

## Investigation of mechanical tension in sheet products by symmetrical Lamb waves

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### Introduction

Longitudinal surface acoustic waves (LSAW) excited on the surface of isotropic solid surfaces by the first critical angle are characterized by the bigger longitudinal component of surface vibration than the transversal component [1]. This determines their property to propagate with phase velocity close to the bulk longitudinal wave phase velocity depending also on the Poisson's ratio of the solid. The prediction that the LSAW phase velocity must depend on a solid surface layer mechanical state can be made. It was theoretically proved that in sheet products with the thickness  $h \ll \lambda_{LE}$  ( $\lambda_{LE}$  is the length of the Lamb wave) the dispersal symmetric  $s_0$  and antisymmetric  $\alpha_0$  Lamb waves of the zero order can be excited [2]. Experimentally it was found that in sheet products, the wave excited by the angle transducer matched for the first critical angle (LSAW wave) is symmetric Lamb wave  $s_0$  of a zero order.

The purpose of this work is to investigate experimentally the properties and the dependence on the mechanical stress of the sheet of symmetric  $s_0$  Lamb waves excited by the LSAW transducer.

### Theory

When the longitudinal surface acoustic wave is excited by the first critical angle. The material particles moves in the trajectory of the ellipse (Fig. 1) with the longitudinal component  $\xi_x > \xi_z$  (where  $\xi_z$  is the normal component,  $\lambda_L$  - bulk longitudinal wave length).

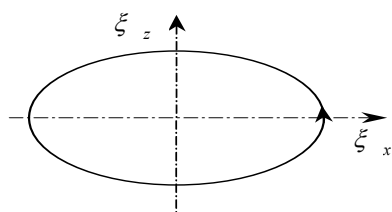


Fig. 1. The LSAW trajectory of surface point movement

The tangential  $\xi_x$  and the normal  $\xi_z$  oscillation components in the symmetric wave are described by [3]:

$$\xi_{S_z} = -A_S q_S \left( \frac{\sinh q_S z}{\sinh q_S \frac{h}{2}} - \frac{2k_S^2}{k_S^2 + s_S^2} \cdot \frac{\sinh s_S z}{\sinh s_S \frac{h}{2}} \right) e^{i(k_S x - \omega t)},$$

$$\xi_{S_x} = A_S k_S \left( \frac{\cosh q_S z}{\sinh q_S \frac{h}{2}} - \frac{2q_S s_S}{k_S^2 + s_S^2} \cdot \frac{\cosh s_S z}{\sinh 2s_S \frac{h}{2}} \right) e^{i(k_S x - \omega t - \pi/2)},$$

where:  $A_S = \text{const}$ ;  $q_S = \sqrt{k_S^2 - k_L^2}$ ;  $s_S = \sqrt{k_S^2 - k_T^2}$ ;  $k_S = \omega h / 2c_S$  is the number of symmetric Lamb wave,  $k_L$  and  $k_T$  are the numbers of bulk longitudinal and transversal waves;  $h$  is the thickness of the plate;  $\omega = 2\pi f$ ,  $f$  is the frequency;  $c_s$  is the phase velocity of symmetric Lamb wave.

Symmetric Lamb waves are dispersal and their phase velocity  $c_s$  depends not only on the thickness of the sheet  $h$ , but also on the sound velocity in a sheet material and changes from  $\sqrt{E / \rho(1 - \sigma^2)}$  to the  $c_R$  (Fig.2); where  $E$  is Young module;  $\rho$  is the density;  $\sigma$  is Poisson's ratio;  $c_R$  is the phase velocity of Rayleigh waves [2].

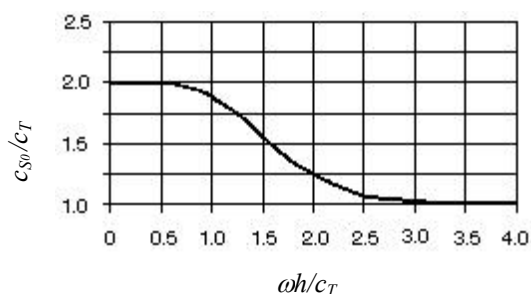


Fig. 2. Theoretical dependence of symmetrical Lamb wave  $s_0$  phase velocity on bulk transversal wave velocity [2]

It excites the symmetric Lamb wave  $s_0$ , with dominating longitudinal component in acoustically thin sheets ( $h \ll \lambda_L$ ) because of LSAW interaction with both free sheet surfaces. Physical origin of such a wave determines that the features of  $s_0$  wave more depend on factors determining propagation of the longitudinal component, but not the transversal components. One of such factors is the mechanical tension of the material, influencing the material density and the Poisson's ratio  $\sigma$ .

### Methodology and results of experimental investigation

Strip-shaped samples of a special shape with the broadened ends for better fixing in a stretch mechanism

were made from a bronze sheet for investigation of the excited LSAW  $s_0$  mode symmetric Lamb wave (Fig. 3). The thickness of the sheet was  $h = 0.09$  mm.

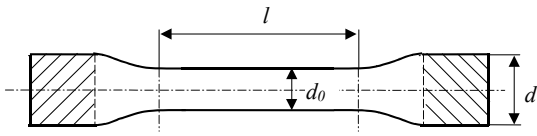


Fig. 3. The form of the sample

The sample is fixed in the stretch mechanism and the signal of symmetric Lamb wave is excited in its narrowed part by the LSAW angle transmitter, picked up by the LSAW receiver situated at the distance  $l_0$  from the transmitter (Fig.4).

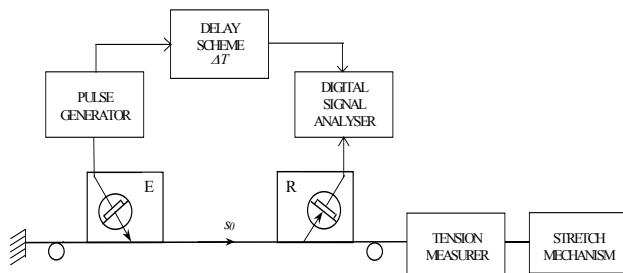


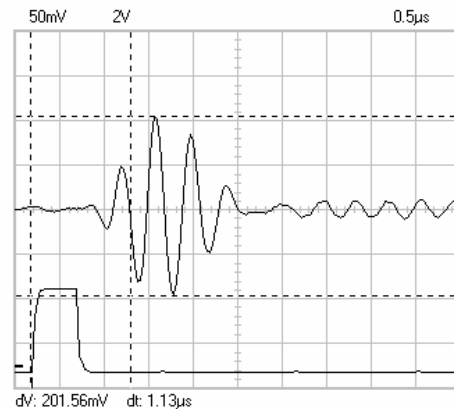
Fig. 4. The investigation scheme: E and R are the emitter and receiver of ultrasound pulses;  $S_0$  is the symmetric Lamb wave

The received  $s_0$  Lamb wave ultrasound signal is indicated by the digital signal analyzer (DSA) synchronized by the delayed pulses of the electric pulse oscillator (Fig. 5). Its amplitude and the position in the time domain are measured at the same instant. As it is seen from the theoretical dependence (Fig. 2), the phase velocity of the symmetric  $s_0$  mode Lamb wave quickly changes in the limits  $c_R < c_s < 2c_R$ , when  $\omega h/2c_T$  changes from 2.5 to 1. The strip-shaped sample is in the range of strong symmetric Lamb wave dispersion, when the ultrasound signal frequency  $f = 2$  MHz, the bronze sheet thickness  $h = 0.09$  mm, and the parameter  $\omega h/2c_T \approx 1.88$  ( $c_T \approx 3000$  m/s). The  $s_0$  mode dispersal Lamb wave phase velocity is calculated having changed the distance between the transducer by  $\Delta l_0 = 32$  mm and having measured the shift of the received signal in the time domain  $\Delta \tau = 7.69$   $\mu$ s, when the mechanical stress  $W = 0$  ( $c_s = \Delta l_0/\Delta \tau = 4160$  m/s).

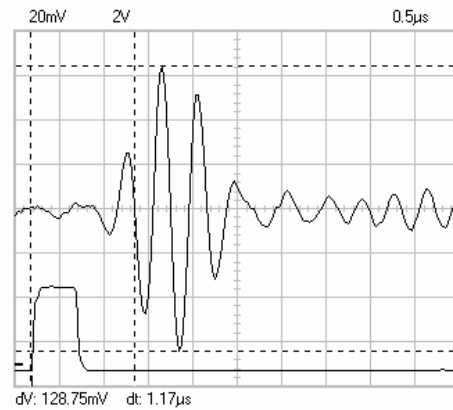
The dependencies  $\Delta A_s(W)$  and  $\Delta \tau(W)$  were measured changing the mechanical tension  $W = F/dh$  (in our case  $F$  is the sample dragging power in the direction  $x$  (Fig. 3)) and recording the change of the received ultrasound amplitude  $\Delta A_s$  and the time shift  $\Delta \tau_s$ .

The ultrasound signals, propagating in the bronze strip-shaped sample, and registered by the digital spectrum analyzer PCS64i discretely changing the mechanical tension  $W$ , are shown in Fig. 5.

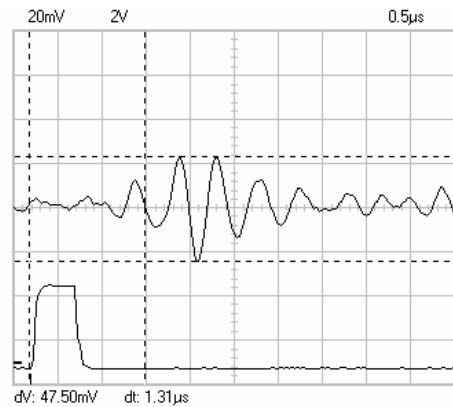
It was noticed that when the mechanical tension increases, the  $s_0$  mode Lamb wave signal amplitude  $A_s$  and phase propagation velocity  $c_s$  decrease.



a)



b)



c)

Fig. 5. Ultrasound impulse  $s_0$  mode Lamb wave signals excited and received by the angle LSAW transducer, when a)  $W = 0$ ; b)  $W = 55.6$  N/mm<sup>2</sup>; c)  $W = 92.6$  N/mm<sup>2</sup>

The calculated according to the measurement results dependencies  $A_s/(A_s)_{max}(W)$  and  $c_s(W)$  of the  $s_0$  mode Lamb wave attenuation are shown in Fig. 6 and Fig. 7.

Stretching of the strip-shaped sample changes the amplitude of the signal (attenuation) as well as the phase velocity, but the dependence  $c_s$  is comparatively weak, so

it is recommended to control the mechanical tension and the state of the strip-shaped construction measuring attenuation of the  $s_0$  Lamb wave.

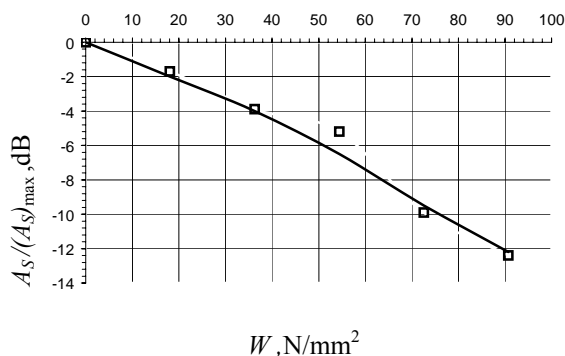


Fig. 6. The  $s_0$  mode Lamb wave signal amplitude versus mechanical tension

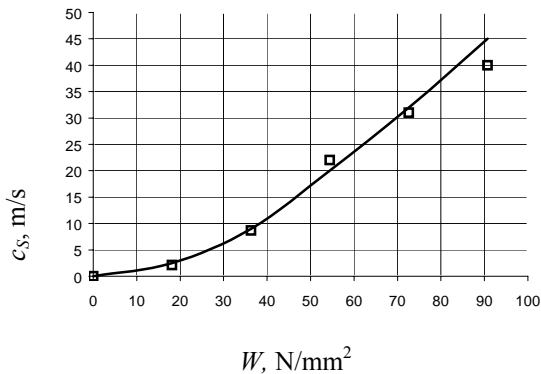


Fig. 7. The  $s_0$  mode Lamb wave phase velocity versus mechanical tension

The angle transducers in this case are not the best because the measurements of the signal amplitude (attenuation) are sensitive to the stability of acoustic contact. The strip-shaped piezoelements or their gratings would be more promising for excitation and reception of the  $s_0$  Lamb wave [3].

## Conclusions

It was theoretically and experimentally shown that symmetric Lamb waves can be excited effectively in acoustically thin sheet by the angular ultrasound angle matched for the first critical angle. The attenuation of those waves strongly depends on the mechanical stress of the sheet and the measurements of the attenuation of symmetric waves can be effectively used for the mechanical state research of sheet materials by non-destructive method.

## References

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## Lakštinių gaminių mechaninio įtempio tyrimas simetrinėmis Lembo bangomis

### Reziumė

Aprašomi simetrinių Lembo bangų lakštuose dispersijos ir slopinimo tyrimai. Simetrinės megahercinio dažnio Lembo bangos akustiškai plonuose lakštuose sužadinamos ir priimamos kampiniais piezokeitikliais, suderintais pirmajam kritiniam kampui. Eksperimentiniais matavimais nustatyta, kad simetrinių Lembo bangų slopinimas tiesiškai priklauso nuo lakšto mechaninio įtempio. Siūloma šią priklausomybę panaudoti lakštinių gaminių mechaninei būsenai tirti neardomuoju būdu.

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