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DETECTION OF DAMAGES IN HYBRID COMPOSITE PLATES WITH THE USE OF ELASTIC WAVES GENERATED BY PZT ACTIVE SENSORS

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Abstract

The presented article is devoted to the problem of detection and localization of damages occurring in components of structures, which are made of hybrid composite materials. The subject of the work is a square plate consisting of a single layer made of aluminum alloy and several layers made of glass fibres (glass fabric) and epoxy resin. On the surface, which is made of composite, 12 piezoelectric elements are installed. These elements sequentially, one by one, generates a signal that is further recorded by the remaining piezoelectric elements. Picked up signal for the selected pair of activator – sensor is compared with the reference signal. The reference signal corresponds to the intact structure. This kind of approach is known as the pitch – catch configuration. In situations when the signal obtained for interrogated structure and reference one differs significantly, this may indicate that a damage exists between the activator and the sensor. Next, taking into account the information obtained from the other sensors, it is possible not only to detect but also to determine the approximate location of the flaw and to estimate its size. In order to visualize the obtained results, an especially dedicated software is developed according to the algorithms available in the literature – probability ellipse. Several computer simulations of wave propagation are performed using the finite element method. The proposed procedure is also tested experimentally. The presented approach makes it possible to detect both single and multiple damages.

Keywords: *elastic waves, hybrid composite plates, piezoelectric active sensors, low velocity impacts, damages, FEM*

1. Introduction

Generally, hybrid composites consist of layers, which are made of different materials. Very often one of external layers is made of steel or aluminium alloy and the other layers are made of classical fibrous composites. These materials are characterized by low weight and high stiffness and strength. However, they are very sensitive on different kind of damages, especially in the case of impacts of objects, which moves with low velocity. These events may cause, for example, matrix cracking or delamination [1, 2]. These damages are especially hard to detect because they are localized inside the composite material. Therefore, it is extremely important to develop appropriate structural health monitoring (SHM) systems in order to detect such problems on the early stage of formation. Majority of modern SHM systems are based on analysis of elastic waves propagation in the investigated structure [3, 4]. The elastic waves (input signal) are generated by one or several piezoelectric (PZT) active elements. The dynamic response of the interrogated structure can be also recorded by similar or identical PZT elements [5]. There are two possible configurations, namely pulse-echo and pitch-catch. In the first case, defects are detected and localized by analysis of the wave reflections or by estimation of group velocity of elastic wave modes [6, 7]. In the second case, the damage is detected by comparison of a reference response, which is received for the intact structure, and a response obtained for investigated structure. If these signals differ significantly, it means that there is a defect inside the material [8-10].

The current work is devoted to the problem of detection and localization of damage in plate-like structures made of hybrid composite materials. The elastic waves are excited by the PZT elements, which are in pitch-catch configuration. The damage is detected by comparing the signal obtained for intact and interrogated structure. The appropriate integral damage index (DI) is defined. The localization and (indirectly) size of a flaw is estimated with the use of probability ellipses. The idea of application of probability ellipses is described in book [11] by Su and Ye and it is utilized, for example, by De Fenza et al. [9]. Finally, it is worth noting here, that also a very similar approach is also applied by Muc and Stawiarski [12]. The mentioned work is devoted to the detection of delamination in composite cylindrical panels. However, now the possibility of detecting not single but multiply defects at the same time is studied.

2. Investigated structure and SHM procedure

The studied hybrid composite plate and its geometrical dimensions are shown in the Fig. 1. The applied material consists of one layer, which is made of aluminium alloy Pa38 with thickness $t_a = 0.5$ [mm], and 6 layers made of glass fabric and epoxy resin with approximately thickness $t_c = 1.5$ [mm]. Thus, the total thickness of the whole hybrid composite is equal to $t_c = 2$ [mm]. The assumed mechanical properties of the alloy Pa38 are as follows: $E_a = 69.5$ [GPa], $\nu = 0.33$ and $\rho = 2.7$ [g/cm³]. The quasi-isotropic properties of the layers made of glass fabric/epoxy resin were determined experimentally and they are equal to $E_c = 20.85$ [GPa], $G_c = 4.15$ [GPa], $\nu = 0.127$ and $\rho = 1.65$ [g/cm³]. The PZT sensors with dimensions 3x3x2 [mm] are installed on the external layer, which is made of glass fabric, as it is depicted in the Fig. 1. The PZT elements are distinguished by the individual number from the range 1-12. Finally, it is assumed that the damage is detected inside the frame of PZT elements, on the surface marked as "area of inspection".

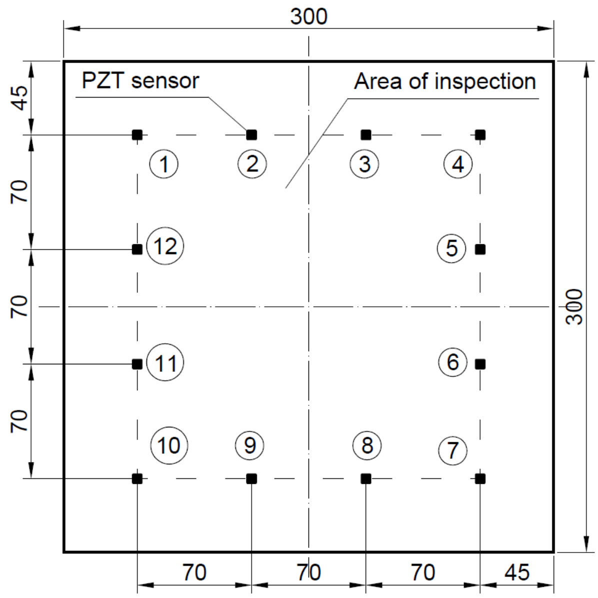

Fig. 1. Investigated hybrid composite plate with network of PZT sensors

In order to detect the damage, the following procedure is applied. Let us assume that at the very beginning we have the intact structure (without any internal or external defects), which can be considered as reference structure. On the external surface of this plate the frame of PZT sensors are installed according to the draft, which is shown in the Fig. 1. The chosen PZT element, let say that it is the sensor 1, excites the input signal. The other PZT elements register the incoming elastic waves. Next, element 2 generates the identical input signal and the all other sensors register the dynamic response. It is worth stressing here that now the sensor 1 is also considered as the receiver. This procedure is repeated for the each installed PZT element. In this way, the whole dynamic response of the reference structure is obtained. In the next step, the damage or damages are introduced in the studied structure or the different but geometrically identical structure is analysed. The described above procedure of registering the dynamic response is repeated one more again for the current structure. Now, the registered dynamic responses obtained for the reference and current structure can be compared. If the damage really exists inside the current structure, the dynamic response will be quite different. I order to define the magnitude of this differences the appropriate DI parameter has to be introduced. In the presented work, the following relationship is utilized, namely:

$$DI_{k,i} = \int_{t_0}^{t_1} \frac{\left[f(t)_{k,i} - g(t)_{k,i}\right]^2}{\left[g(t)_{k,i}\right]^2} dt, \tag{1}$$

where indices k and i denotes the index of the PZT element, which excites and receives the elastic waves, respectively. The $g(t)_{k,i}$ and $f(t)_{k,i}$ are the digital signals obtained for reference and current plate. The values t_0 and t_1 define the size of the time window, where the signals are compared. Here, it is worth noting that the values of $DI_{k,\,i}$, obtained for k, i and i, k pair of PZT elements, are not equal. Therefore, for the further computations the greater value of relationship (1) is taken into account. If the value of (1) is equal $DI_{k,i} = 0$, it means that the signals are identical and between k-th actuator and i-th sensor there is no any flaw. Due to the noise, which is present in experimentally obtained signals, a threshold value should be also introduced. In other words, if the value of (1) is less than some arbitrary value, for example $DI_{k,i} < 0.15$, so it can be assumed that there is no any damage between this pair of the PZT elements. Finally, it is worth noting that in the currently analysed case the total number of mentioned pairs is equal to $N = 42$.

In order to detect and localize the damage, the idea of probability ellipses is utilized [11]. Generally, for each pair of actuator – sensor the following formula can be evaluated in every point with space coordinates (x,y), which belongs to the surface of the studied plate, namely:

$$d_{k,i}(x,y) = DI_{k,i}\left[\frac{\beta - R\left(x,y,x_k^a,y_k^a,x_i^s,y_i^s\right)}{\beta - 1}\right], \tag{2}$$

where β is the arbitrary parameter describing the “wideness” of the probability ellipse, (x_k^a,y_k^a) are the space coordinates of the k-th actuator and (x_i^s,y_i^s) denotes the coordinates of the i-th sensor. The function R is defined as follows:

$$R\left(x,y,x_k^a,y_k^a,x_i^s,y_i^s\right) = \begin{cases} R_C\left(x,y,x_k^a,y_k^a,x_i^s,y_i^s\right), & R_C\left(x,y,x_k^a,y_k^a,x_i^s,y_i^s\right) < \beta \\ \beta, & R_C\left(x,y,x_k^a,y_k^a,x_i^s,y_i^s\right) \geq \beta \end{cases}, \tag{3}$$

$$R_C\left(x,y,x_k^a,y_k^a,x_i^s,y_i^s\right) = \frac{\sqrt{\left(x-x_k^a\right)^2 + \left(y-y_k^a\right)^2} + \sqrt{\left(x-x_i^s\right)^2 + \left(y-y_i^s\right)^2}}{\sqrt{\left(x_k^a-x_i^s\right)^2 + \left(y_k^a-y_i^s\right)^2}}. \tag{4}$$

Finally, the approximate position of the single damage can be estimated by looking for the intersection of all available probability ellipses. However, if the number of expected flaws is greater, their localizations can be estimated by summing up all these ellipses.

3. Numerical simulation of elastic wave propagation in reference and damaged plate

The computational simulations of described above SHM system are performed with the use of finite element method. The commercially available package ANSYS 13.0 is applied. Any other external procedure for signal processing and visualization of obtained results are developed with the use of free software SCILAB. It is assumed that the input signal is the $n = 5$ cycles of sine wave modulated by Hanning window with central frequency $f = 125$ [kHz] and amplitude $a = 100$ [V] (voltage applied to the PZT element, Fig. 2).

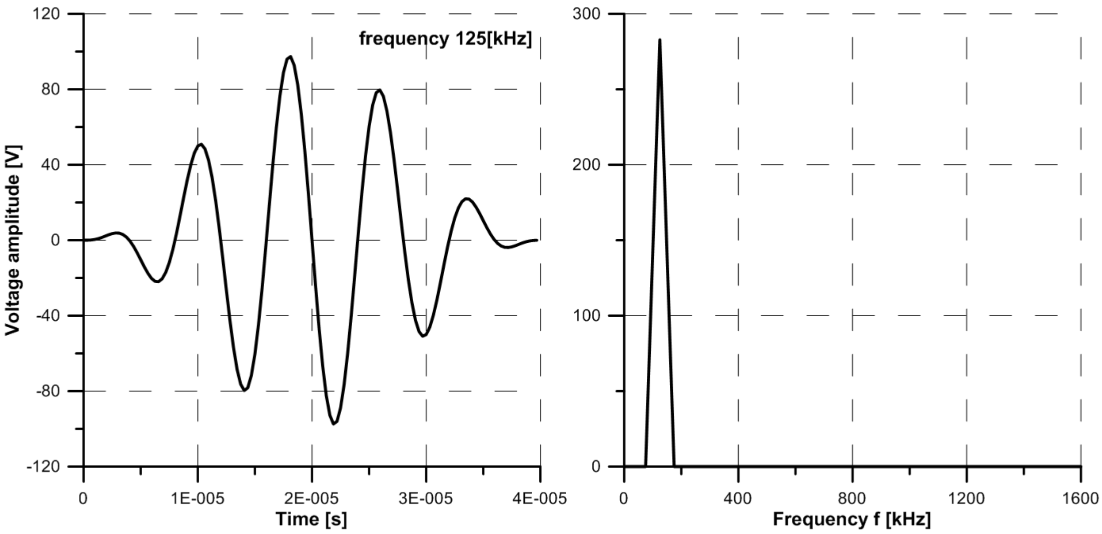

Fig. 2. Excitation signal in time and frequency domain

According to the analysis of the dispersion curves (not presented here), which have been determined for the studied hybrid composite plate, in the case of applied central frequency of the input signal, only the symmetric S0 and the anti-symmetric A0 wave modes are excited. The group velocities of these modes are equal to $c_{gS0} = 4.136$ [km/s] and $c_{gA0} = 1.627$ [km/s], respectively. It is assumed that the further analysis will be based on the A0 wave mode. In practice, this wave mode is less dispersive and it has much higher amplitude in comparison with S0 mode. Besides, the A0 wave mode stronger interacts with the potential defect. The wavelength of the A0 mode is equal to $\lambda_{A0} = c_{gA0}/f = 13.016$ [mm]. Therefore, the element size is assumed to be equal to $l_e = 2$ [mm] (more than 6 nodes per wavelength). The time step should be shorter than the time, in which the wave front travels between neighbour nodes. Thus, the time step is equal to $dt = 3.615e{-7}$ [s] and the total time of simulation is $t_c = 2.651e{-4}$ [s]. The hybrid composite plate is modelled with the use-mapped mesh, which consists of 71148 solid elements SOLID186 (20 nodes per element, 3 degrees of freedom in each node, namely 3 components of displacement, 3 elements along the thickness of the plate). The PZT sensors are also modelled with the use of mapped mesh. Each PZT sensor consists of 8 finite element SOLID226 (20 nodes per element, 4 translation degrees of freedom in each node, namely 3 components of displacement and voltage). All bottom surfaces of PZT sensors are the equipotential surfaces, where the voltage is constant in each node. On the upper surface of the PZT sensor, which is the actuator, is applied the input signal. Finally, the PZT sensors are made of PZT-5A material.

It is assumed that the objects, which move with relatively low velocity, hit in the composite surface of the studied plate. Therefore, the damage is modelled as a reduction of the stiffness of the composite material. In other words, the values of Young's, Kirchhoff's modulus and density are multiplied by some number, which is less than unity.

4. Results of finite element simulations of the SHM system

The computer simulations were performed for the reference structure and for 3 damaged structures, namely plate A, B and C. In Fig. 3 there are depicted these plates with geometrical coordinates of damages. The mechanical properties of the composite in the area of damage are as follows: $E_d = 5.2125$ [GPa], $G_d = 1.0375$ [GPa], $\nu_d = 0.127$ and density $\rho = 0.4125$ [g/cm].

Below, there are presented details of the results of the numerical simulations obtained in the case of plate A and discussed them. However, at the end of this section there are shown the final visualizations of detected damages for all studied structures. The comparison of the received signals, obtained for the intact and damaged structure (plate A) is depicted in Fig. 4. Mentioned pictures are prepared for the two exemplary pairs of the PZT elements, namely 3-11 and 3-8, where the input signal is excited by the sensor 3.

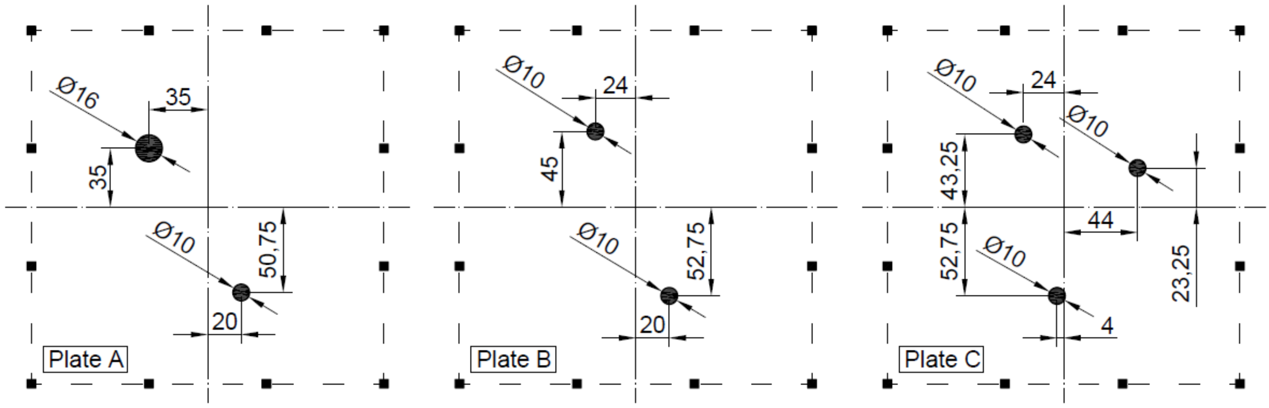

Fig. 3. Localizations of damages in studied structures

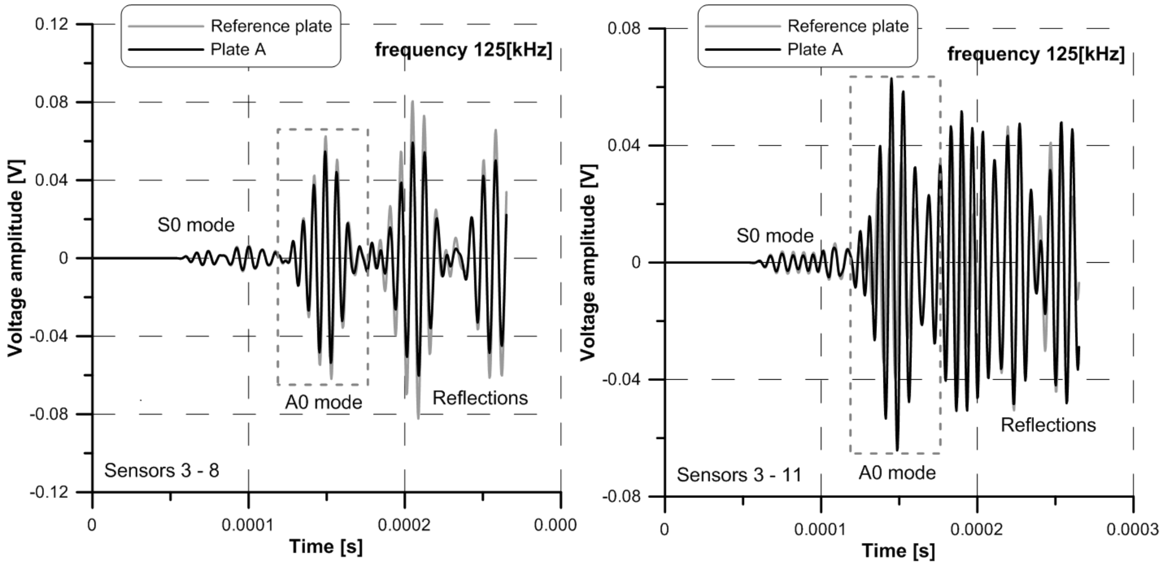

Fig. 4. Comparison of obtained signals in the case of following pair of sensors 3-8 and 3-11

In these figures there are also marked the time window, where the analysed signals are compared. The beginning value of time window is described by the following formula $t_{w0} = s_{i,k}/c_{gA0}$, where $s_{i,k}$ denotes the distance between the i, k sensors. The width of the time window is determined as $t_{w1} = t_{w0} + (n+1)/f$. The comparison of the analysed signals (A0 modes) inside the time window is shown in Fig. 5. The computed value of damage index (1) is also presented. If a damage is present between the PZT sensors, the signals, which are received in the case of intact and current structure, will be quite different. The change of amplitude as well as the shift in phase is mainly observed. However, the central frequency of the analysed signals seems to be unchanged. Moreover, as it is reported in [8], it seems that existence the damage does not affect the symmetric mode S0.

The rest of the values of damage indexes are shown in Fig. 6. It is worth noting here that the obtained value of damage index estimated for the pair of actuator-sensor 3-11 and 11-3 differs significantly. In the first case, this value is equal to $DI_{3,11} = 1.60088$ but in the second case $DI_{11,3} = 2.74523$. Thus, it is necessary to decide which of them should be taken to the further computations. It seems that the best solution is to take the greater value. Next, all 42 values of damage indexes are normalized with respect of the maximum value.

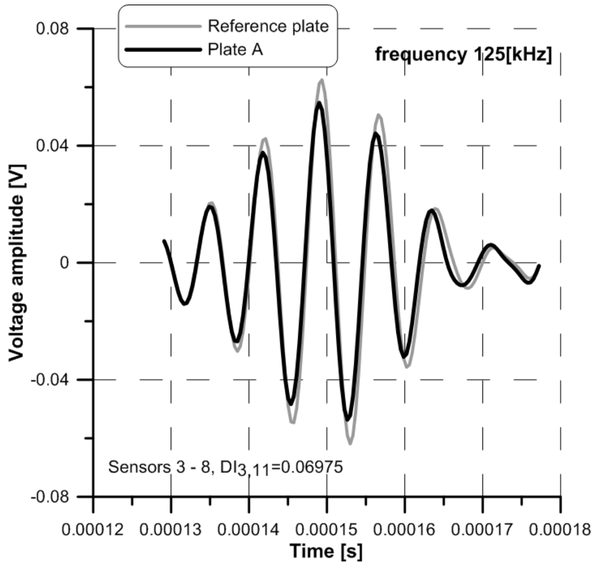

Fig. 5. Comparison of the anti-symmetric A0 modes for intact and damaged structure

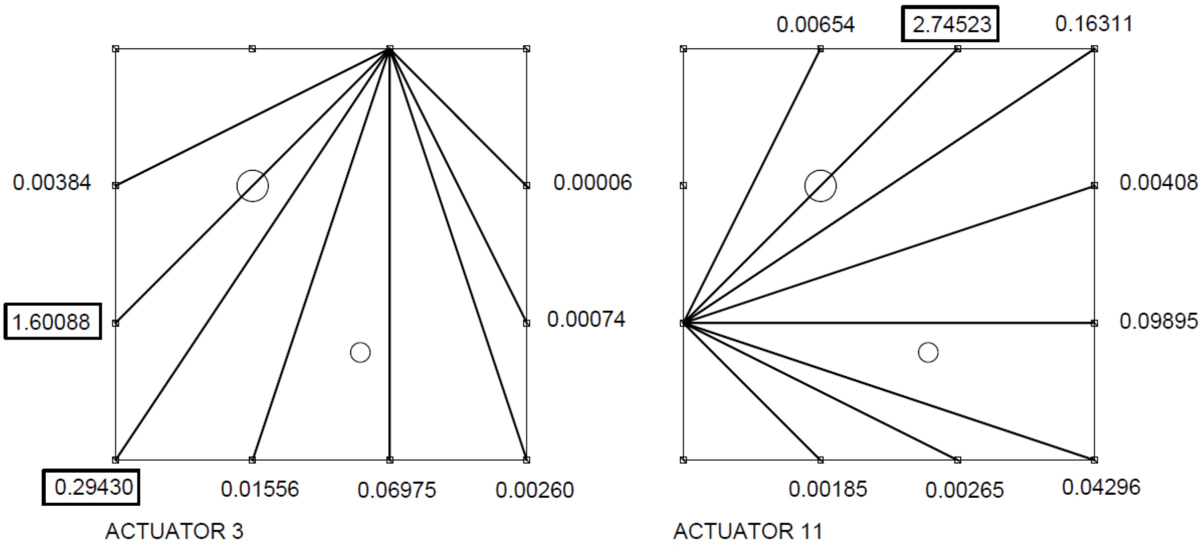

Fig. 6. Comparison of the anti-symmetric A0 modes for intact and damaged structure

In Fig. 7, there are depicted visualizations of the damages. These pictures are generated for plate A, B and C, respectively. As it is mentioned above, for detection of the flaws, the particular probability ellipses are summed up. However, only these probability ellipses are taken into account, where the value of damage index satisfies the following condition, namely: $DI_{k,i} > 0.1$. Moreover, the value of $\beta = 1.0035$ in formula (2). As it can be observed, detected damages are quite visible.

In the case of the structure A, the larger defect is clearly visible. However, for the second flaw, it can be only said that it is located between sensors 5 and 9. There are 3 possible locations of the flaw along the pair of sensors 5-9. It is worth noting that the correct location can be chosen by taking into account the additional pair of sensors 2-8. This pair does not across the location of the first damage. In the case of plate B, where the both defects have the same size, their localization is clear. It can be taken under consideration only 3 pair of sensors for determination of the positions of the defects, namely: 2-8 and 3-11 for the first flaw and 2-8 and 5-9 for the second flaw. However, in the last case (structure C), there is many pairs of sensors, for which the value of damage index is greater than assumed threshold value. Thus, identification of defects could be quite difficult. For the plate C, location of defects is rather unequivocal. They are where the bright peaks are observed. The main disadvantage of the currently presented method is that there is no way to estimate the size or the depth of damage. The width of the probability ellipses, which are shown in Fig. 7, depends on the parameter β. Its value is assumed BEFORE generation of the shown above pictures. Thus, the size of the damages presented in Fig. 7 would be quite different for the different values of β. However, the size of the flaw could be estimated by taking under consideration the maximum values, which are presented in the vertical bars. If the maximum value is greater, it means that the size (or depth) of the damage is larger. In other word, if the damage is larger thus the received signal is more disturbed and the damage index obtains greater values.

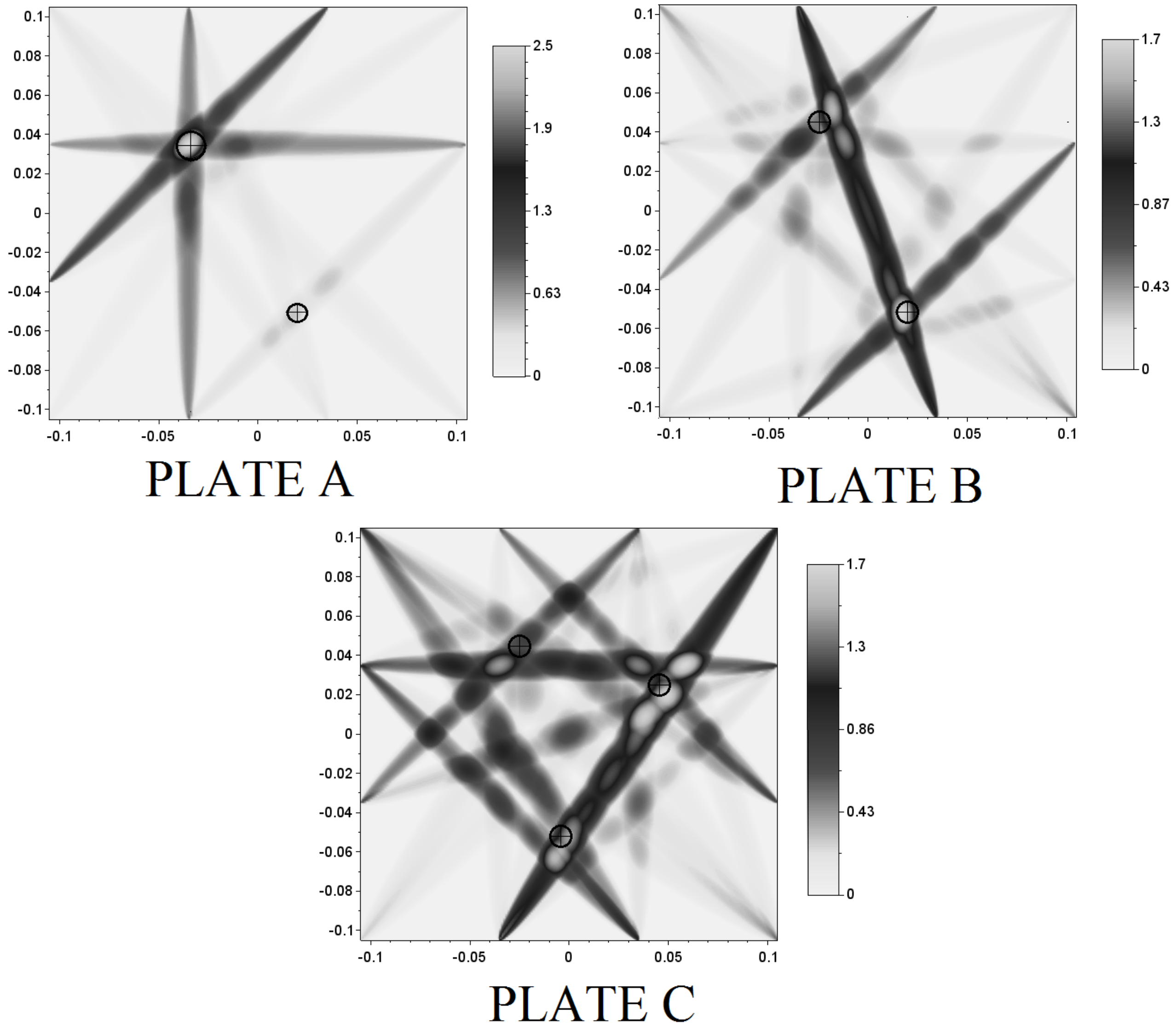

Fig. 7. Localization of damages in the case of plate A, B and C

5. Conclusions

In the presented work, the method based on the analysis of propagation of the elastic waves is applied for damage detection in hybrid composite plates. The effectiveness of the proposed approach is studied with the use of numerical simulations (finite element method). The damages are introduced to the FEM model by the reduction of the stiffness of the elements, which are localized in the area of defect. The existence of a defect between a pair of PZT sensors (actuator – sensor) causes that the received signal could be quite different in comparison with the signal obtained for intact plate. The symmetric S0 mode seems to be not changed by the flaw. Moreover, its amplitude is significantly smaller in comparison with amplitude of the anti-symmetric A0 mode. In practice, the symmetric S0 mode is very difficult to detect due to measurement noise. Therefore, the analysis is based only on the anti-symmetric mode A0. Generally, the change of amplitude and shift in phase of the signal obtained for the current structure is observed. The central frequency of the input signal remains not affected. The magnitude of the observed differences depends on the size and depth of the damage. It seems that the studied method is especially effective in the case of a single damage. In the case, when there exist more than one damage, the obtained results could be not unequivocal.

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