the following: damage localization is approximately known in CM, type of damage is known – number of possible damages is limited, databases with damage symptoms are available, very slight influence of environmental conditions on measurement results, well defined economical benefits from employment of CM procedures. On the other hand SHM has also the following disadvantages: localization of damage isn't known, there are difficulties in measurements, difficult admittance to monitored structural components, type of a damage isn't known, significant influence of environmental conditions on measurement results, relatively high cost of SHM system which is a reason of application of the SHM only on critical structure. CM systems are based on measurements of structural responses during operation but do not use dedicated actuators to excite or trigger effects which can help to detect damage. The differences between CM and SHM system are shown in the Fig. 3.

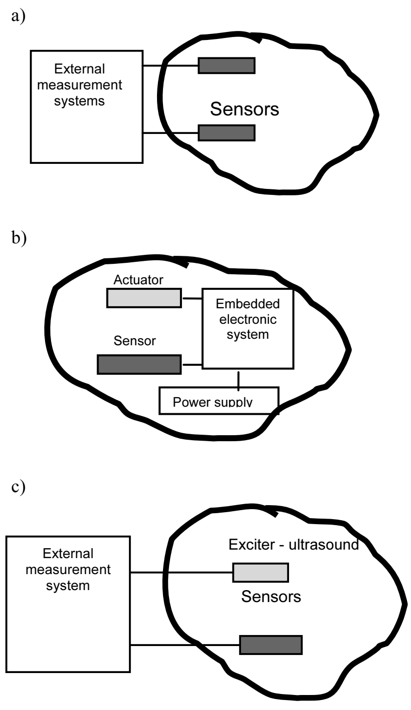

Fig. 3. Scheme of typical a) CM systems, b) SHM system, c) NDT system
Rys. 3. Schematy typowych systemów a) CM, b) SHM, c) NDT

NDT is usually carried out off-line in a local manner after damage has been located, or periodically to improve structure performance. NDT techniques are mainly used to characterize damages and assess their severities if location is known. The main difference between NDT and SHM can be noticed in hardware architecture. In case of SHM system sensors and actuators are build into (or integrated with) the structure but NDT is an external system with independent (not integrated with structure) set of sensors and actuators (Fig. 3). The NDT techniques are implemented offline but SHM are implemented online. SPC systems are dedicated for process diagnostics, not for structural damages, and use a variety of sensors to monitor changes in process parameters. The process parameters can change due to structural failure and in this respect SHM and SPC are comparable. DP process is used to predict remaining life-time of operating structures within which performance will remain above a given threshold. DP systems use knowledge about damage size and location as well as expected operational loads. The remaining life prediction is based on predictive model that acquires information from usage monitoring system (the system which monitors loading cycle during a structure operation), SHM system, past, current and future environmental conditions and expected load levels. Today's DP systems give only very rough estimation of remaining life prognosis, owing to very complex physics of structure destruction if material level is to be considered. Multiscale simulation methods can be helpful to solve this problem in the future. The scheme of interaction between different type of monitoring systems in DP are shown diagrammatically in the Fig. 4. [5]. MP systems use data from installed SHM system but also help to analyze historical data to detect events that could be the reason of performance drop. This approach enables preventive service action before damage occurrs. Several approaches can be distinguished within this discipline, one of the most useful for mechanical structure is RCM that helps minimize maintenance costs and minimize risk of structural failure [6].

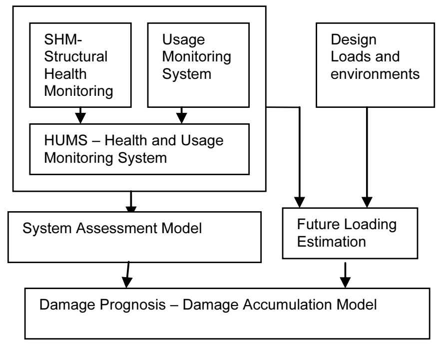

Fig. 4. Scheme of typical Damage Prognosis procedure
Rys. 4. Schemat typowej procedury prognozy uszkodzenia

Typical SHM system includes hardware section, algorithmic section and software. Hardware part consists of: sensors, signal acquisition systems and microprocessor systems. These components are embedded, work autonomously and very often are built into the structure. That creates new problems with energy supply based on embedded energy harvesting systems and necessitates miniaturization of sensors and electronics. One possible solution is to manufacture dedicated MEMS systems for SHM purpose [3]. The software part contains basic procedures for signal procession, signal fusion, hardware control, structure health detection and remaining life prognosis. In more advanced systems software part is related to Health management.

Nowadays, SHM approaches can be classified into two groups; global methods [7, 8, 9] and local methods [10, 11, 12].

The global methods are performed if global motion of the structure is excited during structure operation. Vibration-based methods belong to this class. Local methods allow inducing certain phenomenon which is sensitive to possible damage occurrence. This phenomenon should act locally in relatively small area. These methods include: high-frequency wave propagation based methods, impedance based methods, etc.

The global methods have the following characteristics i) advantages: monitoring the whole structure, only rough sensor network is required, sensors do not necessarily have to be located close to damage and no knowledge about critical location is required, ii) disadvantages; wave length is approximately equal to dimension of structure or component, lower sensitivity to small damages (especially for lower modes). Local methods have the following features: i) advantages; monitoring structural parts without necessity of disassembly, wave length is approximately equal to dimension of damage, sensitivity to small damages, ii) disadvantages; required dense sensor network, sensors that need to be located close to the damage, knowledge about critical location is required. Local methods are applied when critical structures are tested and early phase of damage is to be detected, but high cost of the SHM system could be accepted. Global methods give rough estimation of damage location and size but can be use for damage detection successfully.

Brief overview of different SHM methods is subject of the next sections of this article.

2. Global SHM methods

The global methods make use of the fact that local damage, for example local stiffness reduction has an influence on the global behaviour in terms time and space.

The most commonly used global methods are vibration-based methods [1]. Low-frequency vibrations have been applied in diagnostic purposes for many years [4, 7]. The effects of material defects, supporting structure failures or geometry defects on vibration response of the structure are well known. The relation between structural vibration and damages of structures are used in their health assessment. Two types of methods can be distinguished among global methods; signal-based [4] and model-based [7, 8]. Signal-based methods utilize relations between measured responses of the structure after ambient excitation and possible damages. Signal characteristics in frequency, time and time/frequency domains are most popular now. The methods are very commonly applied in rotating and reciprocating machinery diagnostics for damage detection, but localization and damage assessment need additional information.

Model-based methods employ different type of models of monitored structure to detect and localize damage in structure. The idea is shown in the scheme presented in Fig. 5 [9].

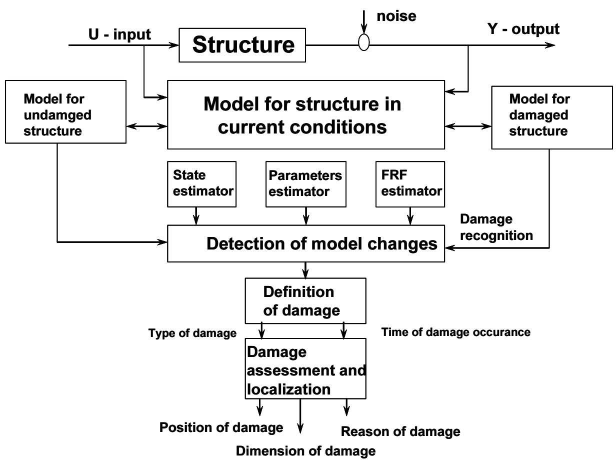

Fig. 5. Idea of model based global SHM method
Rys. 5. Idea modelu opartego na metodzie SHM

Models of undamaged structure and damaged structure are compared for their parameters or output and differences (residues) are related to given damage and help to localize it. One the most commonly used models in SHM is modal model, which can be identified on real structure using external measured excitation or using ambient vibration and measurements of structural responses at many points. These methods monitor the whole structure by detecting shifts of natural frequencies, increases in damping or changes of vibration modes shapes. Modal-model based methods can be classified into the following groups [9]: methods based on modal parameters perturbation (natural frequency, modal damping), methods based on FRF (stiffness and compliance) variation detection, methods based on mode shape analysis, methods based on detection on modes energy, methods based on FE model updating.

The methods based on modes shape analysis, like strain energy analysis method or mode shape curvature analysis are preferred, but required SHM system is more complex then for natural frequency and modal damping based SHM system. The global model based SHM procedures need no density sensor network and sensors can be far from the damage, but methods are less sensitive and have lower spatial resolution compared to local ones. But, sensitivity and spatial resolution of global methods can be improved by computational model to interpret changes of dynamic properties of the structure. The global model based methods are employed mainly for SHM of civil structures. There are several problems which limit application of those methods; the first is cost of monitoring system, which is relatively high because of very complex cabling system, the second being relatively high influence of environmental condition on structural dynamic properties, which are sometimes bigger then changes caused by serious damage of the structure. The first problem can be solved by using wireless sensor based monitoring system [13, 14]. The second one can be solved using special environmental filter, which is based on modal filter [15].

3. Local SHM methods

Local methods monitor structure in a small area surrounding sensor (sensors) using measurements of structural response on certain excitation applied. The ultrasonic waves [10], eddy-current [16], thermal field [17] or magnetic field [3], they are phenomena most commonly employed for local SHM methods. The methods which are mostly in use for SHM are the following: acoustic emission method [11], guided waves method [10], FBG sensor based method [18], vibrothermography [19] and electromechanical impedance methods [12, 20]. There are many more different methods that can be ascribed to SHM, but other methods are not in commercial use [21].

The classic NDT methods, characteristics of ultrasound wave propagation in solid bodies can be used, but in context of SHM, the waves are generated by permanently installed actuators that are integrated with a structure. Response is measured by built-in set of piezo sensors. In thin plate-like structures waves are propagated as Lamb waves and the method based on these guided waves is one of the most often proposed local method for SHM. The actuators for Lamb waves excitation generate high frequency excitation in a range between several kHz to MHz. The length of such a wave is similar to typical damage dimension in the structure e.g. wave with frequency 100 kHz has a length 20 mm for longitudinal wave in steel. Guided waves can be defined as stress waves forced to follow path defined by specimen boundaries. In this application an actuator is generating waves in the form of high frequency pulse signal, modulated by Hamming window sinusoidal signal. The signal travels trough the structure and rebounds from the boundary. But, when the wave comes across structural discountunity, which is comparable to its wavelength in size, it scatters in all directions. To distinguish between damage and structural features (geometrical boundary) one needs earlier information about the structure in its undamaged state. Typical measurement system for guided wave methods is shown in Fig. 7. The system consists of piezoelectric sensor and actuator, power supply for piezoactuator control and charge amplifier for conditioning of the signal generated by piezosensor. Internal architecture of PAQ wave generator and measurement unit are shown in the Fig. 8. The device is based on two integrated circuits - FPGA unit (1) and microprocessor. Additionally, PAQ 16000D is equipped with sections providing proper operation – i.e. package generator in the form of envelope generator (6), frequency generator and multiplier. The feedback measurement channel possesses charge and voltage amplifier and analogue-to-digital converter (3). Communication with the instrument is held by USB interface and MatLabR environment. The USB protocol service is implemented in the FPGA unit. Due to the amount of sampled data during the measurement procedure it is not possible to send them directly to the PC. That is why initially the FPGA unit stores the measurement data in the RAM memory. After completing the acquisition period all data are sent to the MatLabR via the USB port [22].

Guided wave based method has been applied for metallic composite structures. For damage detection and localization many different algorithms are implemented. The most commonly used algorithms are; phase array, beam forming which are adopted directly from radar techniques and time of flight, time reversal which belongs to time domain methods, wavelets transformation based methods which belongs to the group of time- frequency domain methods. Typical approach uses comparison of waves time or frequency characteristics measured during structure operation with the same characteristics extracted from data measured on healthy structure. As it can be noticed from measured time waveforms, they are different and can be used for damage detection and localization.

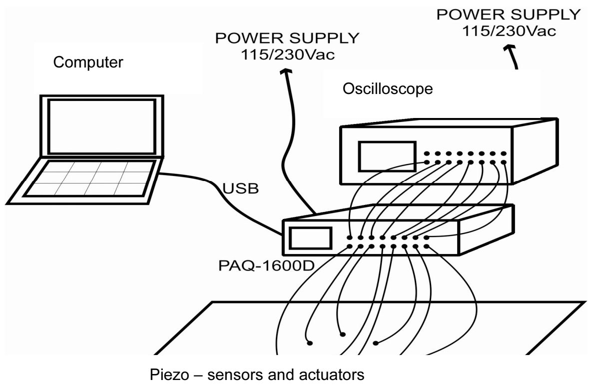

Fig. 6. The scheme of typical SHM system based on guided waves
Rys. 6. Schemat typowego systemu opartego na falach prowadzonych

The PAQ1600 device has been designed in the frame of the project supervised by the author.

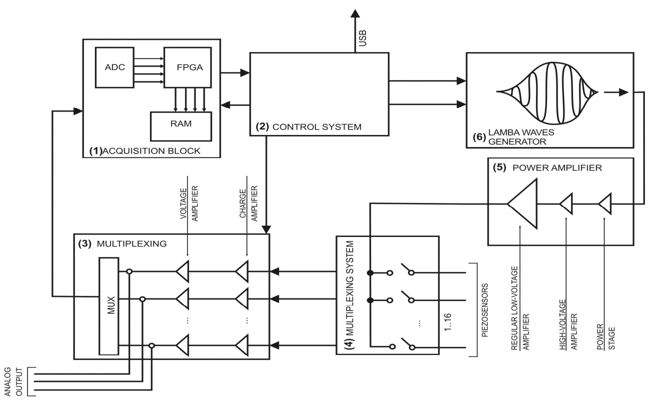

Fig. 7. Internal architecture of PAQ1600 device
Rys. 7. Architektura wewnętrzna urządzenia PAQ1600

Typical waveforms measured on composite plates both undamaged and damaged are shown in the Fig. 8.

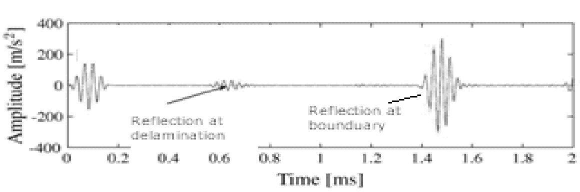

Fig. 8. Typical time waveform of guided waves
Rys. 8. Typowy kształt przebiegu czasowego fal prowadzonych

4. Final remarks

SHM is a new idea of damage detection and localization that assumes that the main cause of damage is material degradation. The SHM methods allow monitoring the state of material properties during operation. It requires interdisciplinary approach which combines mechanics, electronics, computer engineering and materials science. The SHM methods are more efficient in damage detection than classic vibration-based methods. Current development of SHM methods leads to the application of contactless, wireless, high frequency measurement methods, design in real time and embedded SHM systems. New structures currently designed, should fulfill requirements of low risk of damage. They have build-in set of sensors, actuators and embedded electronics with microprocessor and communication capabilities. Further development of SHM systems requires new automatic algorithms of damage detection, localization and assessment, new state prognosis methods and algorithms, and development of self-diagnosis and self-healing of critical structures. Nowadays, two main technologies employed SHM methods. These are aviation (aerospace) and civil engineering.

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5. References

[1] Balageas J, Fritzen C, Guemes A.: Structural Health Monitoring Systems, ISTE, 2006.
[2] Adams D.: Health Monitoring of Structural Materials and Components, Willey, New York, 2007.
[3] Bohler C., Staszewski W.: Structural Health Monitoring Systems of Aerospace Structures, Willey, 2004.
[4] Wenzel H.: Ambient Vibration Monitoring, Wiley, New York, 2005.
[5] Inman D.J., Farrar C.R., Lopes V., Steffen J.: Damage Prognosis for Aerospace, Civil and Mechanical Systems, Willey, 2005.
[6] Pietrzyk A., Uhl T.: Use of RCM methodology for railway equipment maintenance optimization, Archives of Transport, 2005, vol. 17 no. 2, s. 65–83.
[7] Doebling S.W., Farrar C., Prime M.B., Daniel W.S.: Damage Identification and Health Monitoring of Mechanical Systems from Changes of their Vibration characteristics, A literature review, LA-13070 – MS, 1996.
[8] Adams D., Farrar C.: Identifying Linear and Nonlinear damage using frequency domain ARX models, Structural Health Monitoring, An International Journal 2002, vol. 1, no.2, pp. 185-201.
[9] Uhl T.: The use and challenge of modal analysis in diagnostics, Diagnostyka, vol. 30 t. 2, 2004 pp s. 151–160.
[10] Raghavan A., Cesnik CES.: Review of guided – waves structural health monitoring, The Shock and Vibration Digest 2007, 39, pp. 91 – 114.
[11] Pao Y.H.: Theory of acoustic emission, Elastic Waves and Non-Destructive Testing of Materials, ASME, 1978; AMD, vol. 29, p 107.
[12] Park S., Sohn H, Farrar C.R., Inman D.: Overview of piezoelectric impedance – based health monitoring. The Shock and Vibration Digest 2003. vol. 35, pp. 451- 463.
[13] Lynch J.P., Loh K.J.: A summary review of Wireless Sensors and Sensor Networks for SHM, Shock and Vibration Digest, March, 2006.
[14] Uhl T., Hanc A., Tworkowski K., Sękiewicz L.: Wireless sensor network based bridge monitoring system, Key Engineering Materials, 2007 vol. 347 pp. 499–504.
[15] Mendrok K., Uhl T.: Modal filtration for damage detection and localization, in: Structural health monitoring 2008: proceedings of the fourth European workshop: Cracow, Poland, July 2–4, 2008, pp. 929–936.
[16] Grimberg R., Premel D., Savin A., Le Bihan Y., Placko D.: Eddy current holography evaluation of delamination in carbon – epoxy composites, Insight, 2001, vol 34 no. 43, pp. 260- 264.
[17] Maldague X.: Nondestructive testing of materials using infrared thermography, Springer, London, 2007.
[18] Todd M., Nichols J.M., Tricky S.T., Virgin L.N.: Bragg grating- based fiber optic sensors in SHM, Phil. Trans. R. Soc. A vol. 365 pp. 317 – 343.
[19] Uhl T., Szwedo M., Bednarz J.: Application of active thermography for SHM of mechanical structures in: Structural health monitoring 2008: proceedings of the fourth European workshop: Cracow, Poland, July 2–4, 2008 pp. 149–156.
[20] Bhalla S., Soh C.K.: Structural Health Monitoring by piezo-impedance transducers, ASCE Journal of Aerospace Engineering, 2004 vol. 17 no.4, pp. 154-165.
[21] Chung D.D.L.: Structural Health Monitoring by electrical resistance measurements, Smart Materials and Structures, 2001, vol.10, pp. 624- 636.
[22] www.vibx.pl

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