Journal of KONES Powertrain and Transport, Vol. 21, No. 1 2014

ISSN: 1231-4005
e-ISSN: 2354-0133
ICID: 1134050
DOI: 10.5604/12314005.1134050

EXPERIMENTAL AND NUMERICAL ANALYSIS OF GUIDED WAVES PROPAGATION IN NARROW ISOTROPIC PLATE WITH NOTCH

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Abstract

The phenomenon of the guided waves propagation can be applied in order to detect different types of damages in real structures. The existence of flaws, like cracks, notches, or holes, causes the change of the wave propagation in the analysed structure in comparison with the intact one. However, in the vicinity of the free edges the dynamic response is very complicated due to the reflections and interference of the incident waves. Thus, the process of the damage detection and localization can be very difficult. Therefore, the current work is devoted to the experimental and numerical analysis of the guided waves propagation in the narrow, thin plates (beams). The investigated structure is made of aluminum alloy. Mainly, the influence of the notch on the waves' propagation is studied. The waves are generated and picked up by the piezoelectric transducers. In order to carry out the numerical simulations the finite element method is applied. Moreover, the piezoelectric activators and sensors are modelled with the use of the coupled field finite solid elements and the plate with the use of the structural solid elements. Generally, three types of the waves are observed, namely the horizontal and shear wave, which move along the symmetry axis of the plate and the horizontal wave, which propagates in the perpendicular direction. The existence of the notch generally causes that the voltage amplitude of the received signal is reduced in comparison with the results obtained for the intact structure. Qualitatively, the similar effect is observed in the case of the experimental findings.

Keywords: *narrow plate, aluminium alloy, notch, guided waves, piezoelectric transducers, finite element method*

1. Introduction

Nowadays, the use of the Lamb waves, also known as guided waves, are considered to be one of the most efficient way to detect any kind of a flaw in the structure [6]. It is particularly important in the case of the structures, which are subjected to the cyclic load. The guided waves are be also applied in order to interrogate the composite structure [9], [10], where the process of a damage evolution is very complex. The flaw can be detected and localized by an analysis of waves' reflections (pulse-echo method), changes in wave signature (pitch-catch method), or changes in electromechanical (E/M) impedance spectrum [7]. The current work concentrates on the second possibility, namely the guided waves propagation is simulated in the case of the intact structure and the structure, which contains the transverse notch. The obtained results are compared in order to analyse the influence of the notch on the waves' propagation. The three – dimensional, coupled – field FE model is developed. The inspiration of this work are the papers [2], [5], [8], where the similar structure is investigated. However, the plain strain (two-dimensional case) is assumed in mentioned works. Moreover, the influence of the wave reflection and interference is not analysed.

2. Investigated plate and experimental setup

The investigated narrow thin plate with the mounted piezoelectric transducers is depicted in the Fig. 1. The structure is made of the aluminium alloy PA38, where the mechanical properties are as follows: E=69.5 [GPa], G=21.1 [GPa], υ=0.33, ρ=2700 [kg/m^3] (*http://www.dostal.com.pl/metale-kolorowe-aluminium.html*). The one side of the studied plate is clamped. The displacement of the second edge is constrained in the vertical direction. In order to analyse the influence of the flaw on the waves' propagation, two structures (plate A and B) with the transverse notch are investigated. The damaged structures A and B differ to each other by the position of the flaw. They are shown in the Fig. 2. The position of the piezoelectric transducers is the same in the case of the intact and damaged structures.

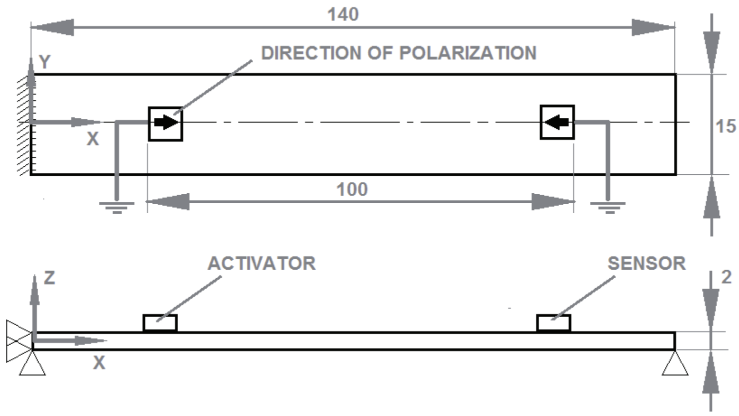

Fig. 1. The investigated intact structure

The waves are excited and received by the transducers CMAP06 (*http://www.noliac.com*). They are made of the NCE57 material with the following mechanical, piezoelectric, and electrostatic properties: s^E_{11}=17e-12 [m²/N], s^E_{33}=23e-12 [m²/N], d_{31}=-170e-12 [C/N], d_{33}=425e-12 [C/N], ε^T_{33}=1800 and density ρ_p=7.7e3 [kg/m³].The piezoelectric elements have cubic shape with dimensions b x b x h = 3x3x2 [mm]. The polarization of the transducers is parallel to the surface of the investigated plate. The transducers are mounted to the investigated plate with the use of the beeswax. Moreover, the piezoelectric elements are connected to the system for the generation and acquisition of the guided waves PAQ-16000D (*http://www.vibx.com*). Additionally, the received signal is processed by an appropriate software in the MATLAB environment.

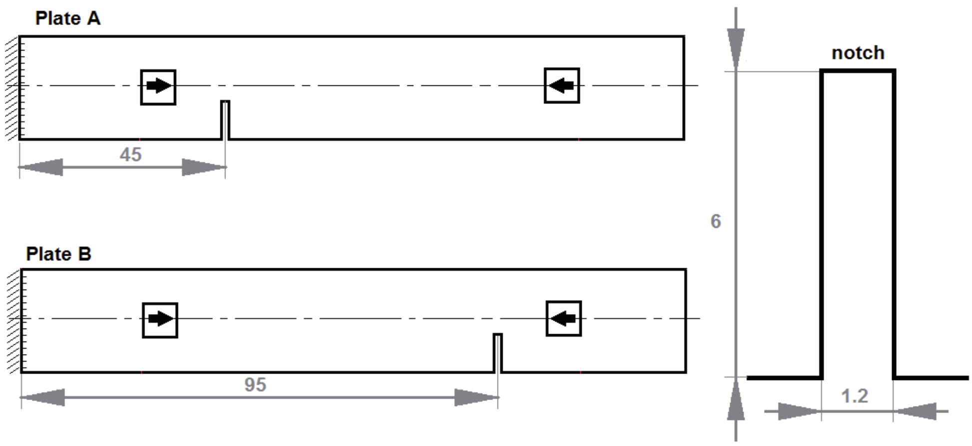

Fig. 2. The assumed localization of the notch in the structure A and B

The piezoelectric activator is excited by the tone burst voltage signal with amplitude V_0=12 [V] and the frequency f_0=100 [kHz]. The applied excitation signal is shown in the Fig. 3. Generally, the activator generates three different types of the guided waves, namely: the horizontal (pressure) and flexural waves, which travel along the symmetry axis of the plate and the horizontal (pressure) waves, which travel in the perpendicular direction. The last one is reflected from the longer sides of the plate. Taking under consideration the assumed frequency of the excitation signal and the thickness of the plate, these waves can be considered as the symmetric S_0 and anti-symmetric S_0 mode of the Lamb waves [1].

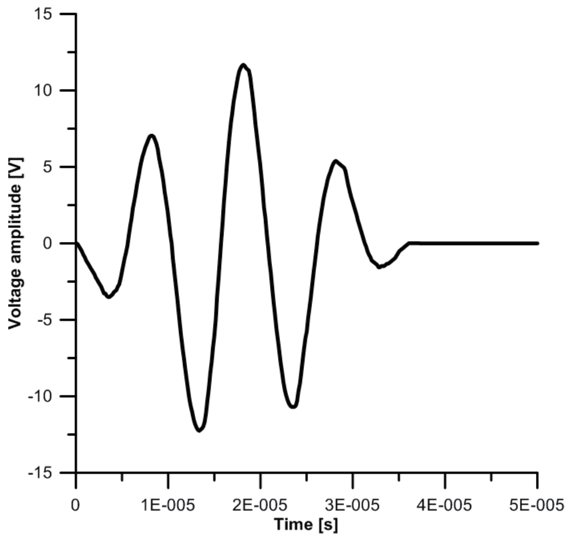

Fig. 3. The real tone burst excitation signal

3. Finite element model

In order to perform the dynamic response of the investigated structures, the finite element method is used. All simulations are carried out with the use of the commercial software ANSYS 12.1 [4]. The plate is modelled with the use of the structural, 24-nodes solid elements SOLID186. The elements have only transitional degrees of freedom, namely UX, UY, UZ, in each node. However, the behaviour of the piezoelectric transducers are simulated by the solid, 24-nodes, coupled field elements SOLID226. These elements have the transitional and the voltage degrees of freedom in each nodes. Moreover, it is assumed the perfect join between the surface of the plate and the transducers. The applied element size should be small enough in comparison with the estimated pressure wavelength. The wavelength can be determined as a result of the following relationships [3]:

$$\lambda = \frac{c}{f_0}, \quad c = \sqrt{\frac{E}{\rho}}. \tag{1}$$

Here the wave speed is equal to c=5074 [m/s] and the wavelength λ=50.735[mm]. The element size should be about 10-20 times smaller in comparison with the obtained wavelength λ. Thus it seems that the element size l_e=1 [mm] is small enough. Moreover, in the single time step the wave should not travel further than the smallest element size, namely:

$$\Delta t \leq \frac{l_e}{c}. \tag{2}$$

In the case of the element size l_e=1 [mm] the time step should be less than Δt ≤ 0.1971e-6 [s]. For the further simulations the single time step is assumed to be equal Δt=0.05e-6 [s]. The finite element model of the investigated structure is shown in the Fig. 4. However, in order to test the accuracy of the numerical solution the simulation is also performed for the following element size and time step, namely l_e=2 [mm], Δt=0.1e-6 [s]. The calculations are carried out for the intact structure. The obtained results are presented in the Fig. 5. It is worth stressing here that the results are almost identical when t < 3e-5 [s]. Next, the amplitude of the picked up signals reveals significant discrepancy. However, the phase is still very similar. This phenomenon can be explained by the fact that the incident waves are reflected from the edges of the structure and they are interfere. Thus the dynamic response for t > 3e-5 [s] is very difficult for numerical simulation.

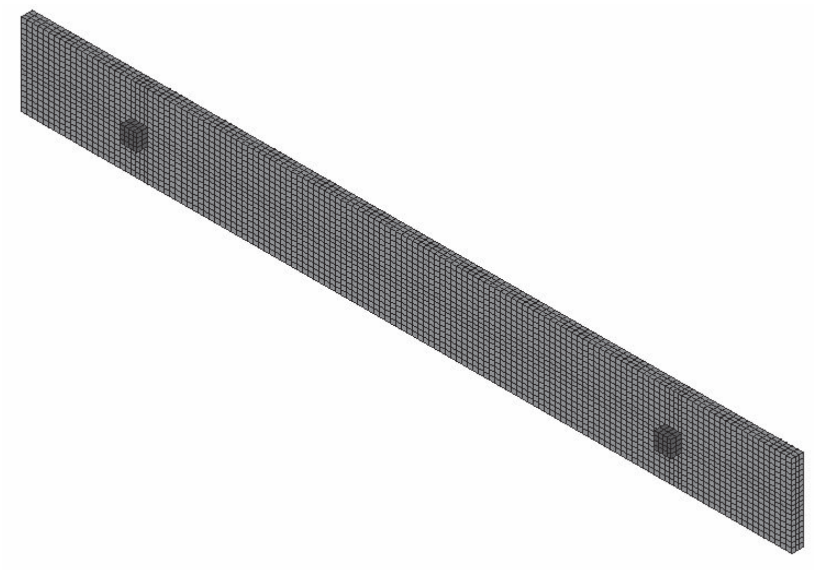

Fig. 4. The finite element model of the analysed structure

Finally, for the further simulations it is assumed the FE model, where the plate consists of the 7668 solid elements and the each transducers consists of 32 elements (l_e=1 [mm], Δt=0.05e-6 [s]. The total time of simulations is equal to t_c=50e-6 [s].

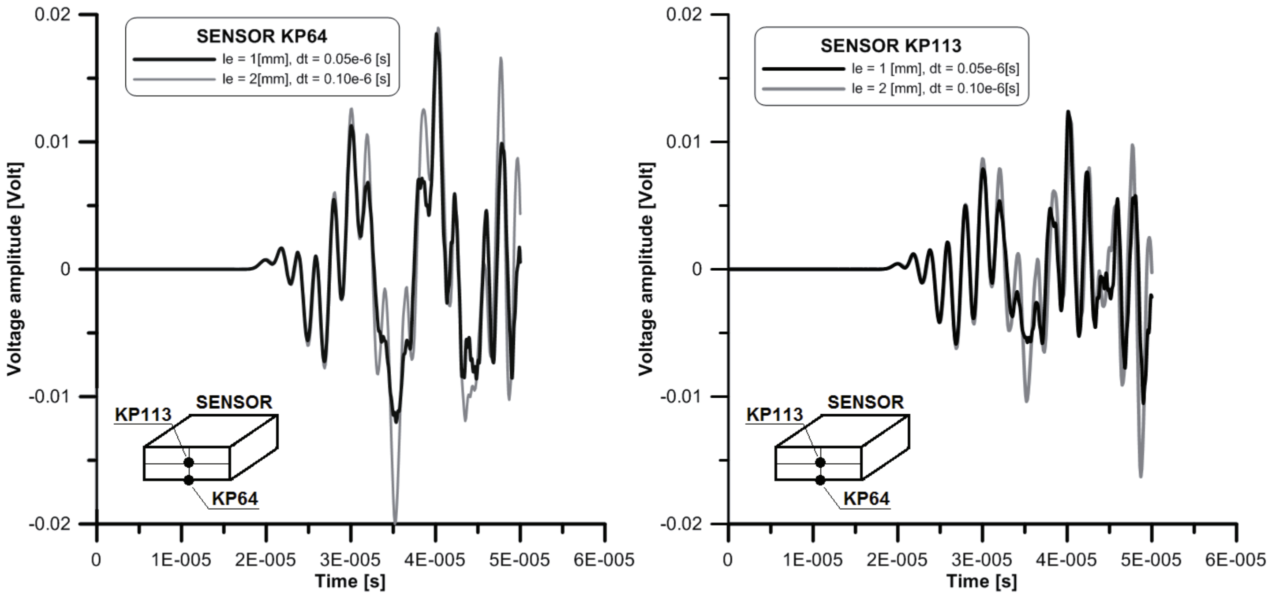

Fig. 5. The voltage amplitude versus time for two different element size and time step

4. Results of simulations

In the Fig. 6 there are depicted the obtained amplitude of the displacement components, namely UX, UY and UZ versus time. These figures are prepared for the characteristic points KP46, KP64, which belong both to the plate and to the sensor generally, the existence of the notch cause the reduction of the displacement amplitude, what can be observed in the case of the UX and UZ displacement components. The phase and frequency of the picked up signals are almost identical in comparison with the intact structure. Furthermore, the position of the notch has almost no influence on this displacement components behaviour. However, in the case of the UP displacement component the observed changes are significant. The amplitude and the phase of the received signal are quite different in comparison with the intact structure. It is worth stressing here that the UY and

UZ displacement components are of order of magnitude less than the UX displacement component. Therefore, the UX displacement component has the decisive influence on the registered voltage signal. In the other words, for the plate A and B the picked up voltage amplitude should be reduced in comparison with the intact structure. The phase and frequency should be almost identical.

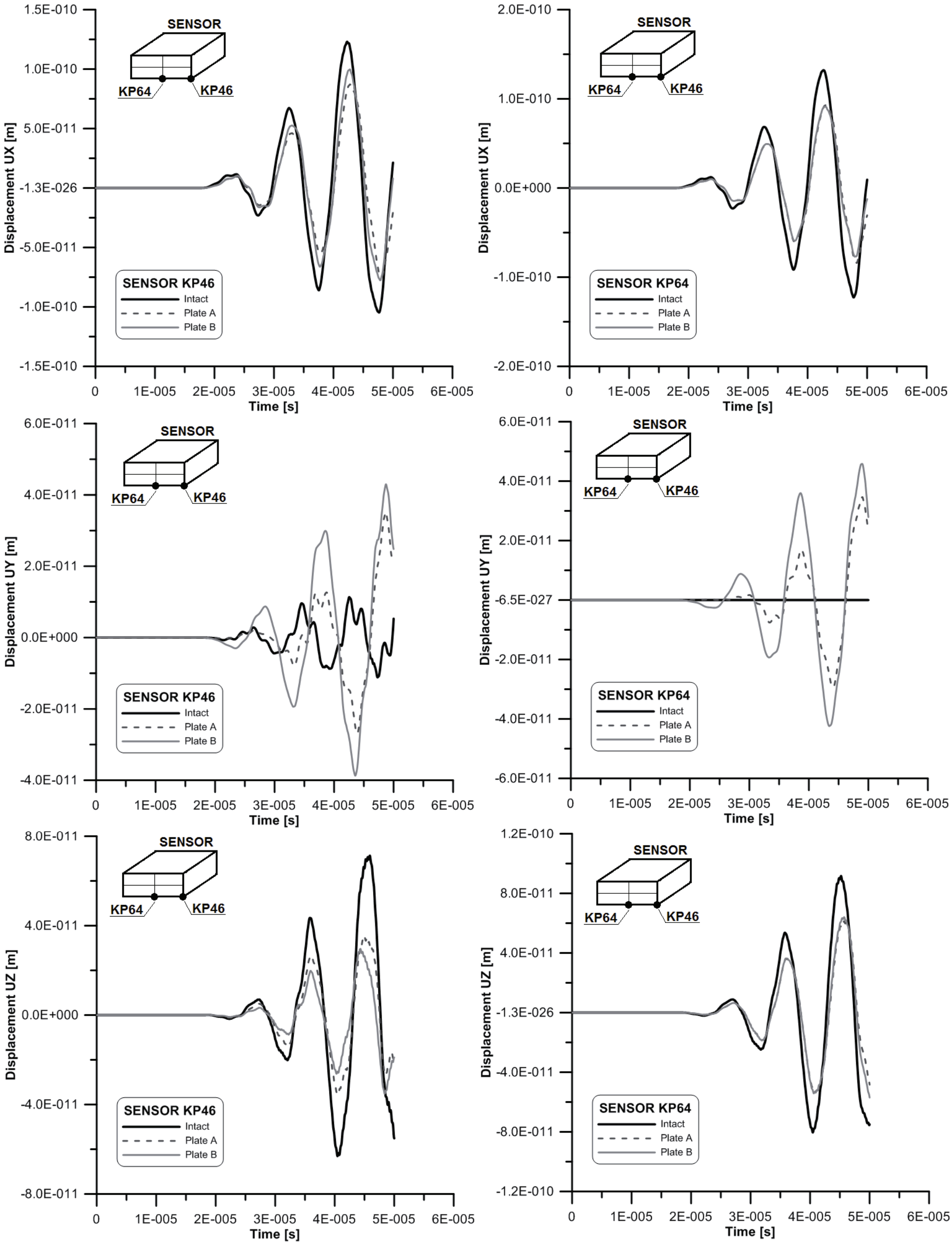

Fig. 6. The component of the displacement versus time obtained for the plate a, plate B and the intact structure

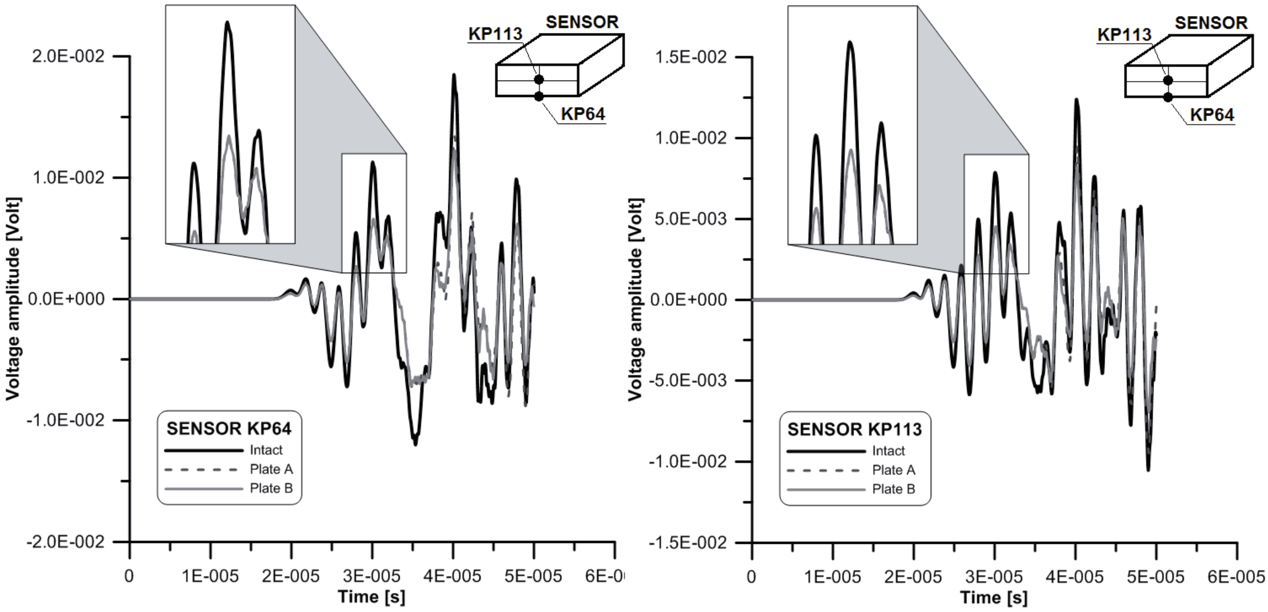

Fig. 7. The voltage amplitude versus time obtained for the plate A, B and the intact structure

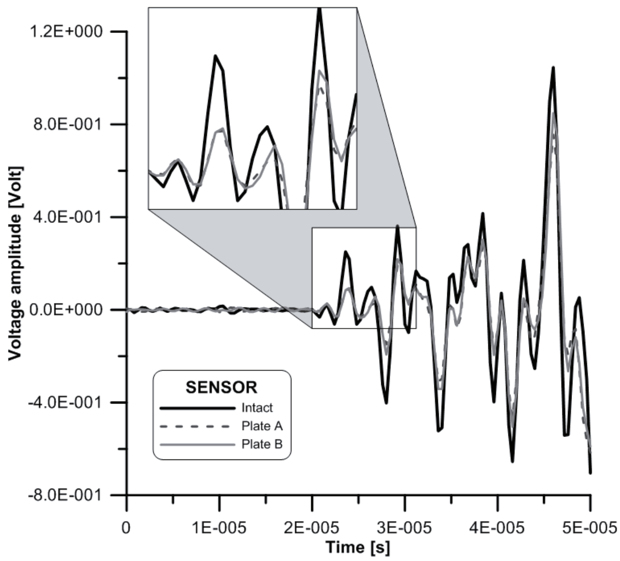

Fig. 8. The voltage amplitude versus time obtained for the plate A, B and the intact structure (experimental findings)

In the Fig. 7 there are shown the voltage amplitude versus time. As it can be observed, the voltage amplitude, obtained for the plate A and B, is indeed reduced in comparison with the intact plate. What is quite surprising, the position of the notch has no influence on the received voltage response of the sensor. Additionally, in the Fig. 9 there are depicted the shapes of the investigated structure during the simulation. It is worth stressing here that the direct (quantitative) comparison between the experimental findings and the computer simulation is rather impossible, due to the fact that on the received signal in the experiment has influence some unknown parameters. Generally, it is very difficult to estimate their magnitude, for example: the global damping, the mechanical properties of the beeswax layer between the transducers and the surface of the plate, the influence of the ambient temperature and humidity, etc. Thus, it is possible only the qualitative comparison between the experimental and numerical results is possible. The experimental findings revel very similar character, namely the existence of the notch cause mainly the reduction of the voltage amplitude. The phase and the frequency of the picked up signal are very similar for all studied structures, however the voltage amplitude, obtained from the experiment (Fig. 8), is off approximately one order of magnitude higher in comparison with the theoretical results (Fig. 7).

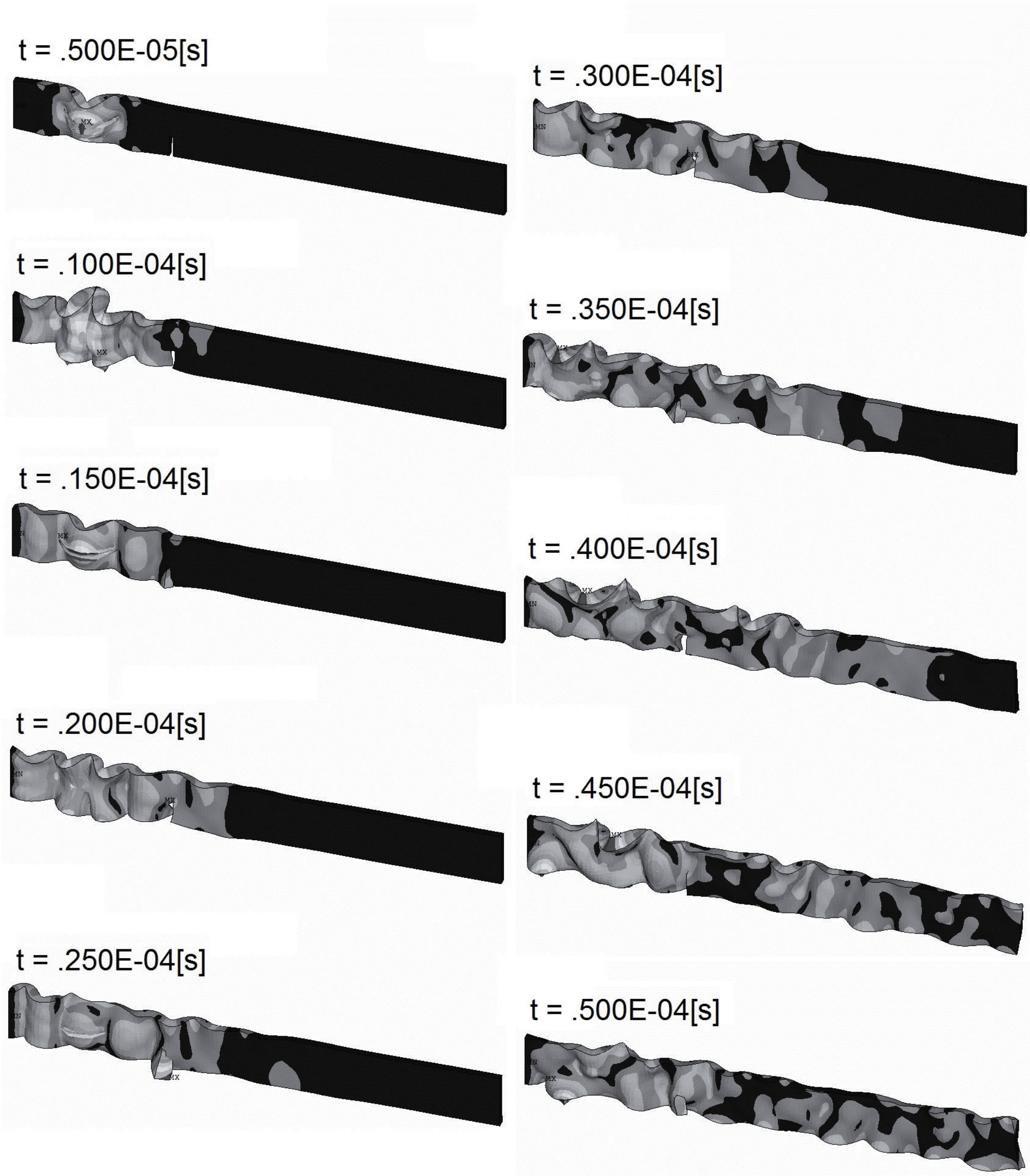

Fig. 9. The dynamic response of the investigated plate

5. Conclusions

It seems that there are the real possibility of carrying out the numerical simulations of the dynamic response of the investigated structure with sufficient accuracy. However, the obtained results, mainly voltage amplitude, should be considered only qualitatively. Due to the reflection and interference of the incident waves, the dynamic response is very complicated. It should be stressed here that the numerical solution obtained from the FEM simulation is not reliable, when the reflected waves are present in the dynamic response. The existence of the notch cause the reduction of the voltage amplitude in the received signal. However, the wave phase as well as the frequency seems to be not changed.

Acknowledgement

This work has been supported by the National Science Centre under grant:
DEC-2013/09/B/STY/00178.

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