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COMPOSITE AEROSPACE STRUCTURE MONITORING WITH USE OF INTEGRATED SENSORS

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Abstract

One major challenge confronting the aerospace industry today is to develop a reliable and universal Structural Health Monitoring (SHM) system allowing for direct aircraft inspections and maintenance costs reduction. SHM based on guided Lamb waves is an approach capable of addressing this issue and satisfying all the associated requirements. This paper presents an approach to monitoring damage growth in composite aerospace structures and early damage detection. The main component of the system is a piezoelectric transducers (PZT) network integrated with composites. This work describes sensors' integration with the structure. In particular, some issues concerning the mathematical algorithms giving information about damage from the impact damage presence and its growth are discussed.

Keywords: structural health monitoring, PZT sensor network, barely visible impact damage.

INTRODUCTION

One basic technical challenge of our time is to enhance safety while keeping the cost of operating machines and the civil infrastructure to the minimum. This is especially important in the case of transportation, especially in the aerospace industry, but also in many other industries, e.g. in the energy sector, where the loss of structural integrity can cause severe injuries or death of many people or high material losses.

Currently, in order to prevent the development of damage to the critical level, especially in the case of aircraft or critical infrastructure in the power, petrochemical or mining industries, various non-destructive testing (NDT) methods are used. Besides methods based on visual assessment of the surface of the inspected structure, e.g. with use of liquid penetrants or magnetic powders indicating surface discontinuities, the most commonly used NDT techniques include ultrasonic testing (UT), eddy current testing (ET) and thermographic testing (TT). UT and TT methods can be used in particular for the detection and evaluation of subsurface damage, e.g. debonding and delamination of composite structures.

Non-destructive inspections are crucial for the current system to ensure the safety and reliability of aircraft and industrial infrastructure [1,2]. However, their use is associated with some limitations, e.g. the inspected object needs to be removed from service for the time of the inspection. Furthermore, most advanced NDT methods are time-consuming, which significantly contributes to operational costs, especially as regards the inspection of components of complex geometry or hard-to-access hot-spots. In some cases, their use may pose a health hazard to operators performing the inspection, e.g. during inspections of wind turbine blades and other power or petrochemical infrastructure.

In order to reduce operating costs while increasing safety, extensive research has been carried out worldwide on the development of Structural Health Monitoring (SHM) systems. SHM systems are supposed to work autonomously and provide continuous assessment of structural integrity. For SHM, a variety of sensors and measurement methods have been applied so far [1,2]. Changing the philosophy – from periodic NDT inspections to continuous structural integrity monitoring – would greatly improve safety, especially with regard to hardly-accessible critical hot-spots or elements subjected to high loads or operated in aggressive environment. Ultimately, SHM systems would become components of the Health and Usage Monitoring Systems (HUMS) capable of assessing residual life of the structure, taking into account its individual operating conditions, e.g. loads spectrum of the wind turbine blades and structural components of aircraft, as well as their current condition. This could reduce the number of unscheduled inspections and overhauls and lead, in consequence, to decreasing the maintenance costs.

PZT TRANSDUCERS

One approach to SHM is based on the elastic waves actuation by PZT piezoelectric transducers. The piezoelectric effect causes changes to the electric potential on the surfaces of materials having appropriate properties due to their deformation [3-5]. The reverse phenomenon causes strain of a piezoelectric material in response to the applied voltage. Both effects are due to the presence of co-oriented ferroelectric domains occurring in crystals of an appropriate structure. Examples of such crystals are perovskites, which are commonly used in the form of ceramics [3-5]. The most commonly used are simple perovskites, e.g. barium titanate – BaTiO3, lead titanate - PbTiO3 and complex, lead zirconate titanate PZT - Pb(Zr,Ti)O3 [2-5] used for manufacturing active elements of acoustic, sonar and ultrasound devices. Fig. 1 shows the shape of an elementary cell of PZT ceramics below the Curie temperature, when it remains in the ferroelectric state. The PZT transducer has the non zero electric dipole moment **p**. Application of the electric field to a transducer polarized in this way causes its extension or contraction when the applied field is parallel to **p** (Fig. 1).

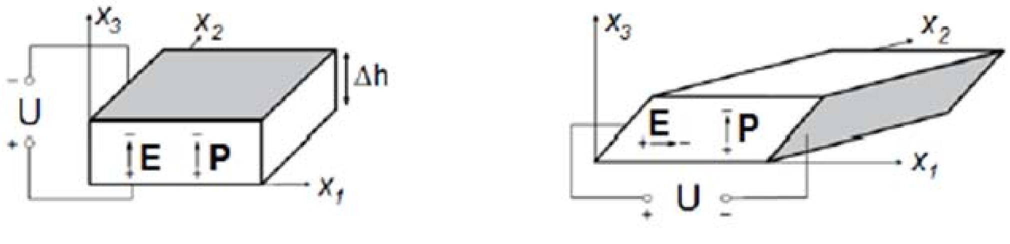

Figure 1. Modes of deformation of the PZT transducer

Applying the electric field perpendicularly to **p** will cause shear stresses. Therefore it is possible to actuate different types of elastic waves: longitudinal, shear, Lamb or SH waves in a structure to which PZT transducers are coupled [1].

The advantages of PZT ceramics are the following: simple technology and low costs of their manufacturing, and easy machining making it possible to obtain transducers of different shapes. Besides single layer transducers also multilayered ones can be manufactured, by joining many layers of PZT ceramics with electrodes. This permits obtaining a higher range of attainable displacements. SHM systems also use Interdigital Transducers – IDT [2], which allow for directional actuation of elastic waves. Their additional advantage is the possibility to adjust the length of the wave, which enables detection of damage of a given type. PZT ceramics are also mixed with epoxy resins, for the production of Macro Fibre Composite MFC – transducers [2], characterized by high elasticity. Also, highly integrated sensor patches are manufactured in this way, e.g. SMART Layer® [2], which are ready to be integrated directly with the structure. Yet another way to obtain elastic piezoelectric transducers is to use polymer transducers, e.g. polyvinylidene PVDF [6,9], which additionally has very small thickness. The inertia of piezoelectric transducers is low, thus they are used in SHM systems as actuators and sensors of elastic waves of high frequencies, sensors of vibrations, strain gauges in fast processes, and accelerometers [1,2].

Structural damage, irrespective of its type, causes local changes of material properties affecting elastic waves propagating through the damaged area [1,2]. Therefore PZT transducers can be widely applied in SHM. Applications of piezoelectrics in SHM systems include passive monitoring techniques, where they are used only as receivers of elastic waves actuated by an event leading to damage (e.g. impacts) or the waves caused by the energy released from the developing damage – Acoustic Emission (AE). PZT networks can be used also as active elements – actuating elastic waves in monitored elements [2].

One common approach to developing SHM systems is to use active networks of PZT transducers for pulse actuation of elastic waves and their sensing at given points of the structure [1,2]. This method is a direct analog of UT, thus one of its advantages is a broad spectrum of its applications. The difference is in the type of waves being actuated and in the network's being stationary. In the *pulse-echo* UT method, short bursts of longitudinal waves at high frequencies are used, which allows for inspection of an element through its thickness. PZT transducers are permanently bonded with the structure, therefore the time of signal acquisition is much longer, to allow the elastic waves to be acquired from a broad area around the receiver, including the waves scattered on damage (Fig. 2) [1,2].

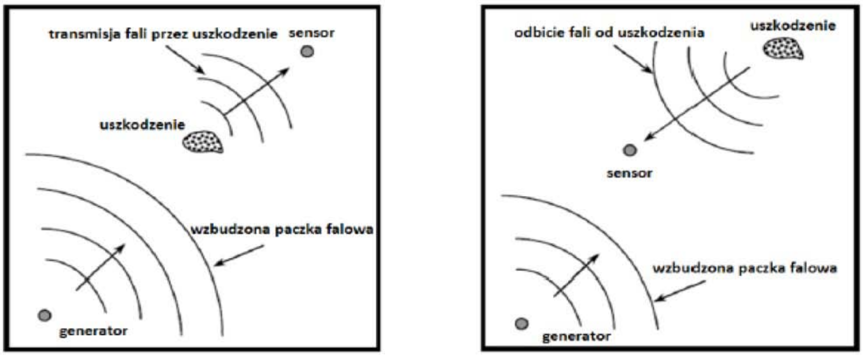

Figure 2. Interaction of elastic waves actuated by PZT transducers with damage

If the thickness of a monitored element is negligible with respect to dimensions of a PZT network, then SH (Shear Horizontal) or Lamb modes of elastic waves are excited due to the actuated wave's multiple reflections from the surfaces of the element [1]. For a given frequency of the excitation, there can exist multiple wave modes having different speeds of propagation, which makes the analysis of the acquired signals more difficult. Furthermore, if the structure contains multiple sources of wave scattering, e.g. rivet joints, the signal is even more complicated, which makes it very hard to assess the state of the structure based only on a signal obtained at a given time. Therefore, for the structure assessment, comparative analysis of currently obtained signals with respect to their corresponding reference signals, i.e. the baselines, is performed (Fig. 3).

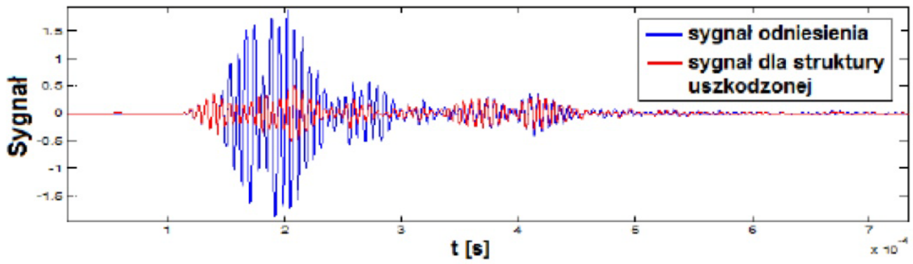

Figure 3. Examples of the signal acquired for a pair of transducers for two different states of the structure (blue – the baseline, red – current signal)

Usually, the signals are compared in terms of their numerical characteristics, i.e. Damage Indices (DIs) [2]. Damage Indices are usually defined in such a way that their values close to zero indicate that there are no significant changes of the signal while DIs values exceeding a given threshold indicate damage. The health of the structure within the range of a given PZT network is finally assessed based on DIs values obtained for all sensing paths of the network, i.e. pairs of PZT transducers (Fig. 2).

BVID DETECTION CAPABILITIES

Let f_{gs}^{env}, $f_{gs,b}^{env}$ denote respectively the envelopes of the signal and its baseline, i.e. the reference signal obtained for the initial state of the structure, acquired on a given sensing path formed by a generator *g* and a sensor *s*. Then Damage Indices considered in the paper are given as follows:

$$DI_1(g,s) = 1 - r_{f_{gs}^{env} f_{gs,b}^{env}} \quad , \quad DI_2(g,s) = \left| \frac{\int (f_{gs}^{env} - f_{gs,b}^{env})^2 dt}{\int (f_{gs,b}^{env})^2 dt} \right| \tag{1}$$

where r_{xy} stands for the sample correlation of series x, y. Structure discontinuities caused by impact damages can alter the received signals, which is captured by the proposed Damage Indices.

In order to indicate the abnormal state of the structure, instead of fixing the threshold levels for the Damage Indices individually for each of the network's sensing paths, one can consider the Averaged Damage Indices:

$$ADI = \frac{1}{N(N-1)} \sum_{\substack{g,s: \\ g \neq s}} DI(g,s) \tag{2}$$

where *N* is the number of transducers in the network merging the information from all of the network sensing paths.

In order to compare the PZT networks' capabilities to detect BVID for different frequencies of the excitation, a GFRP (Glass Fiber Reinforced Plastic) specimen was prepared along with a PZT network containing 8 transducers (Fig. 4). The numbers of the transducers on each network are indicated in red. Below, a brief overview of the networks used is presented.

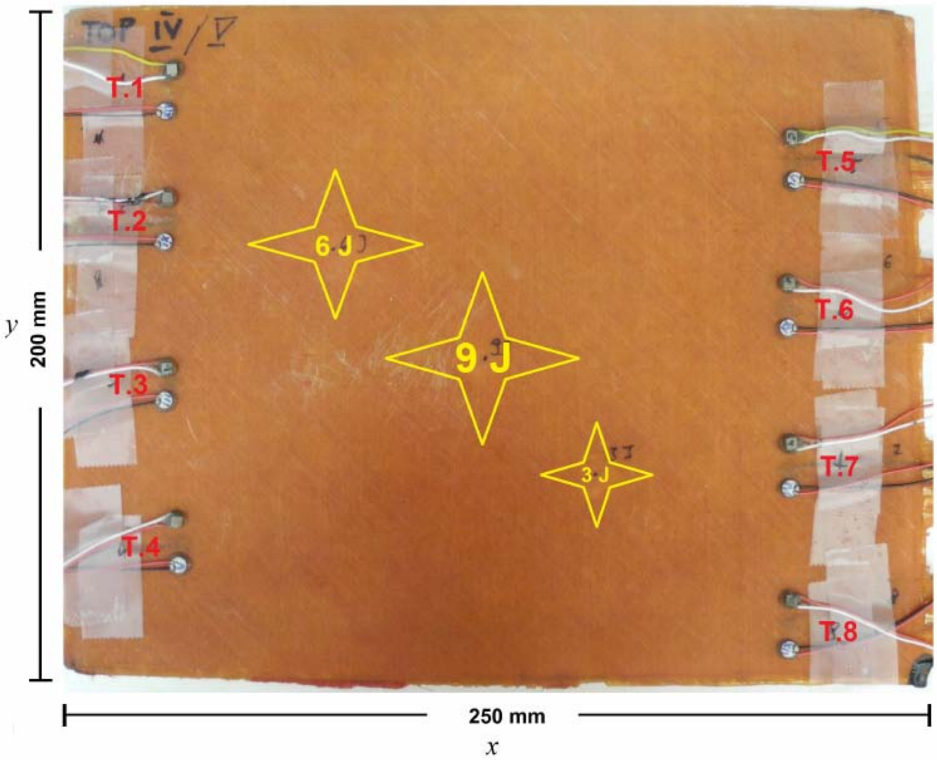

Figure 4. A GFRP specimen containing PZT transducers with introduced impact damages **[6]**

- transducer type: PZT multilayered plate actuators made by NOLIACA/S;
- manufacturing code: NAC2002;
- transducer geometry: edge length: 3mm, thickness: 2mm;
- integration type: surface attached.

In the experiment, three subsequent impacts were performed with the energies of 9J, 6J and 3J correspondingly at the locations shown in Fig 5. Impacts were performed by dropping an axially symmetric impactor from the height levels corresponding to the assumed energies. This caused BVID damages of the specimen, the sizes of which, measured by ultrasonic inspection, were dependent on the impact energies.

Before the experiment and after each impact a series of measurements were performed for each of the deployed PZT networks. The signal was collected in six repetitions and the last measurement in each group of data was conducted just before the impact occured. This signal was taken as the baseline, i.e. the reference signal, for each of the subsequent series. The first measurement of a new series was conducted immediately after the impact, thus minimizing the possible influence of any other factors on the obtained results. The following parameters of the excitation were used:

- excitation frequency [kHz]: 100, 150, 200, 250, 300, 350;
- duration: 8 periods;
- window type: Hanning

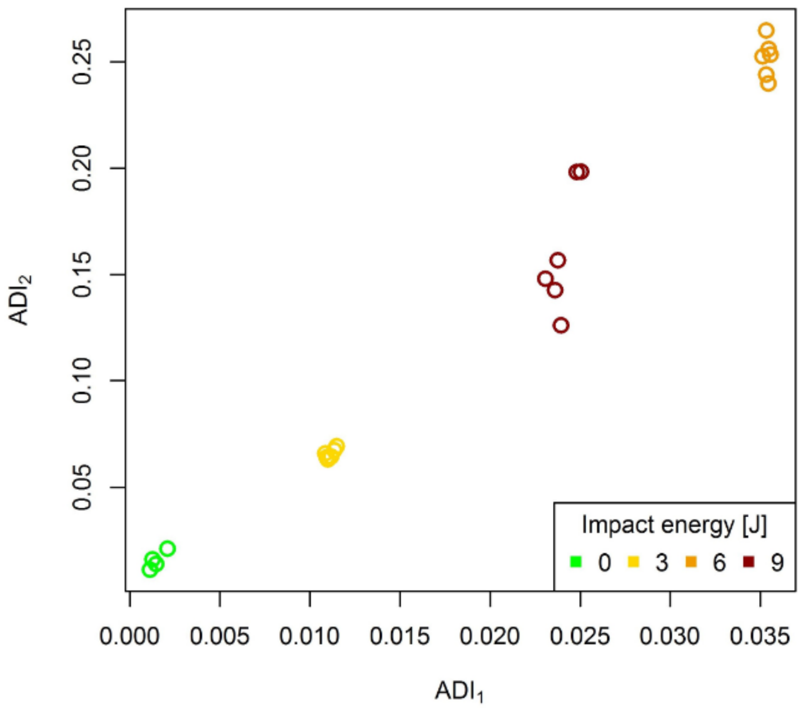

Figure 5. Averaged Damage Indices obtained for different BVID **[6]**

Data corresponding to different BVID are well separated from the base state of the structure as well as from each other. ADIs values depend both on the damage size and on its location within the network as seen from ADIs plots. The 6J impact damage is located near the transducers, therefore ADIs obtained for that BVID are the highest.

SUMMARY

Introducing Structural Health Monitoring systems to future aircraft structural life management programs seems to be inevitable. In the article, an approach to structure monitoring based on PZT sensor network and its application to detect BVID of composite structures was presented. The technique allows for the detection and differentiation between BVID caused by impacts of different energies.

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