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DAMAGE DETECTION AND LOCALIZATION WITH USE OF PZT SENSORS AND TRANSFER IMPEDANCE APPROACH

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Abstract

One of the ideas for structural health monitoring (SHM) systems built is based on analysis of small displacements propagation excited in the element by a network of PZT piezoelectric actuators. Structural damages can result in observable changes of the signal generated by the network sensors, due to elastic wave interaction with damage. There are two approaches how to utilize PZT sensors for SHM purposes. One of the approaches follows closely classical ultrasonic testing. In that case, short pulse excitation of PZT transducers is used, thus guided wave packets can be scattered on different elements of structure, eventually also on the damage. In the different approach, the so-called electromechanical impedance (EMI) method, harmonic excitation of PZT is used, thus steady elastic waves are excited in the structure. As in guided waves approach, the signal can be gather in the pulse echo scheme, i.e. when single transducer is used both as a actuator and the receiver of waves, as well in the pitch – catch scheme, when a pair of transducers, the generator and the sensor, are used. For the latter EMI approach, the term Transfer Impedance Approach is sometimes used. In the article, an approach for damage detection and localization with use of network of PZT sensors excited with harmonic signals in broad frequency spectrum is presented. In particular, some signal characteristics – called Damage Indices (DI's) used for structure assessment are proposed and their properties are discussed. The DI's have the property to assess the location a damage with respect to a single sensing path, formed by a pair of transducers, i.e. the generator and the receiver. Finally, the RAPID algorithm for damage localization with use of the information from all of the network sensing paths is applied.

Keywords: *damage detection, electromechanical impedance method, Damage Index, damage localization*

1. Introduction

In the aviation, there are two main factors determining the cutting edge of the technology development. These are the safety or the cost – effect improvements. It was estimated [1] that about 10% of total aircraft maintenance costs are due to non-destructive inspections (NDI) of the aircraft structure. The most expensive are non-scheduled NDI, since these are related also with the indirect costs of logistic operations, e.g. related to the maintenance of the fleet readiness or availability of the workforce. According to [2], the fraction of such inspections is significant (Fig. 1). In addition, the increased use of autonomous Unmanned Aerial Vehicles (UAVs) can be observed, especially in the air forces. These are intended to be used as disposable means, but also for extremely long endurance mission, when classical approach to NDI would be difficult to be applied. It is supposed that the target number of UAVs in use will greatly exceed the number of classical aircrafts, even considering only large UAVs designed to be used for long-term service. The costs of NDI in that case may fall beyond the accepted level, therefore a new paradigm of such fleet maintenance needs to be developed.

2. Structural Health Monitoring with use of PZT piezoelectric transducers

As the response to the abovementioned challenges of modern aerospace industry, the so-called Structural Health Monitoring (SHM) systems capable continuously to assess the structural integrity are being developed. SHM systems are based on network of sensors permanently deployed in the aircraft structure. Different approaches to SHM are followed, some utilizing techniques of classical NDT such as ultrasonic or eddy current methods, the other based on branch of newly designed sensors, e.g. vacuum or resistance crack gauges.

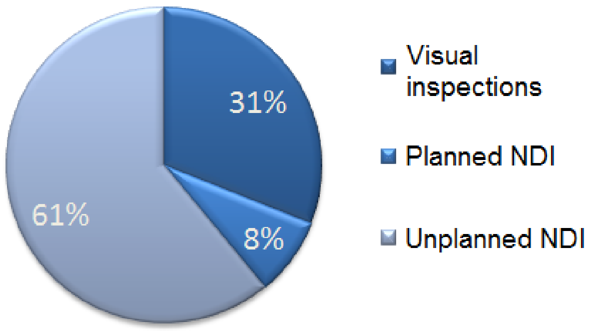

Fig. 1. The percentage structure of non-destructive inspections

One of the approaches to SHM of composite structures is to use networks of PZT transducers capable to actuate and receive elastic waves in a monitored element [3-6]. This approach is complementary to classical ultrasonic testing (UT) thus it derives all of its advantages, mainly the robustness and universality of the application, the main difference is the type of waves which are used for structure assessment. In the classical UT, usually very short pulse excitations are used, which allows to examine the structure across its thickness. The UT transducer is moved around the surface of the specimen and in this way; different kind of damage can be mapped and measured with high precision. In the case of SHM, the transducers position is fixed; therefore, it is required to apply significantly longer acquisition times in order to collect the wave reflections from all of the elements, eventually damages, within the range of network of sensors. In that case Lamb waves are formed, for which numerous different modes can exist for a given frequency of the excitation. This makes the signal analysis significantly harder; therefore, structure assessment is usually based on comparison of signals obtained for its actual state with the baselines, i.e. the signals acquired for the initial condition of the structure.

Yet another method for utilizing PZT transducers in SHM systems is to use harmonic excitation in the so-called electromechanical impedance (EMI) method. An idea of the approach is presented in the scheme (Fig. 2). A transducer bonded with the structure is powered with harmonic voltage $v(t)$ with frequency ω, *which* introduces steady state of displacements field across the structure in its proximity. The solution to the local equation of motion depends on local geometry of the structure, in particular on the presence of damage near the transducer. Therefore, the current $i(t)$ in the circuit, as well as the transducer's impedance Z can change with damage presence or their growth. In EMI method, the components of impedance are measured in broad spectrum, which allows for fine-tuning of the frequency to the damage type. The EMI method was used in particular for bolt, wedge and bonded joints, fatigue cracks or impact damages of composite materials.

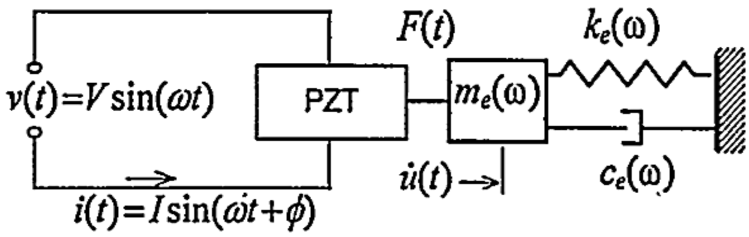

Fig. 2. Idea of electromechanical impedance method

3. Transfer Impedance Approach to SHM

In the above paragraph, the idea of EMI method used for a single PZT transducer was presented. Similar approach can be used also for pair of transducers in which one of them is exciting elastic waves and the other receives them. For such approach, the term Transfer Impedance Method/Approach is usually used [4]. According to Linear Time Invariant (LTI) systems theory, when the generator is excited with harmonic excitation U_{in} with frequency ω the voltage U_{out} on the receiver should also be harmonic with the same frequency but with different amplitude and phase shifted to U_{in} (Fig. 3), i.e. the ratio:

$$T(\omega)=\frac{U_{out}(\omega)}{U_{in}(\omega)}=\frac{|U_{out}|e^{i\omega t+\varphi(\omega)}}{|U_{in}|e^{i\omega t}}=\frac{|U_{out}|}{|U_{in}|}e^{i\varphi(\omega)}=|T(\omega)|e^{i\varphi(\omega)}=\operatorname{Re}T(\omega)+i\operatorname{Im}T(\omega), \tag{1}$$

do not depend on time and can be represented as a single complex number $T(\omega)$.

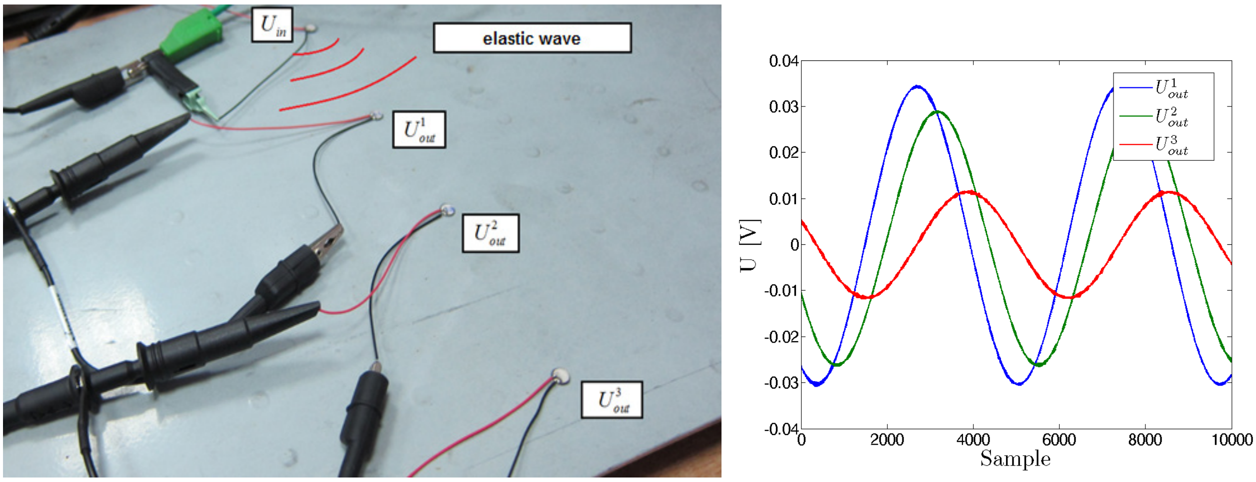

Fig. 3. An example of amplitude changes and phase shifts for a PZT network

In Fig. 4, the ratio $T(\omega)$ obtained for a chosen pair of PZT transducers (Fig. 3) is presented. This is with and without the presence of damage simulated by a mass attached to the structure between the two sensors. The mass attenuates the elastic wave propagating between the generator and the receiver, therefore the modulus of $T(\omega)$ is decreased when it is present (Fig. 4). While the information about the amplitude of U_{out} with respect to the amplitude of U_{in} can be extracted from such data visualization, the information about the phase shift is lost. In addition, for real damage its influence on the modulus of $T(\omega)$ can be much more sophisticated, therefore, such representation (Fig. 4) is of limited usability. More information can be extracted from characteristics

$$DI(\omega)=\frac{T(\omega)}{T_0(\omega)}=\frac{U_{out}(\omega)}{U_{out,0}(\omega)}e^{i(\varphi(\omega)-\varphi_0(\omega))}, \tag{2}$$

being the quotient of the ratio $T(\omega)$ obtained for a given state of the structure with its corresponding baseline $T_0(\omega)$, i.e. T for the initial state of the structure. Such signal characteristics utilizing the notion of baselines, are usually called Damage Indices (DIs). The same data as in Fig. 4, but now in terms of $DI(\omega)$ are presented in Fig. 5. On this plot both, the amplitude change as well as the phase shift caused by simulated damage introduction is well represented.

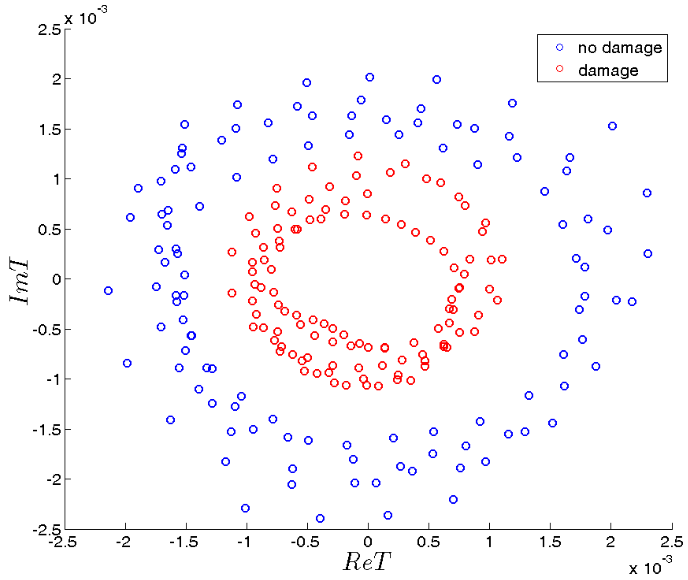

Fig. 4. The ratio $T(\omega)$ for the pristine state of the structure and with damage present

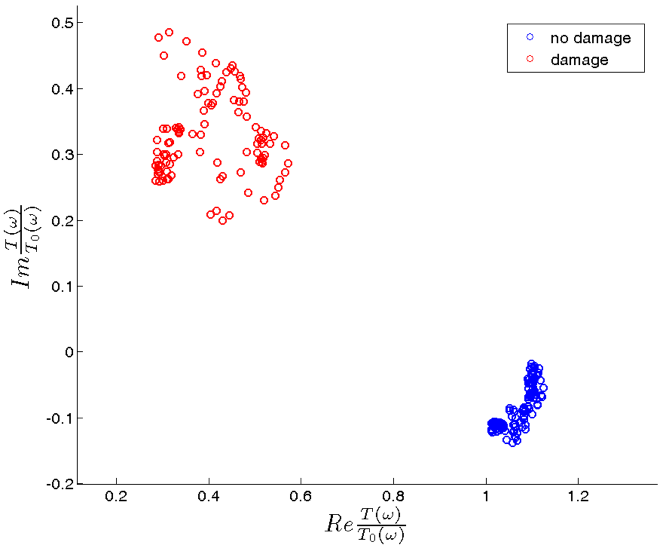

Fig. 5. The quotient $T(\omega)/T_0(\omega)$ for the pristine state of the structure and with damage present

4. Damage localization with use of TIA and RAPID algorithm

Assuming there is a network of PZT transducers deployed in the structure, Damage Indices can be used not only for the purpose of qualitative indication, whether there is a damage within the network or not, but also for estimation of its localization. One of the algorithms, which were originally developed for the short excitations of PZT, is the RAPID imaging algorithm [7, 8].

Due to the energy conservation principle, elastic waves scattered on local damage of a structure are vanishing with the distance from it. Thus, eventual contributions to signal due to damage presence are the most visible for sensing paths running close to a damage. Therefore, in order to visualize it one can introduce partial intensity map of the form:

$$I = \sum_{g-s} DI(g,s) R_{gs} , \qquad (3)$$

where the summation runs over all pairs of PZT transducers, i.e. generators and sensors, $DI(g,s)$

is Damage Index obtained for a given pair and R_{gs} is a function representing the effective range of the given pair of PZTs, i.e. the area in which damage presence should have impact on the $DI(g,s)$ values. An example of such representation is presented in Fig. 6.

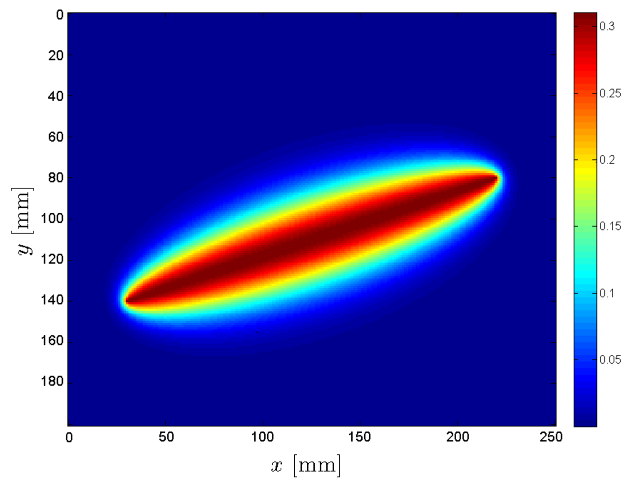

Fig 6. An example of the effective range R_{gs} of a pair of PZT transducers

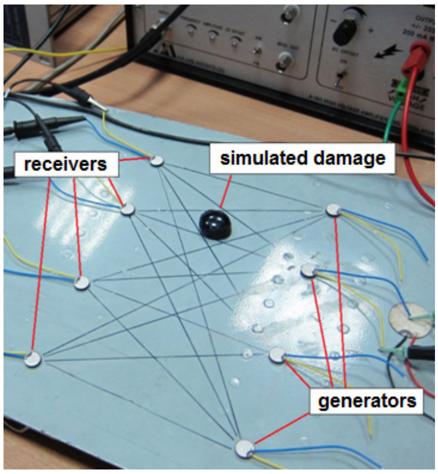

Fig. 7. The PZT network used for the experiment

The RAPID algorithm (3) was used in TIA approach. On a specimen of PZL-130 Orlik structure a network of 8 PZT transducers was deployed in the form of two parallel lines consisted of 4 PZT each (Fig. 7). The sensors from one line were used as generators of elastic waves, the other were the receivers. The following form of the function R_{gs} was adopted:

$$R_{gs}(p) = \left(\frac{l_{gs}}{l_{gp} + l_{sp}} \right)^{\alpha}, \qquad \alpha = 40, \tag{4}$$

where p denotes a given point within the structure, l_{gs} is the distance between the generator g and the receiver s of a given pair of PZTs and l_{gp}, l_{sp} denote the distance between the point p and the generator g or the receiver s respectively. As the Damage Index in (3), the quotient of $T(\omega)/T_0(\omega)$ for a given frequency ω was taken. As simulated damage, a mass element attached at a given point of the structure was used.

In Fig. 8, the results of damage localization using the RAPID approach for two different damage location are presented. In both cases, the value of the intensity map (3) is the highest in the vicinity of true damage location. The resolution of such approach is determined by the geometry of the network used. For the presented case it is rather poor along the x axis since there are no pairs of PZT transducers which could better approximate the damage location in that direction (Fig. 7). For circular network topology, the result could be more accurate however; the presented topology can be the preferred one in some cases [9].

5. Summary

In the article, an approach to damage location based on network of active PZT transducers was presented. The approach is based on TIA method to SHM and RAPID imaging algorithm. For the purpose of damage detection, a Damage Index was proposed. The index was utilized in the RAPID method in order to obtain maps indicating possible location of damage within the network. The method was tested with a network of PZT transducers formed by two parallel lines consisting of 4 PZTs each. The resolution of the imaging algorithm was good in the direction along which PZTs were deployed, but poor in the perpendicular one. The improvement of the obtained result might be achieved by using the networks of PZT transducers of circular topology.

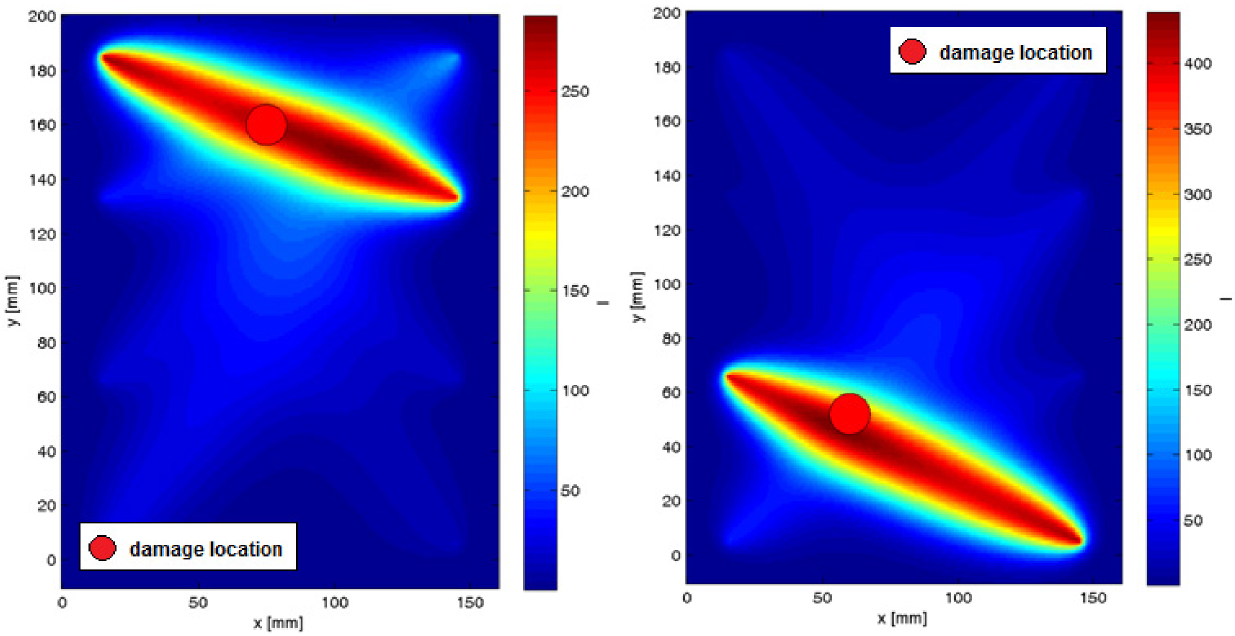

Fig. 8. Results of damage localization with RAPID algorithm and TIA method

References

[1] Cros, G., *FY2013 Maintenance Cost, Preliminary Analysis*, IATA 10th Maintenance Cost Conference, Athens 2014.
[2] Staszewski, W., Boller, C., Tomlinson, G. R., *Health monitoring of aerospace structures: smart sensor technologies and signal processing*. John Wiley & Sons, 2004.
[3] Staszewski, W., Boller, C., Tomlinson, G. R., *Health monitoring of aerospace structures: smart sensor technologies and signal processing*, John Wiley & Sons, 2004.
[4] Giurgiutiu, V., *Structural health monitoring: with piezoelectric wafer active sensors – 2nd ed.*, Academic Press, 2014.
[5] Stepinski, T., Uhl, T., Staszewski, W., *Advanced Structural Damage Detection: From Theory to Engineering Applications*, John Wiley & Sons, 2013.
[6] Su, Z., Ye, L., *Identification of damage using Lamb waves: from fundamentals to applications*, Springer, 2009.
[7] Zhao, X., Gao, H., Zhang, G., Ayhan, B., Yan, F., Kwan, C., Rose,J. L., *Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. Defect detection, localization and growth monitoring*. Smart materials and structures, 16(4):1208, 2007.
[8] Zhao, X., Royer, R. L., Owens, S. E., Rose, J. L., *Ultrasonic lamb wave tomography in structural health monitoring*. Smart Materials and Structures, 20(10):105002, 2011.
[9] Dziendzikowski, M., Dragan, K.,, Katunin, A., Localizing impact damage of composite structures with modified RAPID algorithm and non-circular PZT arrays. *Archives of Civil and Mechanical Engineering*, *17*(1), 178-187, 2017.