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Qualitative Analysis of Different Lamb Wave Excitation Methods

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Abstract: Guided Lamb waves are widely used for qualitative analysis of damage in various types of structures. An important factor for generally successful analysis is the incorporation of suitable excitation method of the desired mode of Lamb wave. This article is aimed to qualitatively evaluate four different methods of excitation of a particular mode of Lamb wave, namely excitation by longitudinal waves with the use of liquid and plexiglass wedge, excitation by longitudinal waves with the use of comb-structure element and excitation by longitudinal waves with the use of the transducer in itself, placed on the surface.

Introduction

Guided waves, especially Lamb waves, play important role in the area of qualitative analysis of damage in various types of structures [1,2]. Lamb waves are one of the types of guided waves, which exist only in geometries with a finite thickness such as plates, tubes or layered media [3,4]. The propagation characteristics of Lamb waves are described by dispersion curves, which represent functional dependence between phase/group velocity of a particular mode of Lamb wave on the frequency-thickness product. The dispersion curves for a single as well as multi-layered media can be obtained numerically and also experimentally [5,6]. No less important role during qualitative analysis with use of guided Lamb waves is the method of wave excitation and reception. The excitation of Lamb waves can be realized by two conceptually different methods [4] – in practice more common excitation on the surface of the plate and excitation within the bounding layers of the plate or at the end face/edge of the plate. The generation of a particular mode of Lamb wave in itself can be realized in various ways. The most common way is the use of piezoelectric transducers [4,5]. In recent years, we can notice increasing use of interdigital transducers [6], benefit from a size and multiple capabilities. However, the main drawback of these transducers is their brittleness, which reflects in handling issues when required to place them on curved surfaces [6]. Another possibility is to use electromagnetic acoustic transducers (EMAT) [5], which do not require a direct contact with surface nor any complaint. The main drawback is the limitation to metallic or magnetic structures and the production of lower power than standard piezoelectric transducers [7]. The use of optical methods such as a laser is still not so common with the main drawback of bulky and expensive equipment [8].

The main aim of presented paper is the qualitative assessment of different methods of Lamb wave excitation, which will incorporate classical piezoelectric transducer producing longitudinal bulk waves.

Derivation of dispersion relation for Lamb waves – solution by method of potentials [7]

Suppose the plane strain problem of a free traction force surfaces as shown in Fig. 1. The motion is defined as two-dimensional so that stresses, strains, displacement and other quantities are independent on *y* coordinate. The unknown displacement vector $\bar{u}$ can be defined with use of Helmholtz decomposition theorem as follows:

$$\bar{u} = \nabla\phi + \nabla\times\bar{\psi}, \tag{1}$$

where $\phi = \phi(x,z)$ and $\bar{\psi} = (0, -\psi(x,z), 0)$ are potential and vector functions respectively. As mentioned above, both of them are functions of only *x* and *z* coordinates.

Fig. 1: Geometry of the plate; h is the thickness of the plate

With help of decomposed displacement vector can be the equation of motion, expressed in terms of displacements, separated into two wave equations, one related to longitudinal waves (Eq. 2) and the second one related to transversal waves (Eq. 3):

$$\nabla^2\phi - \frac{1}{c_L^2}\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2} = 0, \tag{2}$$

$$\nabla^2\psi - \frac{1}{c_T^2}\frac{\mathrm{d}^2\psi}{\mathrm{d}t^2} = 0, \tag{3}$$

where c_L is the speed of dilatational waves, c_T is the speed of shear waves and *t* is time. The assumed solutions of Eq. 2 respectively 3 for the wave propagating from left to right are as follows:

$$\phi = (K_1\sin(pz) + K_2\cos(pz))e^{i(kx-\omega t)}, \tag{4}$$

$$\psi = (K_3\sin(qz) + K_4\cos(qz))e^{i(kx-\omega t)}, \tag{5}$$

where $p^2 = \frac{\omega^2}{c_L^2} - k^2$, $q^2 = \frac{\omega^2}{c_T^2} - k^2$, ω is the angular frequency, K_1, K_2, K_3, K_4 are constants resulting from boundary conditions, *k* is wavenumber variable and i is the imaginary unit. Expressing the displacements *u* and *w* in both axes as well as the stresses σ_{zz} and σ_{zx} in terms of potentials and applying a boundary condition $\sigma_{zx} = \sigma_{zz} = 0$ at $z = \pm\, 0{,}5h$ it is then possible to finally derive the Rayleigh-Lamb frequency equation for symmetric (Eq. 6) and antisymmetric (Eq. 7) Lamb wave modes:

$$\frac{\tan(\frac{qh}{2})}{\tan(\frac{ph}{2})} = -\frac{4k^2pq}{(q^2-k^2)^2} \tag{6}$$

$$\frac{\tan(\frac{qh}{2})}{\tan(\frac{ph}{2})} = -\frac{(q^2-k^2)^2}{4k^2pq} \tag{7}$$

Experimental procedure

There have been used four different methods for excitation of symmetric and/or antisymmetric modes of Lamb wave in total. Namely, excitation with the use of comb-structure with transducer producing longitudinal waves, excitation with liquid and plexiglass wedge with transducer producing longitudinal waves and transducer producing longitudinal waves, which has been placed directly on the surface of the plate. In all four cases, Panametrics C103 1MHz/0,5" transducer has been used as a source of acoustic waves. Vallen AMSY-6 acoustic emission system, manufactured by Vallen Systeme GmbH, has been utilized as a signal generator. A five-cycle sinusoidal tone burst of 250 $V_{peak\text{-}peak}$ and the central frequency of 150 kHz (see Fig. 2) was in all four cases used as driving signal for source transducer.

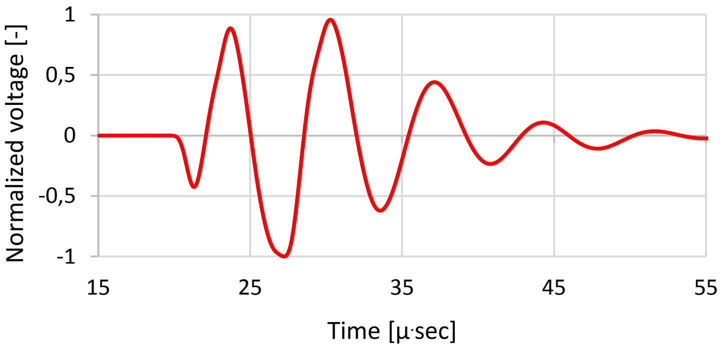

Fig. 2: Driving signal for wave excitation

The signal of a wave, propagating from 200 mm distant source, has been detected by Vallen VS 375-M broadband acoustic emission sensor and further amplified and processed with Vallen AEP5 amplifier and Rohde&Schwartz RTH1002 oscilloscope respectively. The experiments were carried out on one-millimetre thick steel sheet of dimensions 100x70 cm (steel grade 11).

The signal, produced by the transducer, which was placed directly on steel sheet surface, was used as a reference for both symmetric and antisymmetric modes of Lamb wave, further excited by different ways. The angles of incidence in the case of wave excitation with the use of liquid and plexiglass wedges we being calculated using Snell´s law and the knowledge of phase velocity of a particular mode of interest and the excitation frequency:

$$\alpha = arcsin\left(\frac{c_{L-wedge}}{c_{phase}}\right), \tag{8}$$

where α is the angle of incidence, $c_{L-wedge}$ is the speed of longitudinal waves in wedge and c_{phase} is phase velocity of a particular mode of interest, which has to be excited. The dispersion curves for phase velocity (Fig. 3) were obtained by solving Rayleigh-Lamb frequency equation [5]. Dispersion curves for group velocity can be obtained with use of phase velocity dispersion curves and the known relation between these two types of velocities [5]:

$$c_g = \frac{\mathrm{d}(kc_p)}{\mathrm{d}k} = c_p + k\frac{\mathrm{d}c_p}{\mathrm{d}k}. \tag{9}$$

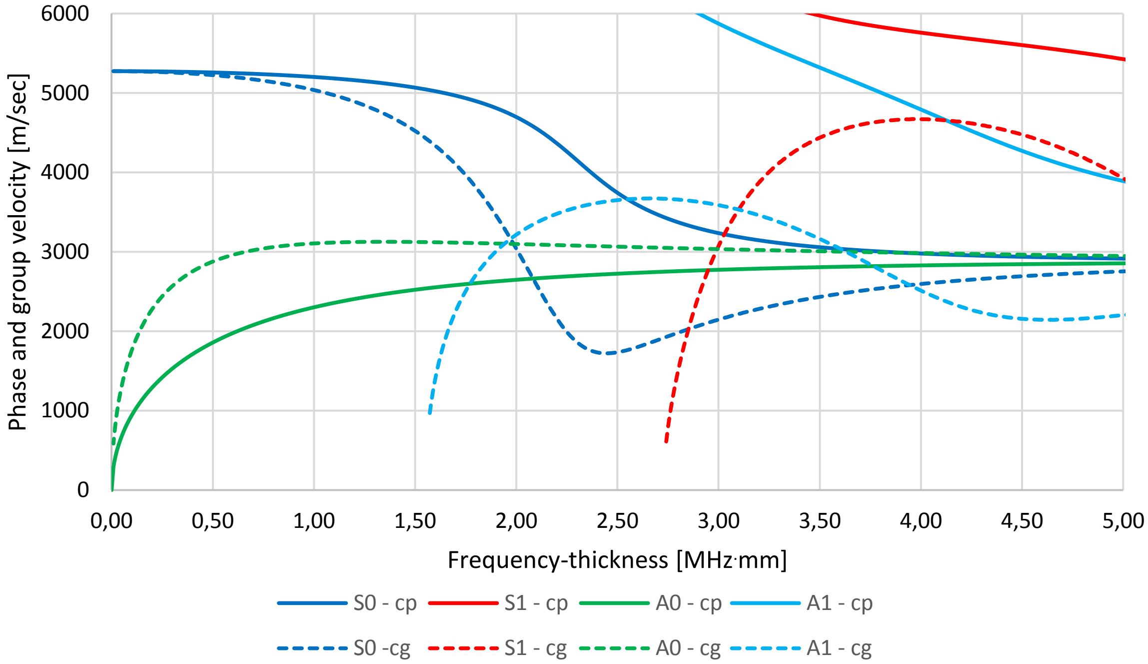

Fig. 3: Dispersion curves for phase and group velocities in case of 1 mm thick steel sheet (c_L = 5900 m/sec; c_T = 3100 m/sec) produced by self-developed code in MATLAB software; S - symmetric and A - antisymmetric modes of Lamb wave

Comb-structure

The comb-structure method has been originally designed for Rayleigh wave excitation [4]. This method can be however used with success also in the case of Lamb wave generation. According to known excitation frequency and known dispersion curve for phase velocity of mode we want to excite, it is possible to calculate the wavelength, which will then define the spacing of two millimetre wide elements that are in direct contact with the plate (See Fig. 4). In the original concept of comb-structure, there is used a piezoelectric crystal, covering the entire upper part of the comb-structure. In our case, we have used the transducer with a contact surface in the shape of a circle with the diameter of 14 mm. The wavelength of the antisymmetric longitudinal wave with the excitation frequency of 150 kHz is equal to 7,5 mm. The excitation area of the transducer barely covers three segments, however, a certain portion of the acoustic pressure perturbation is delivered to the outer elements thanks to multiple reflections.

Fig. 4: Comb-structure element

Liquid wedge

The incorporation of the liquid wedge for Lamb wave excitation is relatively common technique, capable of delivering reputable results when properly adjusted. The advantage of this method lies in the possibility of excitation of S0 - symmetric and A0 - antisymmetric modes of Lamb wave having relatively small wavenumbers. The cause of this fact lies in the speed of longitudinal waves in water, which is nearly 1500 m/sec. Another considerable advantage is the minimum attenuation in liquid unlike plexiglass and also in existence of only longitudinal waves in the liquid with zero shear modulus. A certain disadvantage is clumsy handling. The self-manufactured liquid wedge uses an inflatable balloon, filled with water, which is together with the transducer mounted in plexiglass holder (See Fig. 5). The liquid wedge is used to generate the symmetric mode of Lamb wave, which results in the inclination angle of 16,3° for the S0 phase velocity of 5270 m/sec and frequency of 150 kHz.

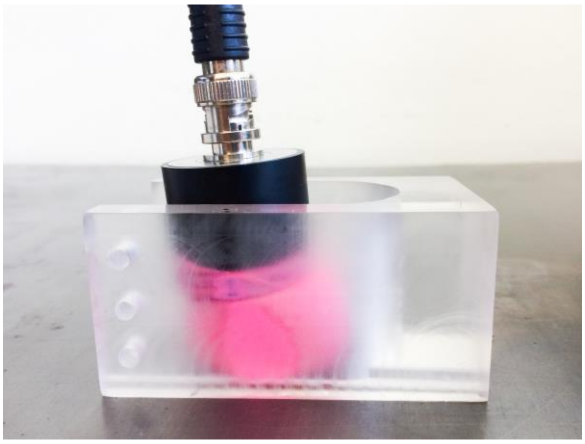

Fig. 5: Liquid wedge

Plexiglass wedge

The plexiglass wedge is suitable for generation of S0 - symmetric as well as A0 - antisymmetric modes of Lamb wave. The wedge is 25 mm thick and the radius after which moves the counterpart with the transducer has a radius of 35 mm. In order to set the proper inclination angle, there has to be measured the velocity of longitudinal waves, whose value is 2667 m/sec. For further experiments, there has been additionally measured the speed of transversal waves, which resulted in the value of 1371 m/sec. The measurement of the speed of transversal waves has been realized with use of Panametrics V155 transducer. The plexiglass wedge (Fig. 6) was in our case used to generate the symmetric mode of Lamb wave, which results in the inclination angle of 30,4° for the S0 phase velocity of 5270 m/sec and frequency of 150 kHz.

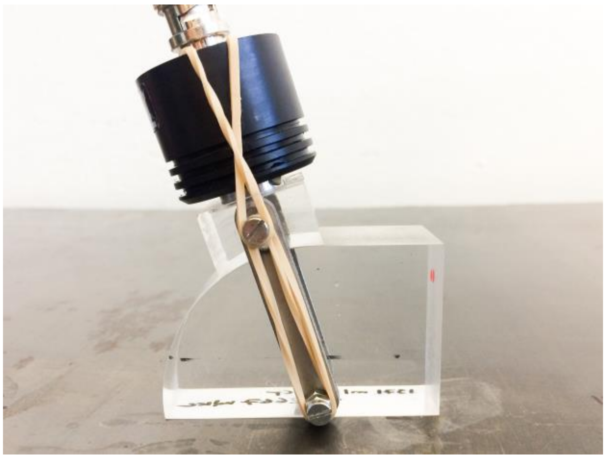

Fig. 6: Plexiglass wedge

Results

The results of detection the symmetric and antisymmetric modes of Lamb wave originating from excitation by the transducer, directly placed on the steel sheet, were used as a reference for the remaining three methods of excitation of a particular mode of Lamb wave. Figure 7 displays us the result of the normalized voltage as the function of time, which belongs to the method when the transducer is directly placed on the steel sheet.

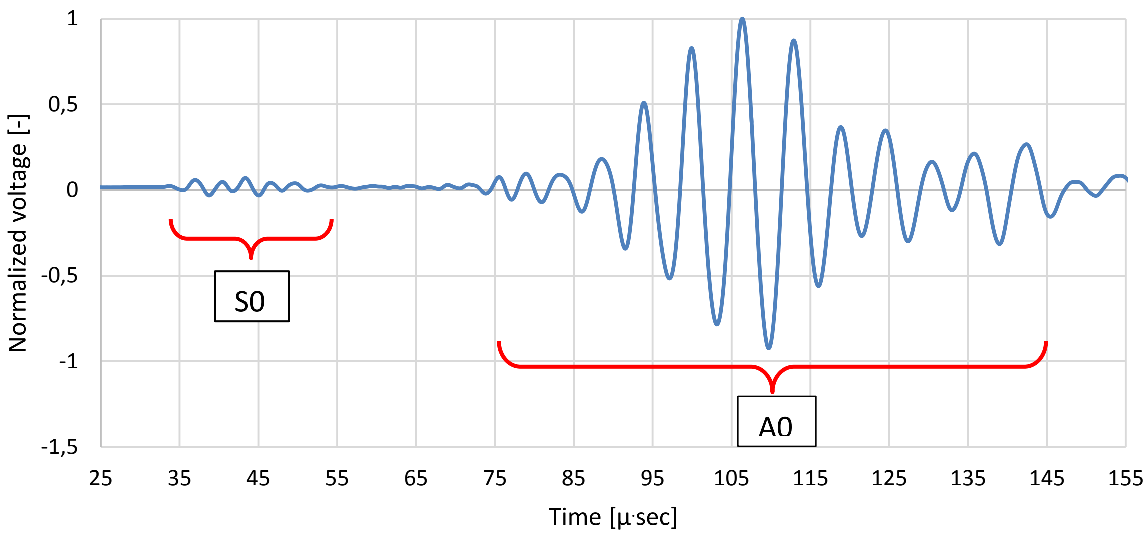

Fig. 7: Normalized voltage versus time (Transducer directly placed on the steel sheet)

The methodology of how to evaluate the efficiency can be realized by the way of comparing the amplitude of selected mode, which has to be excited by a particular method to the amplitude of the same mode, which was excited by the transducer directly placed on the steel sheet. The amplitude of A0 and S0 modes of Lamb wave are 96,3 and 72,5 dB_{AE} respectively. dB_{AE} unit expresses the direct signal of the transducer, referenced to the value of 1 µV. The comb-structure was, thanks to its geometry, utilized to generate purely the A0 mode of Lamb wave. The results met the expectations, the increase of the amplitude, compared to the reference value, is 4,6 dB with the present decrease of the amplitude of S0 mode by 10,8 dB. Figure 8 displays the dependency between the normalized voltage and time for the comb-structure method.

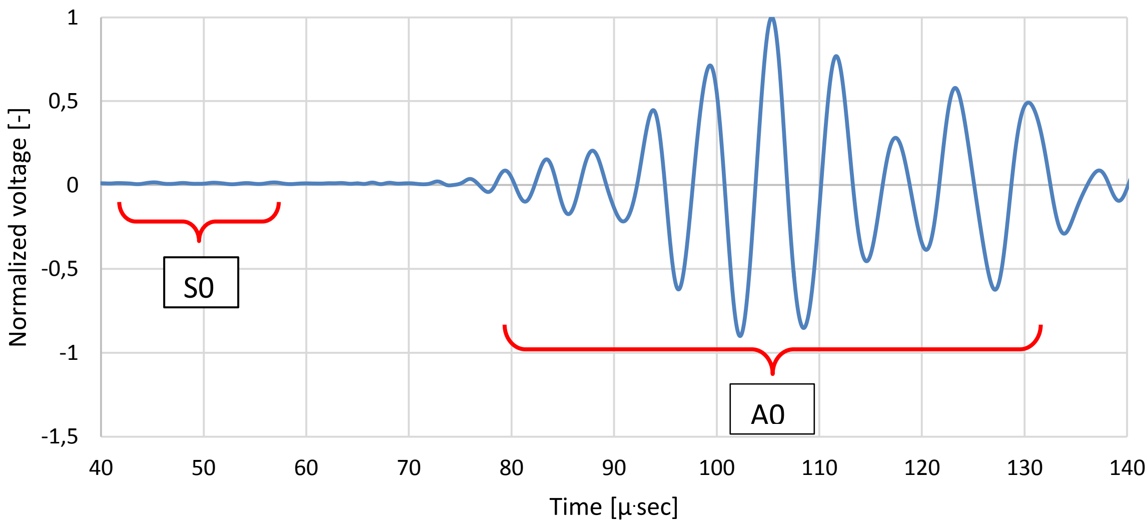

Fig. 8: Normalized voltage versus time (Comb-structure method)

The plexiglass wedge, as well as the liquid wedge, had adjusted their inclination angles in order to generate the S0 mode. The increase in amplitude is 1,8 and 2 dB for the case of liquid and plexiglass wedge respectively. Both methods also naturally produced A0 mode. The decrease of the A0 mode amplitude is in the case of plexiglass wedge equal to 16,5 dB and in the case of liquid wedge equal to 5,3 dB. The dependencies between the normalized voltage and time for plexiglass as well as liquid wedge are displayed in Fig. 9.

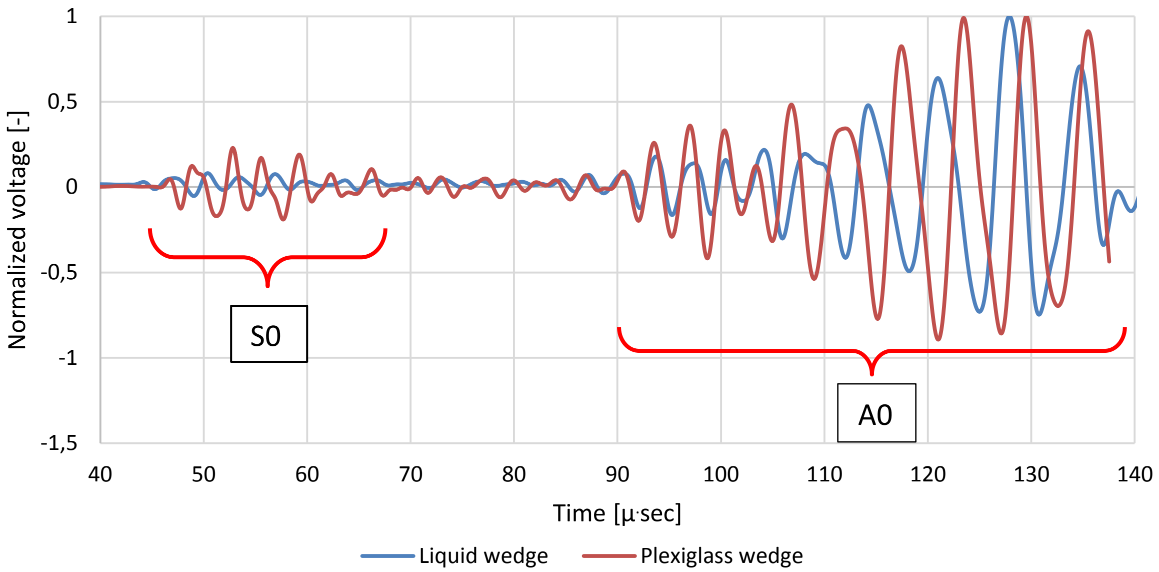

Fig. 9: Normalized voltage versus time (Liquid wedge and plexiglass wedge method)

Conclusion

Four different methods for excitation of symmetric and antisymmetric modes of Lamb wave were used – direct placement of the transducer on the steel sheet, comb-structure method, plexiglass wedge method, and liquid wedge method. In order to compare the methods with each other, the authors have decided to use results originating from the excitation of the S0/A0 modes by direct placement of the transducer on the steel sheet as s reference to which will be the other methods compared. Despite the fact that the comb-structure method, designed for sole excitation of A0 mode, has not used a transducer which will cover the entire area of the comb-structure, has this method reached 4,6 dB higher amplitude of A0 mode compared to the reference value, meanwhile, the amplitude of S0 mode was very well damped. The wedge transducers had adjusted their inclination angles in order to generate the S0 mode. In both cases, the amplitude of S0 mode was approximately 2 dB above the amplitude of reference signal, meanwhile, the amplitude of A0 mode was 5, respectively 16 dB lower than the reference value.

Realized experiments show the specific advantages of used methods. The advantage of the classical approach, when the transducer is directly placed on the plate, is in relatively high amplitudes for both A0 and S0 modes. The comb-structure method belongs to dedicated methods from the perspective of excitation of a particular mode of defined wavelength, which is implicitly bounded to the material properties of the plate including its thickness. The wedge methods proved to be solid performers with the main advantage of the continuous change of the inclination angle, which is directly bounded to various types or modes of waves. On the other hand, the wedge method encounters the presence of leaky waves [4,5], which to a certain extent influence the amplitudes of generated surface wave.

For future work, the authors would like to focus on the design of the liquid as well as plexiglass wedges in order to improve their efficiency.

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