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# STRUCTURAL HEALTH MONITORING (SHM) METHODS IN MACHINE DESIGN AND OPERATION

The present paper is devoted to the discussion and review of the non-destructive testing methods mainly based on vibration and wave propagation. In the first part, the experimental methods of actuating and analyzing the signal (vibration) are discussed.The piezoelectric elements, fiber optic sensors and Laser Scanning Doppler Vibrometer (SLDV) method are described. Effective detecting of the flaws needs very accurate theoretical models. Thus, the numerical methods, e.g. finite element, spectral element method and numerical models of the flaws in isotropic and composite materials are presented. Moreover, the detection of the damage in structures, which are subjected to cyclic or static loads, is based on the analyzing of the change in natural frequency of the whole structure, the change of internal impedance of the material and the change in guided waves propagating through the investigated structure. All these cases are characterized in detail. At the end of this paper, several applications of the structural health monitoring systems in machine design and operation are presented.

## 1. Introduction

In the last decades the new methods based on the vibration and guided waves propagation analysis becomes very promising. What is the most im-

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portant, they can be also used in the on-line modes, what makes possible the permanent monitoring of the engineering structure. These methods are known in the literature as the Structural Health Monitoring (SHM). There is available large number of publications, where the fundamental assumptions of these techniques are discussed. Here can be quoted works [17] and [18]. Generally, the SHM techniques split into two main categories, namely active and passive ones. In the first case there have to be used some additional elements, which plays a role of actuators of the vibrations. A frequently used the piezoelectric elements are applied in order to generate required signal. In the latter method the vibrations, which are generated by the analyzed machine itself, are used to detect the changes in dynamic response of the structure. The detected possible changes could be interpreted as caused by the damage. However, the detection of the existence of the flaw is not the only one aim of the SHM methods. The SHM process [13] can be divided into five following levels.

In the first level the presence of damage is confirmed. It can be done by monitoring the change of some mechanical properties of the structure, like fundamental natural frequency, strain energy, phase information, stiffness reduction or impedance.

Next, in level 2, it is necessary to estimate the location, extend and orientation of the detected damage. It can be performed by a trigger experimentally high frequency content signal through the tested structure. The measured output in some locations will have an additional wave reflection caused by the existence of the damage. The appropriate analysis of the received signal makes it possible to locate the flaw. This part of SHM process is the most difficult. It is necessary to develop very accurate theoretical model of the considered structure and the expected damage. Here it is very useful the finite element method (FEM) due to its versatile character. However, the accuracy of the numerical estimation of the dynamic response of the structure strictly depends on the element size. The higher frequencies of the input signal require the smaller element size. Thus, very often the number of necessary elements is enormously large. The alternative algorithm is the Spectral Finite Element Method (SFEM) and its variants. This method enables one to obtain high accurate results with the use of very small number of elements. Unfortunately, it is not so universal as FEM. The main limitation is connected with the geometry of the modeled structure. Further, the received experimentally signal can be noise polluted. Hence, the appropriate algorithm of signal processing has to be applied.

The main aim of the level 3 of SHM process is to estimate the severity of the detected damage on the safety of the whole structure. If the investigated structure is, for example, made of isotropic material like structural steel and the crack is detected, the Stress Intensive Factor (SIF) or Stress Energy Release Rate (SERR) can be evaluated. If the evaluated SIF or SERR is greater than the threshold value, the crack will begin increasing. In the case of multi-layered composite materials the damage in the form of delamination is treated in a similar way.

The uncontrolled growth of the discovered damage can be very dangerous for the whole structure, especially in the case of delaminations, which grow very fast. That way in the level 4 an appropriate action should be performed in order to arrest or stop the growth of the flaw. The methods of the repair the damage structure are very different and strictly depend on the considered material and structure. The level 5 is strictly associated with level 4, wherein the fatigue analysis is performed in order to estimate remaining time of the safe exploitation of the machine. This analysis is based mainly on the statistical data.

The last two levels, namely 4 and 5, very often are not consider as an integral part of the classical SHM but only as the natural supplement of the activity performed in the first levels. In order to summarize, every real SHM system consists of the following components[18]: the analyzed structure where the SHM system is installed, contact or non-contact sensors, data acquisition system, signal processing, theoretical damage modeling and damage detection algorithm, data transfer and storage mechanisms and data handling and management.

The current review splits into six sections. The experimental equipment like piezoelectric (PZT) and Poly Vinyle Dy Floride (PVDF) sensors and actuators (PZT), fiber optics sensors (FOS) as well as a Scanning Laser Doppler Vibrometer (SLDV) technique is described in the section 2. Next, in the section 3, the damage detection based on the analysis of the natural frequency and guided wave propagation is described. Further, in the section 4, the fundamentals of the FEM, SFEM and damage modeling are presented. Several examples of SHM systems, which are encountered in practice, are presented in the section 5. The article also contains the short conclusions and the list of references.

## 2. Common SMH Sensors and Actuators

An SHM system comprises of hardware (sensors, actuators and associated instrumentation) and software elements for damage detection, modelling and analysis of influence of damage on the mechanical behavior of composite structures. In the acoustic emission and SHM applications, for the generation and sensing of guided elastic waves, the conventional piezoceramics PZT (lead zirconium titanate – Fig. 1), PVDF (Poly Vinyle Dy Floride – Fig. 2) or fiber optic sensors are commonly used. Due to the direct and inverse piezoelectric effect in piezoelectric materials, they are the most popular in the SHM and can be also used for guided-wave tomography in a catch-pitch configuration or in a pulse-echo mode (see section 3.2). In the second application, the same piezoelectric element acts both as a transmitter and as a receiver [18].

Fig. 1. Conventional PZT transducer

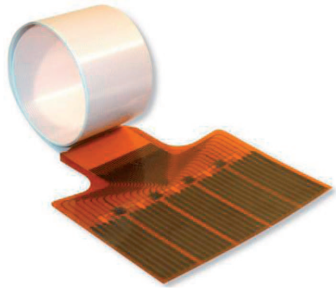

Fig. 2. Piezoelectric film

Piezoelectric elements are mainly made of polymer or ceramic materials. Some material constants of PZT-4 type I (piezoelectric ceramic), PZT polymer and PVDF sensors (uniaxial film, bi-axial film, copolymer) and forms of piezoelectric transducers are described in Ref. [30]. The PVDF material is flexible, tough, light-weight and not brittle like piezoceramics. Due to these properties, PFDV sensors can be formed in the form of the thin films (Fig. 2) and can be easy to embed to the composite structure surfaces. They are very attractive for many applications [30] including structures with complicated shapes or large structural strains. Moreover, PVDF sensors have typically 10÷20 times larger piezoelectric constant $g$ and provide higher voltage field in response to mechanical stress than PZT (Table 1). However, the PVDF has lower Young's modulus and gives a much lower force than piezoceramics. This fact is significant if the sensor is used also as an actuator [17]. The PVDF film sensor can exhibit lower sensitivity and dielectric constant compared to piezoceramic PZT. Other advantages and applications of PZT sensors and actuators are high piezoelectric coupling factors, moderate permittivity, high Q-factors and very good stability under high mechanical loads and operating fields [30]. More detailed information about PZT and PFDV and their applications in damage detection can be found in papers [6, 8, 12, 17, 18, 40].

Piezoelectric material (acting as sensor and actuator) can be used in composite structure in the form of fibers (Fig. 3a) and layers or wafers (Fig. 3b). Such sensors can be embedded in a polymer matrix or bonded to the surface of a structure. Development of such smart structures with integrated piezoelectric sensors and actuators is recently observed. Another form is the Macro Fiber Composite (MFC) patches developed by High and Wilkie [24] and cylindrical piezoelectric fiber composite (CFPC) actuator [2]. Using MFC actuators it is possible to obtain strains and displacements greater than those that could be generated by earlier actuators based on monolithic piezoceramic sheet material. On other hand, the CFPC actuator have been invented as alternatives to MFC patches for applications in which greater forces or displacements (or strains) may be required.

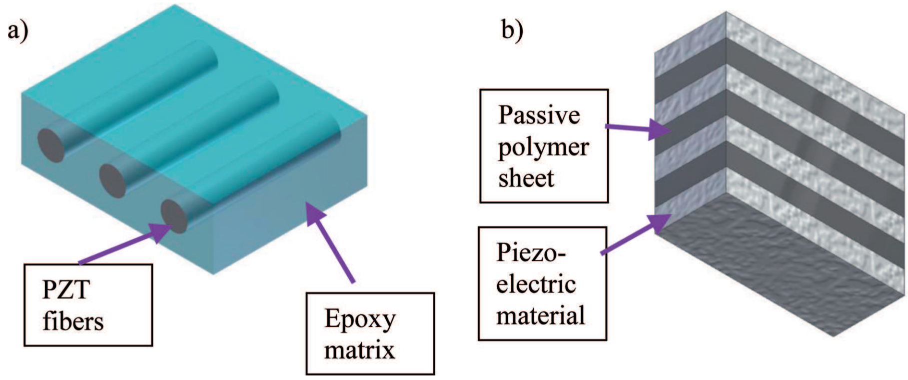

Fig. 3. Examples of piezoelectric composite structures a) in the form of fibers b) in the form of layers

Another type of sensors, which is frequently used in the context of SHM, are fiber optic sensors (FOS). In such elements, the response to external influence results in change of optical radiation and can be used to measure it. FOS can be used as a transducer and can converts measurands like temperature, stress, strains, electric and magnetic currents. Generally, a fiber optic sensor will consist of a source of light, sensing and transmission fiber, a photo detector, demodulator, processing and display optics [17]. Fiber optic sensor can be categorized into three groups [25]: interferometric sensors [78], distributed sensors [50] and grating-based sensors [43, 74]. In SHM applications, the most popular are Extrinsic FOS: Extrinsic Fabry-Perot in-

Table 1.

Comparison of PZT and PVDF properties [17]

| **Property** | **Unit** | **PZT** | **PVDF film** |
|---|---|---|---|
| Density | kg/m$^3$ | 7500 | 1780 |
| Relative permittivity | $\varepsilon/\varepsilon_0$ | 1200 | 12 |
| Piezoelectric strain constant $d_{31}$ | $10^{-12}$ C/N | 110 | 23 |
| Piezoelectric voltage coefficient $g_{31}$ | $10^{-3}$Vm/N | 10 | 216 |
| Electromechanical coupling coefficient for transverse actuation $k_{31}$ | At 1 kHz | 0.30 | 0.12 |
| Young's modulus | GPa | ~60 | ~3 |
| Acoustic impedance | $10^{-6}$ kg/m$^2$s | 30 | 2.7 |

terferometric (EPFI – Fig. 4) and Fiber Bragg Grating (FBG – Fig. 5) fiber optic sensors. The EPFI sensors are made using single-mode optical fiber and a multimode fiber as reflectors and works on the principle of multi reflection Fabry-Perot interference between two reflected mirrors (Fig. 4) [17]. They have a typical resolution about 0.15 $\mu\varepsilon$ and 0.1°C and a strain measurement range of ±1.000 $\mu\varepsilon$ (or extended to ±5.000 $\mu\varepsilon$). They can work at large spectrum of temperatures (−40°C÷ +250°C). One disadvantage of such sensors is that they have low multiplexing capability [25].

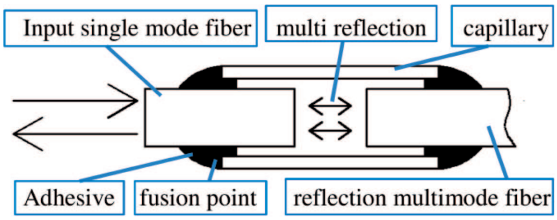

Fig. 4. Schematic of EPFI sensor

The second one, FBG sensor is generally fabricated on a germanium-doped single mode optical fiber using ultraviolet laser. The length of gratings (Fig. 5) is in the range of 1÷20 nm. In this sensor, the portion of the input signal (called Bragg wavelength) reflected from the Bragg Grating is measured. The rest of the input signal passes through the sensor without changing its properties. The Bragg wavelength is defined by the fiber refractive index and grating pitch, which are affected by parameters such as temperature, strain vibration and etc. [25]. FBG sensors have wide applications in the measurement of acoustic or ultrasonic signals, temperature and strain sensing and for damage and crack monitoring. More information about FOS sensors can be found in the Ref. [17, 25, 39].

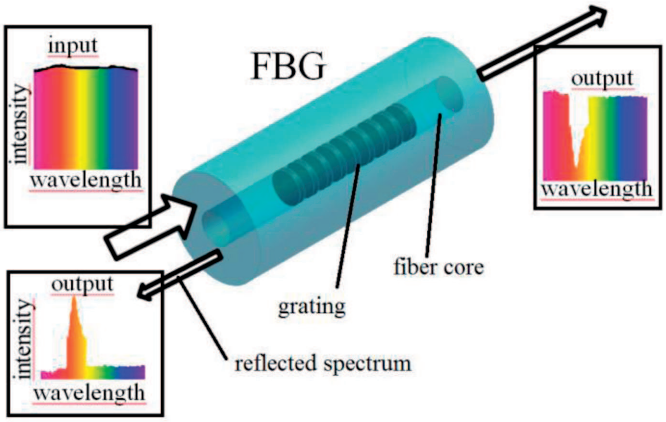

Fig. 5. Functional principle of a Fiber Bragg Grating sensor

In many practical applications related with SHM the Scanning Laser Doppler Vibrometer (SLDV) is used. SLDV is a non-contact sensing device and can detect motion or measure the vibration, displacement, or strain response at thousands of spatial points of surfaces on a structure. It has a large measurement bandwidth (0.1 Hz÷20 MHz), which cannot be achieved using accelerometers. Because of this, it can be used as a sensor to modal analysis purposes and vibration-based techniques to detect the response of the Lamb wave propagation on the investigated surface. For damage detection of composite structures, the boundary effect detection (Fig. 6) [65] and operational deflection pattern recognition methods [65] or non-destructive damage detection techniques can be used.

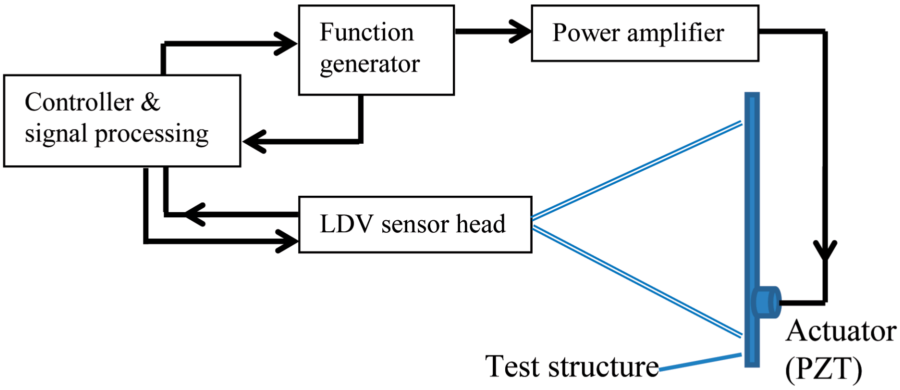

Fig. 6. The experimental setup for wavefield measuring using SLDV sensor

## 3. Damage detection methods

The detection of the damage inside the structure can be divided into three categories [80]. First of all the changes of the natural frequency can be analyzed. The alternative approach is the guided wave propagation analysis. The existence of a flaw causes the changes in the received signal. The last option is to analyze the changes of the internal damping of the material or structure. Below the short survey of the applied models and obtained results are discussed.

### 3.1. Fundamental natural frequency

The existence of the damage inside the material, especially inside the composites, causes the degradation of the stiffness and the increase of the internal damping coefficient. This phenomenon can be observed as a result of experiment as well as the result of the theoretical analysis. The publications, where this phenomenon is investigated, can be divided into three categories with respect to the type of the structure, namely beams, plates and shell with single or double curvature. The presented brief survey is approximately limited to the last decade.

The influence of the delamination on the flexural stiffness, natural frequency and the internal damping in the case of honeycomb sandwich beams is investigated by Hyeung-Yun Kim et al. [27]. The delamination is located between face-layer laminates and honeycomb core. They performed experimental observations and a theoretical harmonic analysis by using the modal parameter identification method. A good agreement between the theoretical predictions and experimental results is reported. The next work by Taoling Yang et al. [69] is devoted to the determination of the overall tensile modulus and natural frequencies of composite laminates with multiple transverse cracks. The modulus is calculated based upon an energy method and the crack opening displacement. The numerical simulation is applied to fiber – reinforced composite laminates. The obtained numerical results are compared with experiment and a good agreement is found. In the case of graphite/epoxy composite, the multiple transverse cracks have rather minor influence on the natural frequency, whereas in the case of the glass/epoxy composite the influence is really significant when the cracks occupies a sufficiently large area of the beam. The growth of the damage is strongly connected with the cyclic loading. That is why a new NDT fatigue prediction model for composite laminates is developed by Tae-Chul Moon [67]. They investigated the relationship between the natural frequency and the reduction of the flexural stiffness reduction. The stiffness reduction is caused by gradually growth of the fatigue damage. Again the theoretical and experimental investigations are performed and a good agreement is obtained. Free vibrations of the composite beams with non-overlapping and overlapping delaminations are investigated by Dongwei Shu et al. [11, 14]. The delaminated beam is modeled as a composition of a several interconnected Euler-Bernoulli beams. Moreover, the continuity and the equilibrium conditions are satisfied between adjoining beams. The obtained results agree with experimental and analytical ones, which are available in the literature. The parametric studies show the significant influence the size and location of the flaws on the natural frequency and mode shape. The modified mixed FEM is used by Ramtekkar [52] in order to estimate the natural frequency of the composite beam with delamination. The unconstrained-interface and the contact-interface model is proposed. The delamination is located in mid-plane and off mid-plane of the beam. The obtained results indicate that the contact-interface model provides more realistic predictions.

The phenomenon of change of the natural frequency is used by Kessler et al. [28] directly in order to detect the different kind of flaws in the composite materials. They investigated composite samples with drilled-though hole, matrix crack with fatigue induced damage and delamination cut with thin utility knife at the mid-plane. In the experimental investigations, the SLDV method with PZT actuators is used in order to determine the natural frequency and the mode shape. Next, the FEM simulation is performed with the use of MATLAB. The authors report that frequency response method is reliable for detecting even small amounts of damage in a simple composite structure. However, the important information about damage type, size and location can be lost. In other word, a different kind of damage could manifest in the same way. In the next work by Heung Soo Kim et al. [22], authors suggest that the new improved FEM model of the multi-layered composite material with a flaw could provide better predictions of the natural frequency change than, for example, widely used First Order Deformation Theory. In the expression, which describes the displacement of the layer, the additional terms are taken into account in order to obtain the more adequate description of material behavior, when the delamination exists. According to the author's opinion, the proposed model in comparison with the other theories provides more accurate natural frequency predictions, especially for higher modes. In the next paper by Wei [73], the composite plate with the rectangular delamination is taken into consideration. Here it is worth to cite the obtained natural frequencies because of their typical character. The studied rectangular plate has 240×180 mm and consists of 16 layers in the following orientations $[0°/0°/90°/90°/0°/0°/90°/90°]_s$. The mechanical properties of the material are: $E_1$ = 125 GPa, $E_2 = E_3$ = 8.5 GPa, $G_{12} = G_{13}$ = 4.5 GPa, $G_{23}$ = 3.27 GPa, $\nu_{12} = \nu_{13} = \nu_{23} = 0.3$ and density $\rho$ = 2400 kg/m$^3$. The geometrical center of delamination is located 60 mm from the right vertical edge and 42 mm from the horizontal one. The rectangular delamination is placed between the fourth and fifth layers counted from the top of the plate. The dimensions of the flaws are in mm: A 18×12, B 36×24, C 54×36 and D 72×48. The obtained results for the free sample are collected and presented in the Table 2. As it can be observed, the existence of the delamination manifests by the decreasing of the natural frequency. For a small sized flaw, the change is almost non-detectable, but for larger one it is possible to detect the damage with use of the described technique.

Table 2.

Numerical results of natural frequency for the free plates [Hz] Wei [73]

| Mode | Intact plate | Plate A | Plate B | Plate C | Plate D |
|---|---|---|---|---|---|
| 1 | 90.518 | 90.518 | 90.518 | 90.517 | 90.515 |
| 2 | 279.17 | 279.16 | 279.08 | 278.66 | 277.95 |
| 3 | 333.59 | 333.58 | 333.52 | 333.13 | 332.48 |
| 4 | 354.22 | 354.21 | 354.08 | 353.41 | 352.06 |
| 5 | 397.62 | 397.61 | 397.51 | 396.96 | 395.91 |
| 6 | 583.71 | 583.71 | 583.68 | 583.41 | 582.72 |

Similar results are presented by Alnefaie [3]. He also analyzed the rectangular plate with delaminations of different size. He used the duplicated node technique. Additionally, it is reported that for higher modes the nodes, which belongs to the area of flaw, interpenetrate the opposed surface. Hence, the conclusion is that in the area of delamination the energy dissipation phenomena occurs. It causes the increase in the internal material damping.

Finally, it is worth nothing that there are papers were the methods of locating the damage based on natural frequency and mode shape information at specific locations are developed. Here can be quoted the work by Kim-Ho Ip [31], where for the composite circular shells the location of delamination is detected by an analysis of sensitivity of natural frequency to damage. The whole simulations are performed with the use of FEM.

### 3.2. Guided waves propagation

The SHM methods based on wave propagation can be classified to non-destructive (NDT) and dynamics-based inspection techniques. Due to this fact they are very popular in industrial applications and aerospace structures. In such methods (i.e. guides ultrasonic waves propagation – GUWs) the reflections and mode conversion of the signal caused by the presence of damage is investigated. In the SHM applications, guided waves can be used for detection of different damage types such as cracks, delaminations, debonding, holes, notches and corrosions in both composite and metallic structures. Acoustic emission (AE) and ultrasonic inspection can be also used to analyze the impact response problems or mechanical properties of different materials.

The acoustic emission (Fig. 7) is one of the oldest and frequently used passive SHM techniques for structural damage detection (e.g. [26, 46, 59]). It is based on transient sound waves (typically 100÷1000 kHz) propagation in the investigated structure. Such waves can be induced by a rapid local stress redistribution in a material (e.g. by the initiation and growth of cracks, slip and dislocation movements, melting and phase transformations in metals; matrix cracking and fiber breakage and debonding in composites).

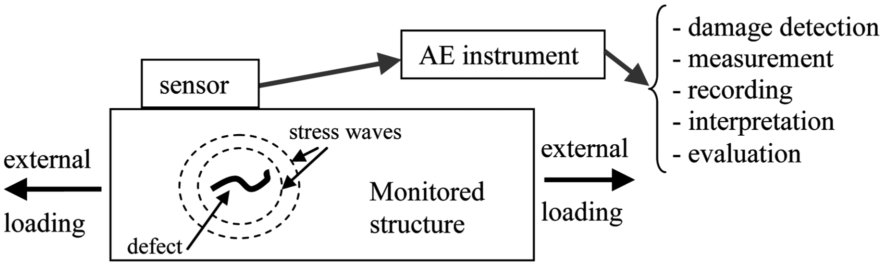

Fig. 7. The principle of techniques based on acoustic emission

They can propagate long distances in all possible directions and can be used for testing and/or monitoring of large areas. The use of AE techniques can provide some valuable information regarding the origin and importance of defects in a structure. In contrast to other NDT techniques, in the AE the energy released by the damage and deals only with dynamic processes or changes (e. g. crack growth) in a material is sensed and analyzed. Furthermore, the different failure mechanisms have different characteristics which can be studied utilizing the AE parametric data [6]. Using AE it is possible to discern between developing and stagnant defects, but in some cases the external loading can be not high enough to cause an acoustic wave [33]. Other advantages of techniques based on AE are fast volumetric inspection using small number of sensors and in many cases possibility to immediate indication relating to the strength or risk of damage. Reduction of the complexity of the sensor system and simplifying the data reduction and analysis can be also made using the sensor network based at structural neural system [21, 33, 34]. However, the AE method can only qualitatively gauge the damage level in a structure. In order to obtain some information about damage, such as size, location, etc., the other sound/ultrasound-based techniques are necessary.

The other structural health monitoring techniques for damage detection and inspection are based at active methods, such as the classical ultrasonic technique and GUWs, in which actuators are used to pulse the structure with a known waveform.

The classical ultrasonic techniques utilize various phenomena of ultrasonic waves propagating in a structure in order to detect defects [61]. In practical SHM applications, the longitudinal (compressional, dilatational pressure, P-wave) and the transverse (shear, S-wave) are the frequently used. Similarly to AE, the ultrasonic waves can also travel long distances in a structure. However, the energy of propagating waves can be decreased or absorbed by some boundaries of a structure. The damage detection in such techniques utilizes wave attenuation, reflection and refraction phenomena [55, 56] and is based on two major inspection modes: pulse-echo (Fig. 8a) and pitch-catch (Fig. 8b). In the first one (pulse-echo) two transducers (receiving sensor and actuator) are necessary. In the second mode only one sensor is required. However, this transducer is working as sensor and actuator. The generated signal is reflected by a boundary of a material and finally received by the same sensor. In both modes, different transducers, described in section 2 of the paper, can be used. However, the type, geometry, method of coupling and frequency bandwidth of transducers and etc. are very important in order to obtain high accuracy of damage detection. The methods for damage detection using ultrasonic techniques are described in Ref. [61].

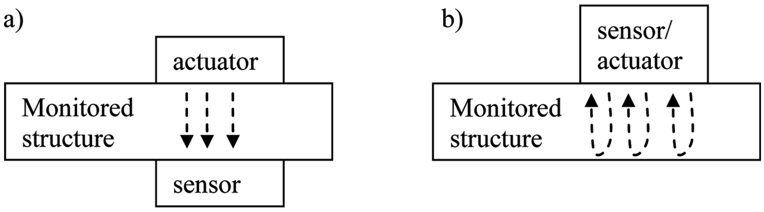

Fig. 8. Ultrasonic inspection modes a) Pulse-echo, b) Pitch-catch

The use of the guided waves, which are governed by the same equations as bulk waves, but they have an infinite number of modes associated with propagation is currently a research field of significance in SHM as methods for damage detection in composite structures [63]. The guided waves are high sensitive to both surface and embedded structural discontinuities in a material. They are able to propagate for a relatively long distances within the investigated structure and to interact with structural damage (delamination, debonding, cracks, notches, holes, corrosions in metallic and composite beam, plate or shell structures). Various types of guided waves are used in practice. The Rayleigh waves, which are the best known surface waves, are non-dispersive for uniform material properties. However their mechanism of propagation is very complex and amplitude of wave decreases rapidly with depth [61]. Because of this, the SHM techniques based on the Rayleigh waves are mostly used to detect only surface defects.

The other one, the Lamb waves [72], which are frequently used guided waves for damage detection [56], are dispersive plate waves that occur for traction-free forces on both surfaces of the plate. Due to this fact and their multiple modes, the use of them in anisotropic media is complicated. However, they have many attractive traits, which motivate the utility of the Lamb waves: (i) active generation of controllable Lamb waves and (ii) effective signal processing and interpretation [63]. Moreover, they can propagate long distances and are used for damage detection of plate-like structures.

The Lamb waves as a means of damage detection most likely were introduced by Worlton [76] in 1961. Fundamental information about ultrasonic guided wave propagation can be found in many textbooks [1, 5, 19, 32, 44, 48, 55, 72]. A literature review of the most salient studies on ultrasonic guided waves is presented by Rose [56] and Su et al. [64].

Guided waves can be generated and received by piezoelectric transducers described in section 2 of the paper. Two popular techniques with use an angle beam transducer and comb transducer are illustrated and described by Rose [56]. The use of PZT elements makes it possible to induce wide frequency responses with lower power cost. In many cases, the sensor network with PZT transducers used to achieve a multi-point measurement gives us opportunity for more reliable analysis.

The damage of the structure (such as cracks or delamination) can be investigated by comparison between distribution of guided waves (or displacements) of the intact and defected structures [75]. However, in the damage detection process, the localization of the sensors and actuators is very important. Distribution of waves (displacements) is strongly depended on location of above sensors. It can be observed that, for the same structure but with different sensors localizations, in one case the difference between displacement for the intact and damaged structure (Fig. 9) can be negligibly small (sensor s4 – Fig. 10), but for another one the difference is more significant (sensor s1 – Fig. 10) [63]. Such an analysis of cylindrical composite panels with a single delamination is performed by Stawiarski et al. [63]. It is observed that the largest difference of displacements between intact and damaged structures is obtained when the sensors are placed on the edge of the defected influence zone. In such a case, the measured signal is going near the corner of the damage. The difference of signals in the sensors which are placed in the larger distance from the defected area is much smaller.

The data collected by the system of sensors have to be processed for identification and localization of a potential damage. It indicates the impor-

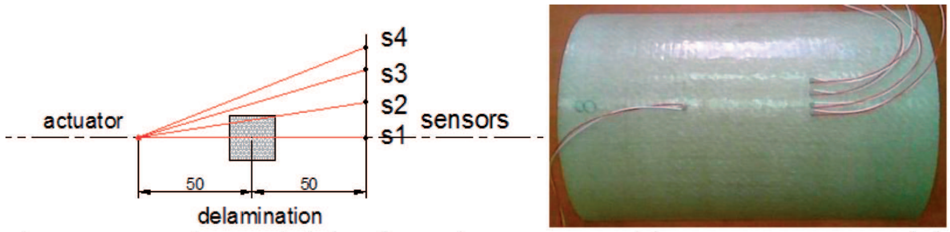

Fig. 9. Top view of delaminated structure with 10 mm square delamination and assumed sensors configuration (permission given by Stawiarski A.)

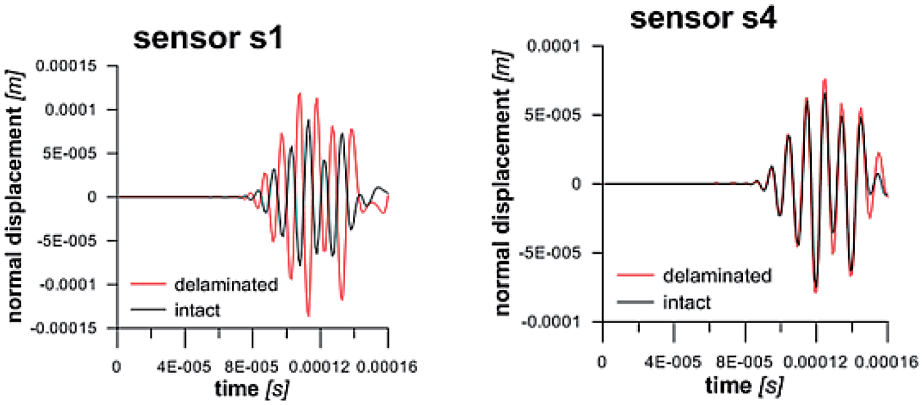

Fig. 10. Comparison of normal displacements for intact and defected structure with delamination measured by different sensors (permission given by Stawiarski A.)

tance of damage modeling (finite element method – FEM, spectral finite element method, finite difference techniques, boundary element methods, etc.) and damage detection algorithms. The selection of above techniques mainly depends on the size of damage that needs to be detected. Among all mentioned methods, the FEM is the most popular and widespread due to its ability to model complex geometries. However, the numerical model of damaged composite structure has to fulfill several requirements, which have been pointed out by Ye and Su [77]. The dimensions of finite elements in a numerical model depend on both the speeds of the medium in which the signal is propagating and the signal frequency. Moreover, there should be more than 8 nodes per wavelength to obtain good spatial precision. The laminate should be divided into sub-laminates in thickness to characterize individual laminae especially when we consider interlaminar delamination in composite structure. Finally, the time step for dynamic calculation should be less than the ratio of the minimum distance of any two adjoining nodes to the maximum wave velocity. The exemplary 3D FEM modeling of composite multilayered cylindrical structure with a single delamination and application of damage detection method based on elastic wave-based damage identification technique for laminated composite cylindrical structures is presented by Stawiarski et al. [45, 62, 63].

## 4. Computational Simulation-Based Techniques for SHM

In order to locate and estimate orientation and extend of a detected flaw, an appropriate algorithm should be developed. It is necessary to perform theoretical simulations which show how the existing damage changes the fundamental natural frequency, guided wave propagation, etc. Next, the appropriate algorithm of damage detection can be created. There are several numerical methods which can be used. The most versatile seems to be the FEM. However, in the case of a dynamic response simulation of structures, this method has some disadvantages. Thus, alternative computational techniques are still under consideration. The frequently used method is the Spectral Finite Element Method (SFEM). The use of this method allows one obtaining accurate results. Besides, there is possible to apply other numerical method, for example Finite Difference Method (FDM), Boundary Element Method (BEM) or Perturbation Method (PM). However, the FEM and SFEM are frequently used and encountered in the literature. Below, the FEM and FEM as well as the damage modeling technique are shortly presented.

### 4.1. Finite Element Method

The FEM method is the one of the most common method in different kind of the engineering problems [54, 62, 66]. There are many publications devoted to FEM and its practical use, for example [79, 42]. Thus, here the general idea as well as the fundamental assumptions of this method will not be discussed. This method is characterized by high versatility. That is why there are available advanced commercial FEM package: ANSYS, ABAQUS, NISAII, etc. The authors of this article are very familiar with ANSYS system. Using this computer application it is possible to simulate dynamic response of the considered structure, which can be made of isotropic material or multilayered composite material [7]. However, the two important questions need to be answered [18], namely*: what should be the mesh size for a given input loading? And what should be the frequency content of the input signal for a given flaw size?* It is assumed that the number of nodes per wave length $\lambda$ should be greater than 8, but sometimes it is necessary to use 10 or even more. The wave length $\lambda$ depends on the wave propagation speed $c_0$ and the angular frequency $\omega$ [rad/s] of a given wave mode (obtained from the spectral analysis of the input signal), namely:

$$\lambda = 2\pi c_0/\omega. \tag{1}$$

Hence, the mesh size is frequency dependent. Moreover, the wave length of the applied input signal should be comparable with the dimension of the damage. Hence, the appropriate frequency $f$ of the input signal can be obtained from the following relationship:

$$f = c_0/a, \tag{2}$$

where $a$ is the characteristic dimension of the flaw. The main conclusion is that the mesh size is frequency dependent. In order to simulate the dynamic response of the structure with high accuracy, it is necessary to use an enormous number of elements. Thus, the time of computations, as well as the amount of obtained data, is very large. This is the critical disadvantage of FEM in the case of the SHM simulations. However, the FEM is still a very useful method, when the fundamental natural frequency of the structure should be determined [42].

### 4.2. Spectral Finite Element Method

As an alternative for the FEM, especially in the case of a simple construction of regular geometry (rods, beams, plates or panels), one can consider the Spectral Element Method. The basis and the fundamental assumptions can be found in publications [18, 36, 37]. The considered problems are transformed from time domain into the frequency domain via Fast Fourier Transform (FFT). The dynamic response of a structure is described by the frequency-dependent shape functions, which are exact solution of the governing differential equation. Hence, in the case of simple structure, only one element is required and the obtained solution can be considered as *exact*. In comparison with classical FEM method, the SEM has several important advantages [37], namely: as it has been already motioned, extremely high accuracy, smallness of the problem size and, in consequence, low computational cost, effective to deal with the frequency-domain problems and in the case of non-reflecting boundary conditions of the infinite- or semi-infinite-domain problems, effective to deal with digitized data. Unfortunately, the SEM method has also inconveniences. The most important are as follows.

1) The exact SEM formulation is possible only in the case of problems, where the exact wave solution of the governing equations is known. It means that the practical use of this method is limited to the structures characterized by simple geometry. In the other case, the technique base on the approximate spectral element modeling can be adopted. It is worth stressed that approximate SE models may still provide very accurate results.

2) The SEM method is formulated in the frequency domain and it cannot be applied in non-linear, time-variable systems, where the principle of superposition is not satisfied.
3) In practice, the time-domain solution from the SEM is obtained by applying the Inverse Fast Fourier Transform. This process causes that the solution in the time domain is not free form errors, like aliasing or leakage.

In 1941 Kolousek [35] developed the dynamic stiffness matrix for Euler-Bernoulli Beam. This is probably the first paper on this topic. Next, the dynamic stiffness matrices for a bar and beam element in terms of frequency-dependent mass and stiffness matrices were formulated by Przemieniecki [51]. For last decades, a number of the element stiffness matrices were developed. The authors, as well as the literature, can be found, for example, in [36]. For the first time, the SEM method was used by Doyle [15] in order to simulate wave propagation in a structure. Here it is worth noting that the SEM is relatively new. In Poland, this method is mainly developed by Ostachowicz [49] and his coworkers in order to detect the damage in composite structures.

Let us assume that the governing differential equation, which describes the structural member subjected to forced vibration, can be expressed in the following general form [37]:

$$Lu\,(x,t) + M\ddot{u}(x,t) = p(x,t), \tag{3}$$

where $L$ is a linear homogeneous differential operator matrix in time and space, $M$ denotes inertial operator matrix, $u(x,\ t)$ is the unknown displacement vector of the structural member and $p(x,\ t)$ describes the force vector. The dots (.) denote the derivatives with respect to time. Next, the external forces $p(x,\ t)$ as well as the unknown displacement $u(x,\ t)$ are represented in the spectral form, namely:

$$p\,(x,t) = \frac{1}{N}\sum_{n=0}^{N-1} P_n\,(x,\omega_n)\,e^{i\omega_n t}, \quad u\,(x,t) = \frac{1}{N}\sum_{n=0}^{N-1} U_n\,(x,\omega_n)\,e^{i\omega_n t} \tag{4}$$

where i is the imaginary unit $\mathrm{i}^2 = -1$, $P_n(x,\ \omega_n)$ and $U_n(x,\ \omega_n)$ are the spectral components or Fourier coefficient. Next, assuming that $P_n$ and $U_n$ satisfy Eq. (3) at each discrete frequency $\omega_n$, the above expressions are substituted into Eq. (3) and finally the $N$ governing differential equation in frequency domain can be obtained as follows:

$$\alpha U_n\,(x,\omega_n) - \omega_n^2 M U_n\,(x,\omega_n) = P_n\,(x,\omega_n)\,, \tag{5}$$

where $\alpha$ is the linear differential operator matrix in space only. The frequency dependent shape functions, which are used to formulate the spectral element matrix, are obtained from homogeneous Eq. (5), where the $P_n$ is omitted, namely:

$$\alpha U_n(x,\omega_n) - \omega_n^2 M U_n(x,\omega_n) = 0. \tag{6}$$

The general solution to the above differential equation is:

$$U_n(x) = ce^{-ikx}, \tag{7}$$

where $c$ is a constant vector and $k$ is a wave number. Further, substituting Eq. (7) into Eq (6) leads to the eigenvalue problem, namely $A(k, \omega)c = 0$. The condition for the existence of the nontrivial solution of $c$ is that $\det A(k, \omega) =$ $= 0$. In the next steps, the wave numbers $k_i$ and the associated eigenvectors $c_i$ are computed. Finally, after several further substitutions and transformations, taking under consideration the vector of the external forces $P_n(x, \omega_n)$ and the boundary conditions, the following relationship is obtained:

$$f_c = S(\omega)\,d, \tag{8}$$

where $f_c$ is the concentrated load vector specified at two end nodes of the element, $d$ is the vector of the DOF at two end nodes. The matrix $S(\omega)$ is the frequency-dependent exact dynamic stiffness matrix, called also the spectral element matrix. Finally, the solution of Eq. (5) obtained in the frequency domain should be transformed into the time domain with aid of the Inverse Fast Fourier Transform (IFFT).

### 4.3. Damage modeling

In order to simulate the influence of flaws on the fundamental natural frequency or on the guided wave propagation, an appropriate damage model must be developed. There are three possible approaches [18], namely: stiffness reduction method, duplicated node method and kinematics-based method. The former is based on the assumption that, in the vicinity of the damage, the mechanical properties, especially the material stiffness, will deteriorate. In the numerical model of the structure, the Young's modulus is reduced by the damage parameter $\alpha$ [0,1] ($\alpha = 1$ means intact structure, $\alpha = 0$ the material is completely damage), namely: $E' = \alpha E$. This technique is very universal and almost all kind of flaws, like fatigue cracks in isotropic as well as in composite materials, could be modeled in this way.

The second approach is mainly dedicated to the simulation of delaminations in composites or horizontal cracks in isotropic materials. In the area of crack the nodes are duplicated. This causes that the edges of the crack are able to deform independently. This idea can be easily adopted to beam, plane of solid FE model. In the Fig. 11, the concept of the discussed approach is depicted.

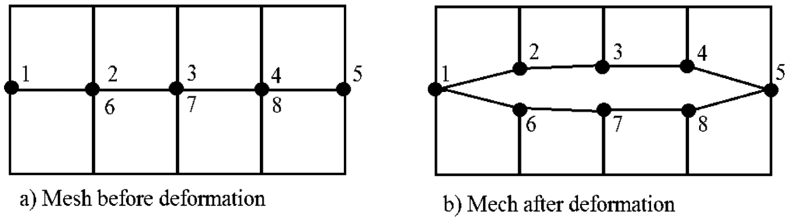

Fig. 11. The draft of the duplicated nodes technique

The nodes 2-6, 3-7 and 4-8 are coincident. In other words, the nodes 1, 2, 3, 4, 5 and 1, 6, 7, 8, 5 create the independent edges of the crack. This approach is very universal, but it has some disadvantages. The most important is that during the deformation process the nodes, which belongs to one edge can interpenetrate the opposed edge. Theoretically, there is possible creation of appropriate contact elements, but in this case the computational analysis is extremely time consuming (in the case of guided wave propagation) or even impossible (the determination of the fundamental natural frequency – modal analysis).

The latter approach is based on the analysis of the kinematics relations between the nodes in the area of flaw. In the commercially available FE package it can be defined by use of the well-known Equation Constraints [71]. However, the usage of this technique is rather limited to simple models of the structure like, for example, beam models.

## 5. Examples of Practical Applications

Structural health monitoring techniques have many applications in different real structures, such as aerospace, civil and other. Two different general types of SHM are currently being developed – passive and active SHM [34]. The passive SHM method (e.g. AE) can be used for real-time monitoring of a structure. In this method, the waves caused by degradation of the material are sensed and analyzed. On the other hand, the active SHM methods are mainly used for damage prognostics and diagnostics of structural elements.

Applications of active and passive SMH techniques for monitoring and damage localization of real-life structures can be found in many civil engineering structures, such as nuclear power plant [47], wind turbine blade (the analysis of the 9 meter and 160.5 kg TX-100 glass-epoxy and carbon-epoxy is performed by Rumsey et al. [57]), bridges, for example the "Concerto Bridge" in Brunswick [21]. In this case, the wireless sensing technique, based at AE and consisting of signal detection, denoising, localization, etc., is used for real-time bridge monitoring. Other examples of real-time online health monitoring of bridges (Horsetail Falls Bridge in Oregon [58], Beddington Trail

Bridge in Canada [41], the longest suspension bridge in the world – Tsing Ma Bridge in China [10], The West Mill Bridge [16]) and civil structures, can be found in Ref. [38, 70].

The SHM methods are commonly used in aerospace applications [61], for example: AE monitoring system in F-111 [9], detection of damaging impacts and debonding between stiffeners and composite skins of composite aircraft wingbox (which are the major causes of in-service damage of aircraft) using active and passive SHM [20] or a composite wing structure monitoring with the use of fiber Bragg grating sensors [68]. Other applications of SHM with the use of fiber Bragg gratings sensors (for beams, reinforcing bars, reinforced concrete beams, concrete piles, offshore platform, cross-ply CFRP) are described with references in the papers [4, 43]. Many other examples of SHM applications in real structures (aerospace industry, civil infrastructure – bridges and buildings, beams, composites, pipeline systems using Lamb wave and others), non-mentioned above, are described in Ref. [60].

## 6. Summary

In the presented paper, the most important problems connected with the SHM technique are discussed. In the first part, frequently used actuators and sensors as well as their physical and mechanical properties are presented. Next, the use of the computational methods, like FEM and SFEM in the SHM simulations is shown. In the next part, the influence of a damage on mechanical properties of the structure, like natural frequency and guided wave propagation, is discussed. Finally, several applications of the SHM technique in real structures are briefly mentioned.

It should be stressed here that nowadays the SHM techniques are the ones of the most dynamically developing field of the engineering science. This research has an interdisciplinary character and joins the knowledge about the modern materials, advanced computer simulations of the structure dynamic response and mathematical theory. The benefits, which can be achieved by the use of SHM in the real machines and structures, are very promising.

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## Zastosowanie badań nieniszczących (SHM) w projektowaniu i eksploatacji maszyn

### Streszczenie

Obecnie prezentowana praca poświęcona jest zagadnieniom związanym z szeroko rozumianym pojęciem badań nieniszczących. Dotyczy to przede wszystkim metod opartych na analizie drgań jak również propagacji fal sprężystych w elementach konstrukcji maszyn. Pierwsza część pracy zawiera przegląd najczęściej wykorzystywanych typów wzbudników oraz czujników, a mianowicie przetworników piezoelektrycznych, włókien optycznych. Przegląd ten uzupełniono opisem zaawansowanej technologii pomiaru drgań przy wykorzystaniu technik laserowych. Zebrane w ten sposób dane muszą być następnie odpowiednio przetworzone tak, aby uzyskać informacje na temat występowania uszkodzeń, ich lokalizacji i rozmiaru. W tym celu niezbędne jest przygotowanie odpowiednich modeli teoretycznych opartych na technologii Metody Elementów Skończonych lub Elementów Spektralnych. Ponadto, należy również opracować i przetestować komputerowe modele uszkodzeń w materiałach izotropowych jak również kompozytowych. Istnienie uszkodzenia w materiale powodować może zmianę wartości częstotliwości drgań własnych oraz odpowiadających im form drgań, impedancji mechanicznej jak również zakłócenia w rozchodzeniu się fal sprężystych. Przypadki te omówiono szczegółowo w niniejszej pracy. Przegląd ten uzupełniono wybranymi przykładami praktycznego zastosowania powyższych technik kontroli stanu konstrukcji.