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Article

On the Directivity of Acoustic Waves Generated by the Angle Beam Wedge Actuator in Thin Walled Structures

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Abstract: The paper is aimed to develop an improved acoustic-based Structural Health Monitoring (SHM) and Non-Destructive Evaluation (NDE) techniques, which provide the waves directivity emitting by the angle-beam wedge actuators in the thin-walled structures made of plastic materials and polymeric composites. Our investigation includes the dispersive analysis of the waves that can be excited in the studied plastic panel. Its results allowed to find two kinds of the generated acoustic waves - anti-symmetric Lamb waves A0 and shear horizontally polarized SH waves SS0. The bounds of the chosen frequency range for the experimental and numerical studies were accepted as a compromise between the desire to obtain high defects resolution by generating short waves, their adjustable directivity and maximum propagation length. The finite element model for the transducer was built by using the results of actuator structure experimental study. The frequency response functions for the actuator current and oscillation amplitude of the footprint surface demonstrated good agreement. The found eigenfrequencies of actuator's structure were used for the numerical and experimental study of the Lamb and SH wave generation and propagation in a thin-walled plastic panel. Our results convincingly demonstrated the satisfactory directivity of the actuated waves at their excitation on the frequencies that corresponded to the natural modes of the actuator oscillation. The authors assume that an efficient use of the proposed technique for other analyzed quasi-isotropic materials and applied actuators can be provided by a preliminary research using the similar approach and methods presented in this article.

Keywords: acoustic based SHM; plastics and polymeric composites; Lamb waves; horizontally polarized SH waves; angle-beam wedge transducer; waves directivity

1. Introduction

The goal of the paper is to develop an improved technique for Nondestructive Evaluation (NDE) and the Structural Health Monitoring (SHM) of the load carrying thin walled structures using controlled by direction on the part surface acoustic waves, which are generated by the surface mounted piezoelectric transducers.. The Lamb waves are used in the active SHM systems because they can propagate over large distances in the thin walled parts, interact directly with the potential defects that allows to estimate the state of health and reliability of the aircrafts, rotorcrafts and another machines. The most interesting benefits of using guided Lamb waves is their abilitie to detect such defects in thin walled structures as inclusions, porosity, undesirable local changes of the material's mechanical properties and sometimes a possibility to control the waves directivity, i.e.

beamsteering. The aspects of using acoustic waves in the active SHM system are outlined and considered in the monographs [1-3], in the papers [4-8] and in thesis [9-12].

Typically, every full-featured Lamb waves based SHM involves four levels referred as [5]:

- detection of the occurrence of an unsafe irregularity;
- identification of the geometric location of the irregularity;
- determination of the magnitude or severity of the irregularity;
- prognostic estimation of the remaining service life/strength.

The first phase of every acoustic SHM technique assumes the proper choice of the wave excitation frequency, its intensity, propagation distance and directivity that depend on the geometry of the part under investigation, on the material damping and its structural anisotropy. Among these degrees of freedom, which should provide the selected wave motion excitation method, the directivity of wave propagation is most difficult to implement as desired. In order to excite the acoustic waves in a structure a variety of different techniques is used, including piezoelectric transducers in the forms of circular [4, 6], annular tablets [13] or rectangular piezoelectric (PZT) patches [12, 13], by PZT wedge transducers [11, 14 16], piezoelectric wafer active (PWAS) and macro-fiber composites (MFC) actuators [17-19], and by laser beam excitation [20]. For the sensoring of the waves, which are reflected or scattered on the defects, the small piezoelectric transducers or non-contact Laser Doppler Vibrometry (LDV) are most often used.

The distance of the acoustic wave propagation depends on the contact stress amplitude generated by the surface mounted actuator. In the most common case the wave amplitude *A(r)* at a distance r from the source of excitation is determined as

$$A(r) \cong A_0 / \sqrt{r}\ , \tag{1}$$

where A0 is the wave amplitude at the excitation source [21]. Along with the so-called geometric attenuation (1), in plastics and polymeric composites the wave attenuation due to material damping is observed [5, 21]. This phenomenon allows to determine experimentally the studied material damping properties at the cases of use some omnidirectional transducer, which excites the waves in the part of simple geometry and homogeneous distribution of material's properties. But the correct localization of a possible irregularity requires an ability to control the direction of excited waves propagation that is provided only by the PWAS, MFC and angle-beam wedge actuator. The latter one has the advantage that it can be moved along the surface of the part, while the PWAS and MFC should be fixed on the part surface. In the NDE and SHM practice the angle-beam wedge actuators, which use the principles of refraction and mode conversion to produce refracted shear or longitudinal waves in the test material, are very efficient for inspection of thick metallic components as providing a large scanning index. These abilities have been studied and confirmed by earlier [23-26] and later theoretical and experimental researches [16, 27, 28]. First work dedicated to the use of the wedge actuator for the wave generation in thin-walled plates is [29], where the wedge method of generating guided waves was analyzed with particular attention being focused on the relationship between the angularly dependent excitation amplitude of a given mode and the physical parameters of the transducer and wedge used to excite the mode. This theoretical investigation used the analytical approach assuming that the transducer produces a roughly parabolic pressure distribution on the contact footprint of the form

$$p(\alpha) = \begin{cases} \sigma_0\left(1 - \dfrac{\alpha^2}{(D/2)^2}\right) & if \quad |\alpha| \le D/2 \\ 0 \quad if \quad |\alpha| > D/2 \end{cases}, \tag{2}$$

where σ_0 represents the maximum pressure which occurs at the center of the transducer face, $\alpha = 0$, and the transducer has a width D. More detailed later studies [16, 26-28] based on the finite-element analysis, established a very complex contact stress distribution that produces both out-of-plane and in-plane displacements within the elliptic footprint.

Later papers [14,15] discuss difficulties of the wave tuning at its excitation in thin-walled structures. First, the phase velocity c_w (the velocity of the longitudinal or transverse acoustic waves in the wedge) must be smaller than c_{phase}.(the phase velocity of a desired wave mode at a selected

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frequency in the thin-wall structure). This can limit either the choices of wedge materials appropriate for generation of a desired mode or the availability of modes that can be generated with a given wedge material. Secondly, spurious signals, resulting from wave reverberation inside the wedge, may deteriorate the quality of the useful signal, that is, intended applied wave. Thirdly, due to beam spreading of acoustic waves propagating through the wedge to the structure surface, other wave modes beyond the mode of interest may be generated. This statement is confirmed by the results of the work [26], where it is reported that at enough large wedge-specimen contact area the undesirable aperture effects can appear.

The papers [27, 28] propose an analytical approach to the problem of modeling linear Rayleigh wave sound fields generated by angle beam wedge transducer. In these papers, the reciprocity theorem for dynamics of elastic bodies is transformed into integral representations, and the fundamental solutions of wave motion equations are obtained using Green's function method. The authors show that the results obtained by the proposed technique, which neglects the waves attenuation both in the excited aluminum specimen and wedge, are more numerically stable than those obtained by the 3-D Rayleigh wave model. In order to improve the developed technique the authors propose to take into account the leaky energy of Rayleigh waves back into the wedge from underneath it. Moreover, if such transducers are used to excite the acoustic waves in plastics and polymeric composite materials, which have a very intensive structural damping, the upper bound of the excitation frequency range is limited by the fast attenuation of wave energy and amplitude.

In this article we present results of numerical and experimental study of acoustic wave excitation in a square quasi-isotropic plastic plane panel with dimensions 50x50x0.4 cm surrounded by the absorbing layer. This layer is made of the porous rubbery belt, which simulates a perfectly matched layer intended to minimize reflection of the traveling waves and formation of the standing waves. The mechanical properties of the studied panel's material were preliminary measured experimentally using modified technique described in [30]. On the base of calculated elastic properties the dispersion analysis for the Lamb wave and for shear horizontally polarized wave has been performed. This allowed to determine the types of the waves that can be generated in the chosen frequency range without intensive attenuation. In order to determine the properties of the used angle-beam wedge transducer Olympus V414-SB - ABWS-3-45 for their subsequent use at the numerical modeling, it has been subjected to self-testing to determine the electrical capacitance, the frequency response functions (FRF) of the consumed electric current and the amplitude of the normal displacements on the contact surface. In the frequency range 10 - 100 kHz three resonance frequencies were chosen, at which the experimental and numerical studies of generated wave field on the surface of plastic panel were fulfilled. For two generated waves types - anti-symmetric Lamb wave and shear horizontally polarized wave SS0 the wave directivity has been studied using the finite-element model of the system, where wedge dimensions and its electric and mechanical properties were fully consistent to those for the real transducer. The numerical results, obtained for the Lamb waves, were supplemented by the experimental measurements. In these experiments the small-sized piezoelectric sensors that sensitive to the out-of-plane displacements of the excited panel surface were used. Our results show that satisfactory directivity (beamsteering) at the wavelengths till 1 - 2 cm that can be used in NDE and SHM technique for testing the heavily damping plastic or composite materials can be provided by using angle-beam wedge actuators at the frequencies match to the transducer's natural vibration modes, which should be preliminary determined. These results confirm the relevance of a similar study for more complex - orthotropic composite materials, whose anisotropy can sufficiently distort the directional characteristics of the waves generated by the angle-beam wedge actuator.

2. The experimental investigation of acoustic waves excited in the plastic panel under study

Our experimental study has been divided into three subsections. In order to calculate the dispersion relations for the waves that can be excited in the studied panel, which is made of Polypropilen GC40S-402 (BASF Procom®). Its mechanical properties were measured in the series of tests using testing machine, and further numerically processed. Used in subsequent experiments, the

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angle-beam wedge actuator Olympus V414-SB - ABWS-3-45 was tested alone to reconstruct its characteristics, which were used at the development of its finite-element prototype. At the final stage, the angular and radial intensity distributions of the wave fields generated by this actuator in a plastic plate were investigated.

2.1. Determination of elastic properties for the material of the studied panel

The specimens with dimensions 250x25x4 mm were tested by the testing machine TIRA test 2850 with extensometer, which measured the small displacement during stroke of the crosshead. The extensometer having the base of 100 mm was calibrated for determine a dependency between displacement and output voltage. The calibration curves obtained at the tensile loading and unloading allowed to correctly calculate a tensile strain during specimen elongation and contraction. All tests were performed within the elastic region by two - three cycles of loading-unloading with the crosshead speed 1 mm/min. The strain and tensile force time histories were stored in the text files, then those were recalculated to remove experimental noise and calculate elastic module. The Poisson ratio were measured using the pairs of strain gauges placed on the samples surfaces normal to their length, and calculated according to the similar technique. All obtained values of the elastic modules have been verified in the experiment of resonance frequency determination. The samples with known dimensions were fixed as cantilever and harmonically excited by the shaker at the changing frequency. The eigenfrequencies of the 1st bending vibration modes were used to calculate the Young module using the classical formula for the Euler-Bernoulli beam. The observable discrepancy for modules, which were calculated by the different methods did not exceed 3.5%. Comparison of the moduli measured for the specimens carved along two perpendicular directions from the sheet of material under study, proved that the material can be considered as quasi-isotropic. All data for the studied specimens are summarized in Table 1.

Table 1. Mechanical properties of the studied plate's material.

Young module, GPa	Poisson ratio	Density, kg/m3
7.4±1.1	0.33±0.04	1230±42

2.2. Reconstruction of the wedge actuator structure and electro-mechanical properties

The present research combined two parts - experimental and numerical, and the last one was fulfilled by using the finite-element approach. Therefore, it was important to the fullest possible matching between the characteristics of the simulated and real actuator (see Figure 1), both for dimensions and electromechanical properties.

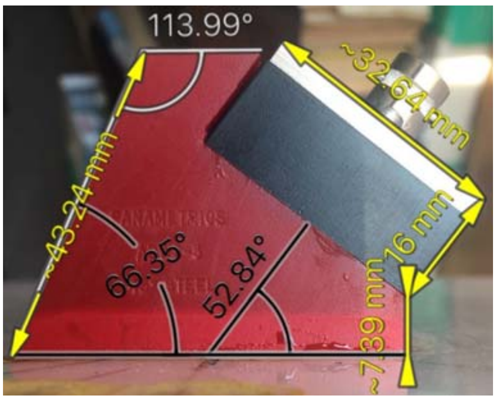

Figure 1. Photo of the used Olympus angle-beam wedge transducer with dimensions

Topology of actuator's structure has been reconstructed by using the technical notes of the developer. The properties of active PZT element were determined using the transducer sketch, dimensions of the waveguide made of Lucite and measured electric capacity of the transducer. The

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properties of the backing, which is usually highly attenuative, high density material that is used to absorb the energy radiating from the back face of the active element, were derived from experimental measurements of frequency response function for the consumed electric current and amplitude of normal displacements on the contact surface of the transducer. The value of the acoustic impedance of the backing was chosen to match the acoustic impedance of the active PZT element. The result is a heavily damped transducer that displays good frequency range resolution but not very high in signal amplitude. The properties of the matching layer were chosen to serve it as an acoustic transformer between the high acoustic impedance of the active element and the waveguide wedge, which is of lower acoustic impedance. In order to shape to simplify the finite element (FE) model of the device the upper part of the corps was transformed to a cylindrical shape (See Figure 2).

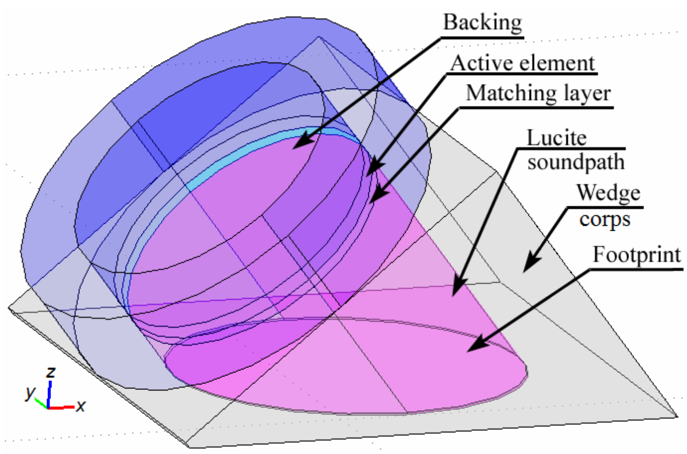

Figure 2. Geometry of the finite-element prototype for the used wedge transducer

The mechanical properties for the actuator's parts material, which are determined after performing the above listed experiments, are present in the Table 2. The values of the stiffness and matrices for the active element made of PZT-5H polarized ceramics are taken from the producer's data. These matrices are used to formulate and solve the piezoelectricity equations at the FE calculations in the stress-charge. In the built FE model these matrices were defined in the tilted coordinate system that is conforms to the wedge actuator geometry.

Table 2. Mechanical properties of actuator's parts material.

Actuator's part	**Young's module, GPa**	**Poisson ratio**	**Mass density, kg/m³**	**Loss factor**
Corps	6.0	0.33	1500	0.075
Backing layer	50	0.1	7500	0.15
Matching layer	6.0	0.3	1500	0.025
Lucite soundpath	4.0	0.33	1200	0.025
Active element (PZT-5H)	The elasticity, coupling and relative permittivity matrices contain all data		7500	0.15

In our numerical study of the FE prototype actuator we simulated the frequency response functions for actuator's consumed electric current and amplitude of normal displacements on the contact surface of the transducer's model, like during experiments with used Olympus angle-beam wedge transducer. Our FE model's simulation demonstrated the global maximum of the current's FRF at the frequency ~550 kHz and three local maxima in the low frequency region: at the 15 kHz, 30 kHz and 65 kHz. Our subsequent experimental study showed that at frequencies above 100 kHz, the attenuation of acoustic waves in a plastic material of the considered type is so large that it is

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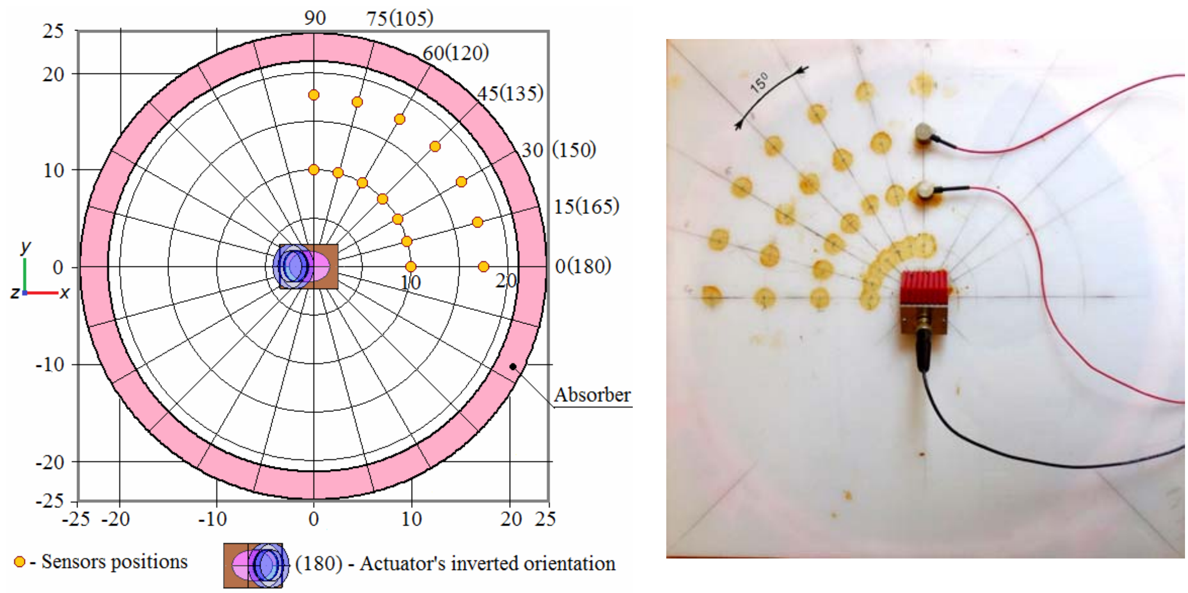
meaningless to study the directivity of waves at such high frequencies. Therefore, the thorough analysis of acoustic waves excited at these three frequencies has been fulfilled.

2.3. Experimental study on the directivity of acoustic waves excited by the wedge actuator in a plastic panel

Due to quasi-isotropic mechanical properties of the plastic material only one quarter of panel was studied (see Figure 3). The measurements of out-of-plane displacement amplitudes have been carried out by the small piezoelectric sensors. They were installed in the points, which are positioned at the intersections of radial straight lines drawn from the center of the plate, with circles of radii of 10 and 17.5 cm. The angular step between adjacent radial lines was 15^0. In order to cover the range of angles (0^0 - 180^0) the measurements were made in two stages: at the actuator oriented along x-axis, and with the opposite orientation (see Figure 3, a). The actuator's and sensors' signals were registered by oscilloscope LeCroy and stored for each orientation angle in the text files for further numerical processing. To avoid reflection of the traveling waves from the panel edges and formation of the standing waves the studied circular area was surrounded by an absorbing layer made of the porous rubber. This means was used also at the FE modeling.



(a) (b)

Figure 3. The plastic panel under study: (a) - schematic view; (b) - photo of studied plastic panel with installed angle-beam wedge actuator and one pair of sensors

In order to supply the tight contact between the panel surface, sensors and actuator the very viscous couplant SWC-2 (Olympus) was used.

Two different driving signals (see Figure 4) were prepared using AWG/AFG Windows-based software, then are formed by the wide frequency range generator Tektronix whose output is amplified by the piezodrivers PA94 (Apex Co., USA), and drives the actuator.

To avoid a sharp jump in the driving potential and unwanted response of the mechanical system these signals have zero value first derivatives:

$$U_{TB} = Ampl \cdot \sin 2\pi f_{car} t \cdot \begin{cases} \sin \dfrac{2\pi f_{car}}{N_W} & at \quad 0 < t < f_{car}/2N_W \\ 0 \quad at \quad t > f_{car}/2N_W \end{cases}, \qquad (3, a)$$

$$U_{SI} = Ampl \cdot \sin 2\pi f_{car} t \cdot \tanh^2 t/\tau \,. \qquad (3, b)$$

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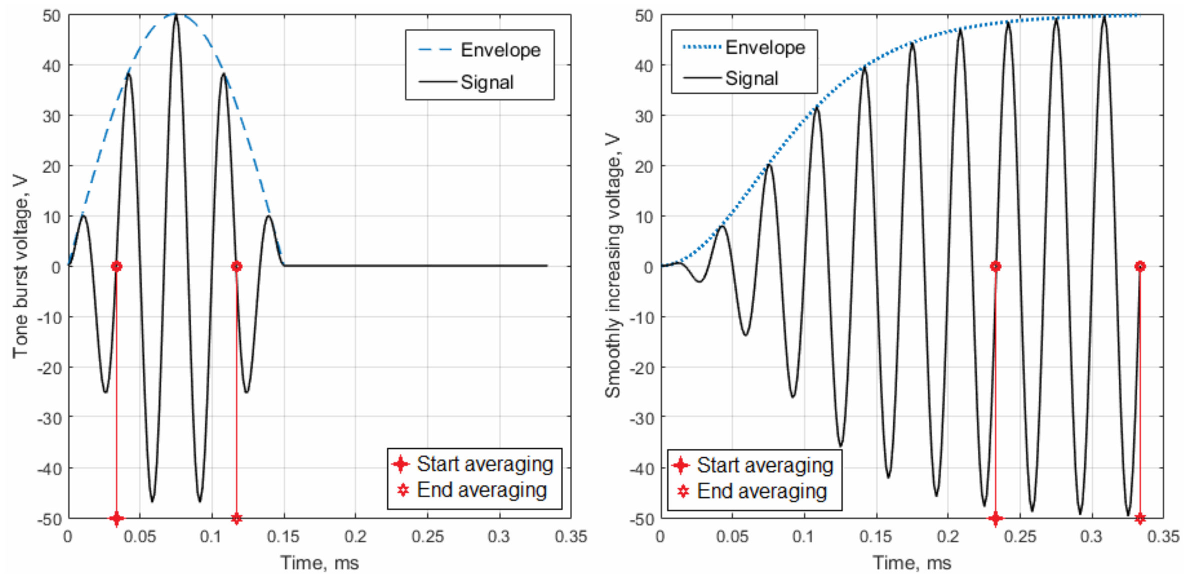


(a) (b)

Figure 4. Two kinds of the actuator's driving signals used for determination of the generated waves speeds and of the actuator's directivity: (a) - tone burst signal; (b) - signal with a smooth increase and stabilization of the amplitude. Both signals have the carrying frequency 30 kHz

Both signals (4, a) and (4, b) depend on the voltage amplitude $Ampl$, the carrier frequency f_{car} and time t. The envelope of tone burst signal (4, a) depends of the waves number N_W in the signal, whereas signal with the smoothly increasing and stabilizing amplitude (4, b) depends on the time constant τ, which determines the settling time for signal amplitude.

Wave speed was calculated on the base of time lag between two signals registered by the sensors placed on the wave path. For the assessment of directivity of excited waves the time history of signal registered by the sensor placed on the distance 10 cm from the center of elliptic footprint of actuator was processed by the averaging algorithm. This algorithm performed integration of signal's module within the time interval, correspondent to two time instants of driving electric potential depicted in Figure 4. The right boundary of the integration interval was always chosen before the wave reached the edge of the plate.

The main experimental results are presented below together with results of the theoretical study to demonstrate their accordance.

3. Numerical study of acoustic wave propagation

Both experimental and theoretical studies of acoustic waves propagated in the investigated plastic panel have been fulfilled at the excitation frequencies below 100 kHz. It was due to high attenuation of excited waves and due to limited abilities of affordable experimental equipment. In order to understand, what kinds of acoustic waves can be excited in the panel at these frequencies, the dispersion analysis of the Lamb and the horizontally polarized waves has been implemented.

3.1. Dispersion analysis of acoustic waves that can be excited in the plastic panel under study

Numerically obtained solution of the dispersion equations [1] for the symmetric (4, a) and anti-symmetric (4, b) waves are presented in Figure 5.

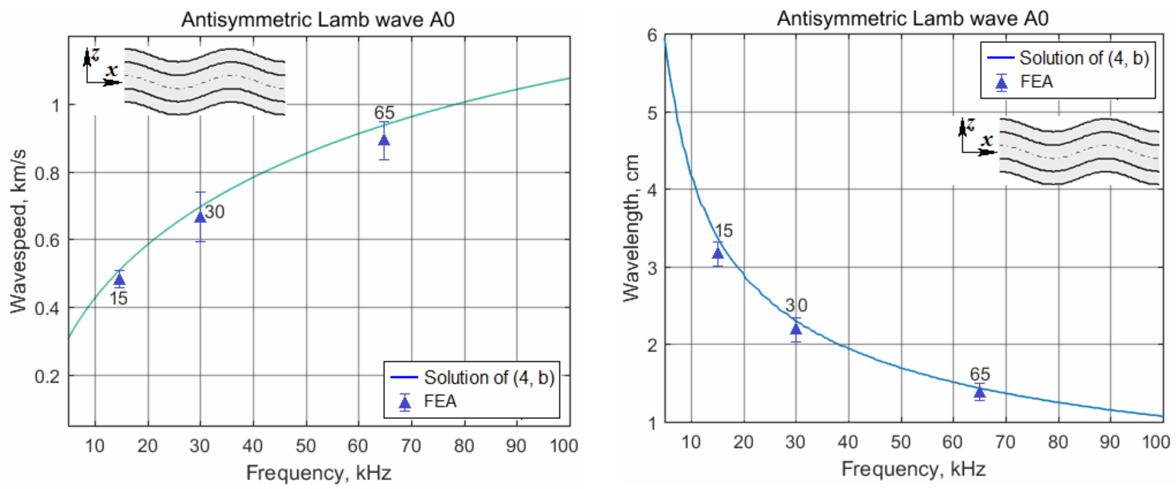
$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{\left(q^2-k^2\right)^2}, \qquad (4, a)$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{\left(q^2-k^2\right)^2}{4k^2pq}, \qquad (4, b)$$

where

$$p^2 = \frac{\omega^2}{c_L^2} - k^2; \quad q^2 = \frac{\omega^2}{c_T^2} - k^2 \qquad \text{(5, a, b)}$$

$k = \omega/c$ is the wavenumber, $c_L^2 = (\lambda + \mu)/\rho$ and $c_T^2 = \mu/\rho$ are the pressure (longitudinal) and shear (transverse) wavespeeds, λ and μ are the Lame constants, h is the half-thickness of the elastic layer, and ϱ is the mass density. Equations (4, a) and (4, b) were solved numerically by calculation left parts of these equations within some intervals of wavespeeds $c \in [c_1, c_2]$ and frequencies $\omega \in [2\pi f_1, 2\pi f_2]$ for given plate thickness $2h$ and wavespeeds of longitudinal c_L and shear c_T waves, which depend on the material properties. The calculation results establish only one, zero-order anti-symmetric Lamb wave can be excited at the accepted frequencies. It was confirmed by the finite element simulation of the waves propagation using FE model described in the next section of this article.



(a) (b)

Figure 5. The dispersion curves for the Lamb wave A0 that can be excited in the studied panel at the frequencies 10 - 100 kHz together with the values of the wavespeeds and wavelenghts, which are computed by the postprocessing of FE simulation

In order to analyze the frequency spectrum of horizontally polarized SH waves in the studied structure we used the frequency equation in the dimensionless form [1]

$$\Omega^2 = n^2 + \xi^2, \qquad (6)$$

where the dimensionless frequency Ω and the dimensionless wavenumber ξ are defined as

$$\Omega = \frac{2h\omega}{\pi c_T}; \quad \xi = \frac{2kh}{\pi}. \qquad \text{(7 a, b)}$$

Equation (6) yields an infinite number of continuous curves, called branches, each corresponding to an integer value of n. A branch displays the relationship between the dimensionless frequency Ω and the dimensionless wavenumber ξ for a particular mode of propagation. Our calculations revealed only one symmetric zero-order mode SS0 of the horizontally polarized SH waves that can be excited in the panel at the accepted conditions. As one can see on the Figure 6 the wavespeed (and wavelength, too) for this wave does not depend on the frequency, but because the solution of Equation (6) is highly dependent on the mechanical properties of the material where the wave propagates, we present in Figure (6) three wavespeeds, which correspond to the upper, middle and lower values of the confidence interval for the Young's module of the panel's material. This plot also contains confidence intervals for the wavespeed, calculated from the FE simulation results for the three cases of modeled excitation frequencies.

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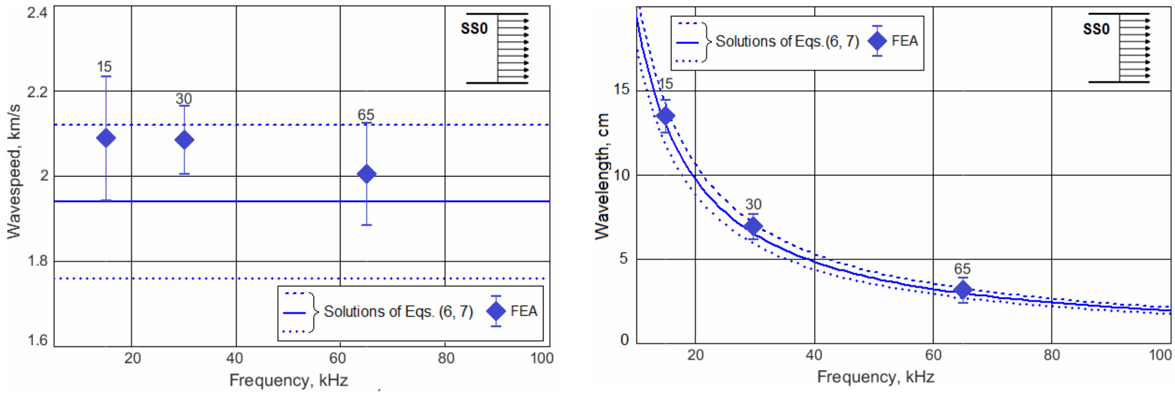

(a) (b)

Figure 6. The dispersion curves for the horizontally polarized SS0 wave that can be excited in the studied panel at the frequencies 10 - 100 kHz together with the results of FE simulation

The contemplation of Figures 5 and 6 suggests that A0 Lamb waves can be used for the detection of enough large imperfections in the tested structures in the whole excitation frequency range, whereas the horizontally polarized SS0 waves can be useful only at the higher frequencies of the considered frequency range. The features of the wave directivity at their excitation by the angle-beam wedge actuator were studied in detail at the finite element simulation of the wave generation and propagation.

3.2. Finite element analysis of acoustic wave propagation in the studied quasi-isotropic panel

The FE model, which was constructed in Comsol Mutiphysics soft tool, copied the experimentally investigated situation presented in the Figure 3. All properties of the modeled parts were match to the experimentally measured and identified as it is present in part 2 of this article. Geometry of the modeled system is present in Figure 7.

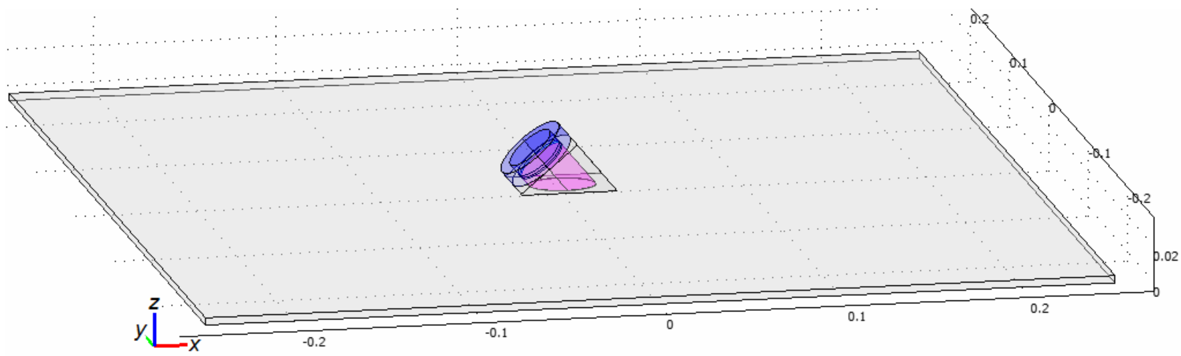

Figure 7. Geometry of the finite element model for the studied system

The great advantage of the developed model is the ability to analyze phenomena that was not possible during experimental research. The wave generation and propagation process was considered by the transient analysis. The piezoelectric actuator was driven by the tone burst voltage signal described in subsection 2.3. The simulated driven potential was always stopped before time instant when the wave reaches the edge of the plate. This eliminated the occurrence of reflection and distortion of the recorded sensor signals. The postprocessing abilities allowed to monitor the out-of-plane and in-plane displacements of the points on the panel surface independently.

Wavespeed along the radial lines was estimated by the time of flight - time lag between two synchronized signals of sensors, which were positioned on the distances 10 cm, 15 cm or 17.5 cm from the center of elliptic actuator's footprint. The choice of the optimal distance depended on the frequency of excitation. Numerical processing of the files containing a time history of the process was carried out using the developed program module in MATLAB environment. To calculate the wavespeed, 4–5 time lags of waves in the signal were used, which made it possible to obtain the

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confidence intervals like those presented in Figures 5, 6. The careful observation during some periods of oscillations of displacements in the slices, which are normal to the panel surface and oriented along the radial lines confirmed two types, lengths and speeds of propagating waves: Lamb A0 and horizontally polarized SS0. The discrepancies between the values of wavespeeds obtained on the base of FE simulation and those calculated from the equations (4 - 7), which use the experimentally studied plate's material properties, are enough small that confirms validity of present results.

3.3. Analysis of directivity forA0 Lamb and SS0 horizontally polarized waves excited by the angle-beam wedge actuator

In order to determine the waves directivity, each waves type has been analyzed along the radial lines oriented at the angles 0^0 - 180^0 during time intervals depicted in Figure 4. The angular step for the analyzed orientations was accepted to be 10 degrees. The virtual sensor's signal was allocated on the time interval, then its module was integrated to obtain its averaged value. Such averaging was necessary due to some distortions of waveform during its propagation. Most reliable results were obtained for the sine excitation signal with a smooth increase and stabilization of the amplitude, which was taken from the sensor located at the distance 15 cm from the geometrical center of the panel. The normalized values of averaged out-of-plane (for A0 waves) and in-plane (for SS0 waves) displacements, which were calculated for 15, 30 and 65 kHz that correspond to the first three natural vibration modes of actuator are presented in Figure 8. For the Lamb wave A0 mode at the frequency 30 kHz the calculated directivity diagram is combined with the confidence intervals for the wave intensity, which were obtained after the numerical processing of experimental data.

The fancy shapes of the waves intensity angular distributions can be explained by the forms of actuator's vibration modes. The very large computational complexity of the task did not allow us to reveal the distribution of contact stress on the actuator footprint in the same way as was done in [31]. These stresses sharply increase near the border of the footprint and change around its perimeter. Reliable identification of these stresses requires an extremely fine finite element meshing, which could increase the task's DoF above 1.5 million that corresponds to the very big RAM. Therefore, the amplitude contact displacements at the used frequencies excitation were analyzed. The radial distributions of the out-of-plane and in-plane displacements amplitude under footprint of actuator are present in Figure 9, which demonstrates that angular distribution of the generated waves intensity (see Figure 8) follows the shape of the amplitudes of normal and radial displacements within the elliptic contact area. Plate excitation at the different eigenfrequencies of actuator leads to the significant modification of the waves directivity pattern. The well-defined directivity of the generated waves and their length of 1–2 cm make it possible to use them for identification of relatively large imperfections in the structure of the material, such as delamination, local change of the mechanical properties, inclusions and another defects [6, 7, 9, 10, 17].

5. Conclusions

In order to improve the abilities of acoustic-based SHM and NDE techniques for the thin-walled structures made of plastic materials and polymeric composites, in particular the waves directivity, their propagation in a plastic panel exciting by the angle-beam wedge actuator has been studied both experimentally and numerically. Our study was motivated by the impossibility to control direction of the emitted waves at the use of well known circular or annular piezoelectric transducers.

The dispersive analysis of the waves that can be excited in the studied plastic panel, was fulfilled using preliminary measured material properties. The found values allowed to find two kinds of the generated acoustic waves - anti-symmetric Lamb waves A0 and horizontally polarized SH waves SS0, which both are zero order modes. The presence of two types of waves generated by the investigated actuator in the low-frequency range, and their characteristics, are confirmed by the comparison of dispersion curves, finite element calculations and experiments, which were performed under the studied plastic panel. The upper limit of the frequency range for our study was chosen due to the material damping that causes the very intensive frequency dependent attenuation

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of propagated waves. The chosen frequency range was the result of a compromise between the desire to obtain high defects resolution by generating short waves, their adjustable directivity and maximum propagation length.

The finite element model of the studied system includes the actuator's sub-model (see Figure 7), who's properties corresponded with great accuracy to the properties of a real actuator used in experiments. In order to identify the actuator's structure (dimensions of the parts, elastic, damping and electro-mechanical properties) it was studied experimentally by using the measurement of its electric capacitance and frequency responses of the consumed electric current, and oscillation amplitude on the surface of elliptic contact. These results were used at the development of the finite element model of the transducer.

Our experiments with the real excited panel and numerical simulation of its finite element prototype convincingly demonstrated the satisfactory directivity of the actuated waves at their excitation on the frequencies that corresponded to the natural modes of the actuator oscillation. The considered results suggest the possibility to efficient use the angle-beam wedge transducers to the SHM of the thin walled structures made of high damped materials. Their efficiency can be provided due to the ability of beamsteering of exciting waves that is unavailable to the circular, annular and another types of omnidirectional transducers [12, 13, 22]. However, the efficient use of the proposed method for other analyzed materials seems possible only after conducting a study similar to that presented in this article. It should be noted that reported technique, which has been applied to the enough simple quasi-isotropic plastic, relates to the initial stage of a project aiming to the development of controlled acoustic monitoring of high loaded structures made of materials with orthotropic anisotropy, in particular, glass and carbon reinforced plastics.

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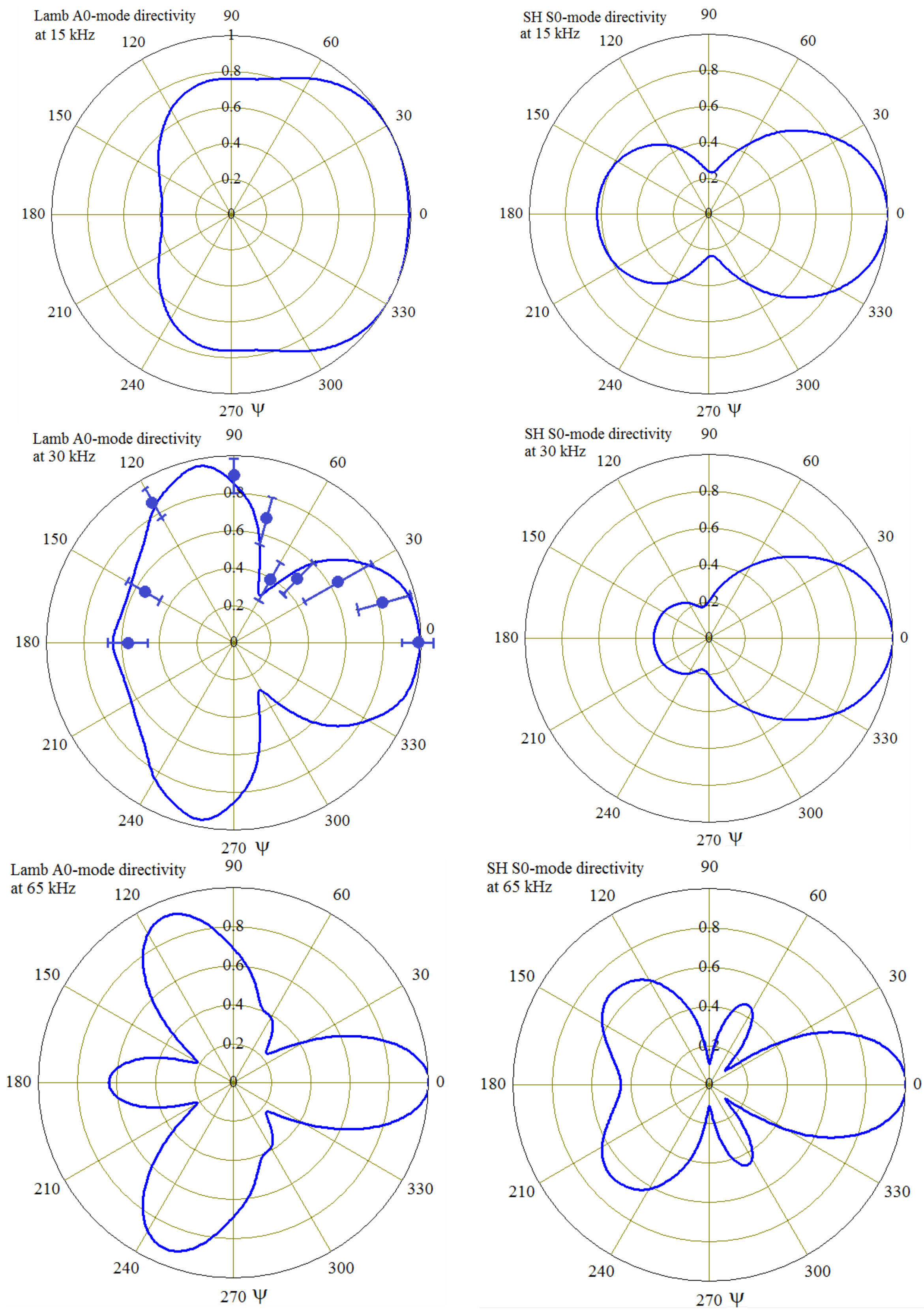

Figure 8. Directivity diagrams for the Lamb A0 waves (left) and horizontally polarized SS0 waves

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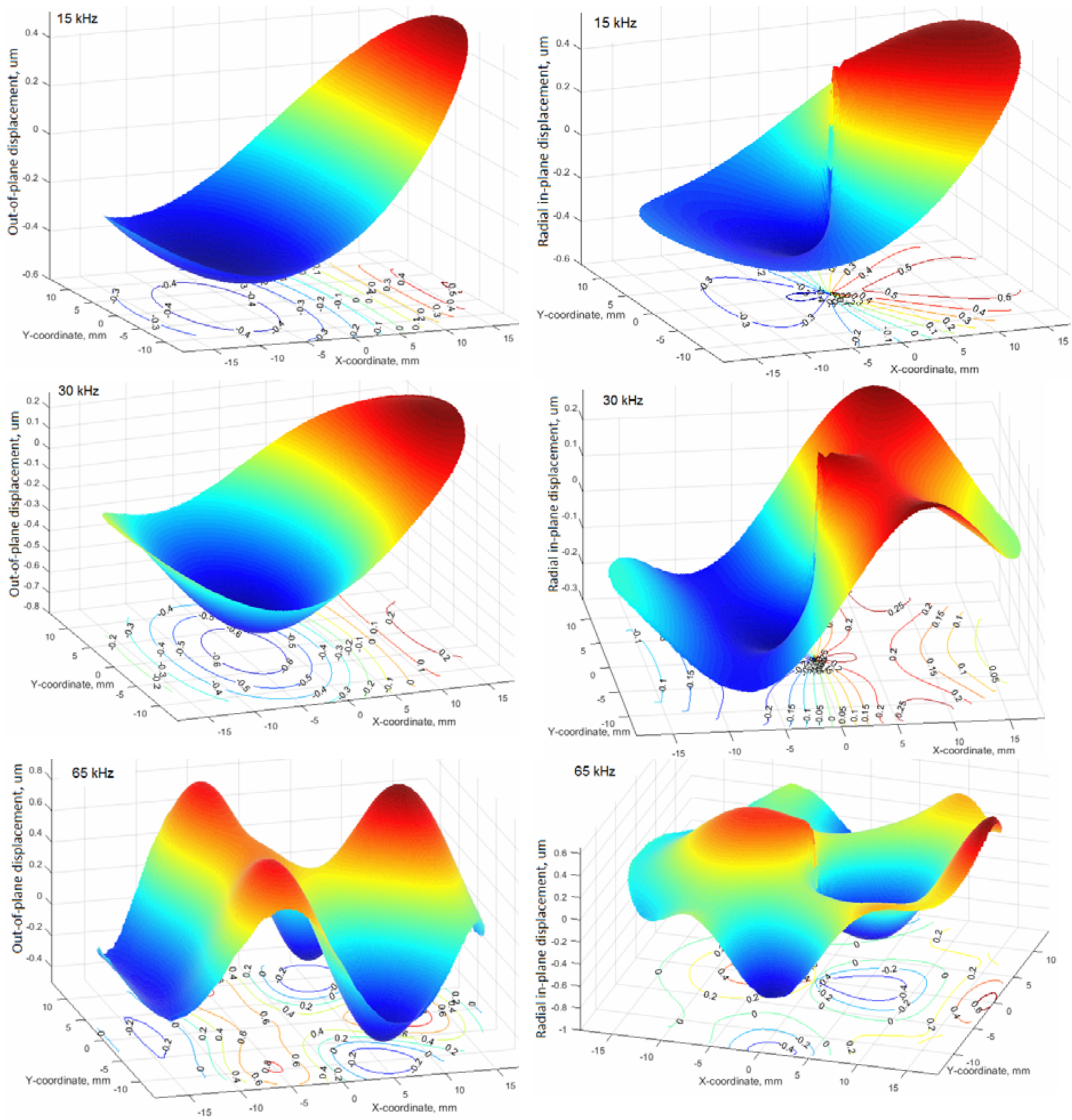

Figure 9. The radial distributions of the out-of-plane (left) and in-plane (right) amplitude displacements under footprint of angle beam wedge actuator exciting the studied plastic panel at the frequencies 15, 30 and 65 kHz

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