ULTRASONIC WAVE PROPAGATION IN MATERIALS WITH MECHANICAL STRESSES

Yonka IVANOVA, *Todor PARTALIN, Mitko MIHOVSKI,

INSTITUTE OF MECHANICS-BAS, Sofia, Bulgaria
e-mail: nntdd@imbm.bas.bg , yonka@imbm.bas.bg
*SOFIA UNIVERSITY, Faculty of Mathematics and Informatics, Sofia, Bulgaria, e-mail: topart@fmi.uni-sofia.bg

ABSTRACT
The present paper concerns ultrasonic wave propagation in materials with mechanical stresses. In order to evaluate the stresses by ultrasound the investigation is performed. The variations of the velocities, phases and spectra of the ultrasonic impulses in stressed media are studied.
KEY WORDS: ultrasonic surface waves, velocity, mechanical stresses

1. Introduction

The possibilities of application of ultrasonic surface waves for the evaluation of mechanical stresses are studied in the papers [1,2]. The experiments on the metal sheet with a stress gradient as transversal so longitudinal are carried out. That formulation makes the results difficult to be compared and assessed. In order to find quantitative interrelations between the parameters of the stress-state of the material and the parameters of surface ultrasonic waves it is necessary to create a model in which only the transversal stress gradient is significant.

The aim of the work is to find the dependence between the parameters of the stress-state and the ultrasonic surface wave.

The procedure of the experiment is realized by consecutive loading of metal sheets and registration the ultrasonic wave parameters. A triangular shaped beam with constant strength is subjected to bending so that desired stress distribution is obtained. The propagation of ultrasonic surface waves in bent metal beam is evaluated depending on the stress gradient and the ratio λ/h, where λ is ultrasonic waves length and h is thickness of metal sample.

The sample, made from low carbon steel, is loaded with force P as shown in fig. 1. The width of the beam $b(x)$ at the distance x from the application point of bending force P is defined by the expression

(1.1) $$b(x) = 2xtg\frac{\alpha}{2} = 2xk$$

where α is the angle at the apex of the triangular beam and $tg\frac{\alpha}{2} = k$.

The normal stress σ is determined by the formula [3]

(1.2) $$\frac{M_y(x)}{W_y(x)} = \sigma < \sigma_s,$$

where M_y is a bending moment toward axis y, W_y is a resistance moment, σ_s is a yield stress. The axes y and z are principal axes of inertia. The maximum value of the normal stress is determined following (1.2)

(1.3) $$\sigma(x) = \frac{M_y}{W_y} = \frac{Px}{\frac{b(x)h^2}{6}}$$

where x is the arm of the applied force P [3,4]. Taking into account of (1.1- 1.3) we obtain the normal stress that is independent of x

(1.4) $$\sigma = \frac{3P}{h^2 k} .$$

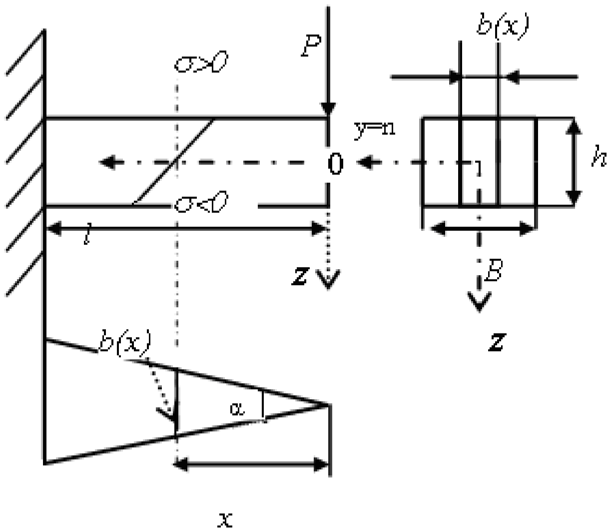


Fig.1. Scheme of bending: metal beam with constant height and variable width, loaded by bending force P

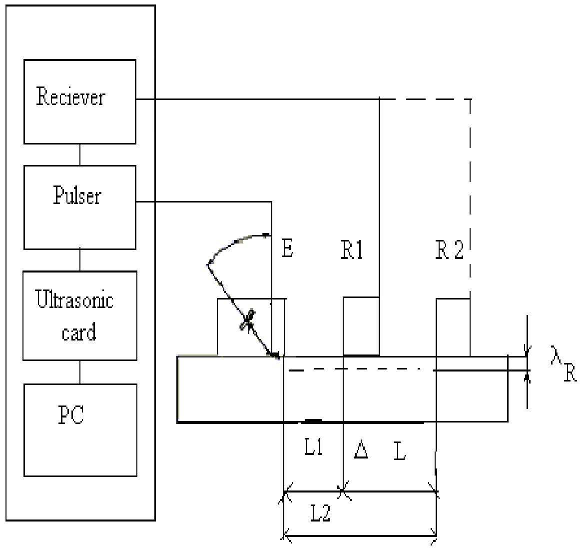


Fig.2. An experimental set-up for ultrasonic investigation

According the scheme in fig.1 the part of the beam where $z<0$ is compressed and the part where $z>0$ is strained.

The samples have the same length, width (l=0.5 m, B=0.4142 m), and angle $\alpha=45^o$ or k =0.414 and different thicknesses *h (5, 6, 8, 10 mm)*. The bending loads are chosen small enough to prevent residual deformations and stresses. The stress gradient is constant and equal to the ratio $2\sigma / h$.

2. Ultrasonic investigations

An experimental set-up is shown in fig. 2. A computerized ultrasonic instrument is used [8]. The ultrasonic instrument allows measuring the time of ultrasonic impulse with accuracy up to 1 ns and 8 bits resolution at sampling rate of 100 MHz. In order to attain a higher accuracy of investigations precautions for maintaining constant conditions for the acoustic signals generation are undertaken.

3. Experiments and results

Surface Rayleigh ultrasonic waves are excited by an angular transducer with variable angle, at an angle of refraction close to the second critical one of a system plexiglass-steel. The nominal frequencies of the transducers are 2 and 4 MHz. The wave lengths λ_R are approximately 0.75 mm and 1.5 mm for the frequency 4 MHz and 2 MHz. The propagation depth of surface wave is of the order of 1.7 λ_R [5,6] which makes about 2.5 mm and 1.25 mm for 2 MHz and 4 MHz.

A digital form signals emitted by transducer E and received by transducer R are recorded by a through transmission technique as shown in fig.2. The receiving transducer moves along the acoustic path covering distance ΔL .Velocities of surface waves are measured for beams with varying thickness h and loads till 500N, so the stress to be less than 50-60 MPa. Velocity of the surface wave C_R is estimated following (3.1) [7] and measured as shown in the fig. 2 .

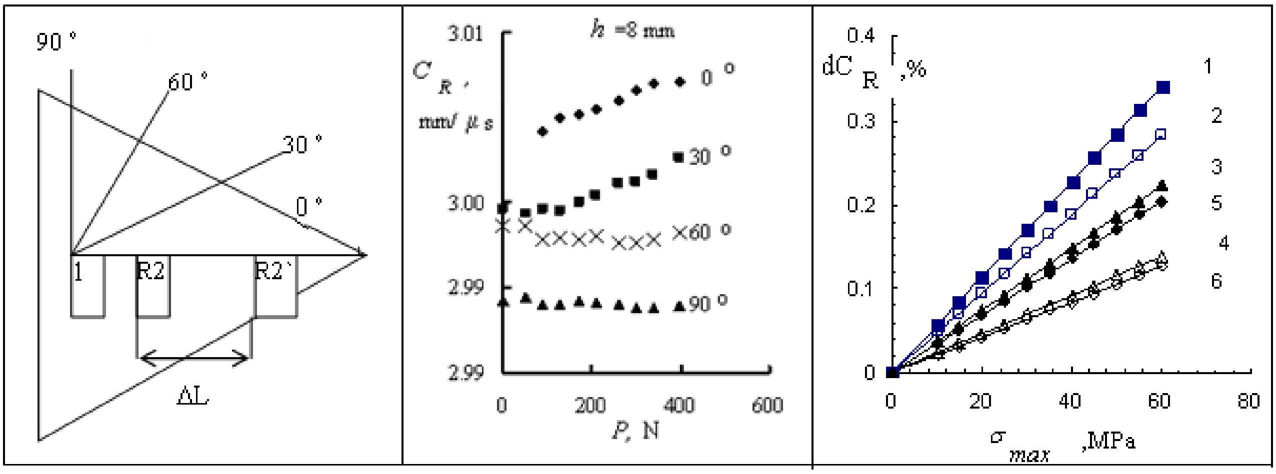
(3.1) $$C_R = \frac{2(\mathrm{L2} - \mathrm{L1})}{\tau_2 - \tau_1} = \frac{\Delta \mathrm{L}}{\Delta \tau} ,$$

where ΔL is the distance between position R1 and R2 of the receiver R, τ_1 and τ_2 are transit times of the wave obtained at distances L1 and L2. The transit time is registered from the beginning of the ultrasonic pulse. The distance L1 is approximately 30mm that makes about 20 λ_R for 2 MHz and 40 λ_R for 4 MHz. The distance L2 is about 7 times higher. The relative change of the surface wave velocity under stress is determined by (3.2)

(3.2) $$dC_R = (C_R - C_{R_o}) / C_{R_o}$$

where C_R and C_{R_o} are the velocities in stressed and unstressed sample.

Measurements of the velocity in different directions without load show anisotropy of the material. The anisotropy is assessed as a relative change in velocities in directions from 0 to 90 ° toward the *x* axis as shown in fig.3(a). Figure 3(b) gives a change of velocities that are measured in different directions under loads. Anisotropy does not change the influence of the stress on the propagation of ultrasonic wave. Additional studies are necessary to make clearer how significant anisotropy is.



a b Fig.4

Fig.3. Ultrasonic investigation of the anisotropy:
(a) Scheme of ultrasonic measurement of the anisotropy
(b) Dependence of C_R on loads P

Fig.4. Dependence dC_R-σ max: 1-h=5mm f=2MHz;2-5mm,f=4MHz;3-h=8mm,f=2MHz, 4-h=8mm,f=4MHz; 5-h=10mm,f=2MHz; 6-h=10mm,f=4Mhz

Figure 4 show the dependence of the relative changes dC_R on the maximum stresses at the surface, obtained for the frequencies 2 MHz and 4 MHz for different thicknesses *h*. The results are obtained for the direction 0 degree according the fig.3a, in other directions are measured but not presented. The use of the various frequencies allows the observing the stress gradient influence on the surface wave velocity. The changes in velocity are different for different ratio λ / h. The relative changes of the surface wave velocity obtained at 2 MHz with deeper penetration of ultrasonic wave are higher than these at 4 MHz.

Signals from ultrasonic surface waves before and after loading for samples are shown in fig. 5(a) - 5 (d). The signals when sample is loaded are received earlier than those of unloaded sample and their shapes and lengths are changed.

The presence of the stress gradient cause a change of spectrum of the pulse wave [2]. Analysis of the dependence on the stress gradient is a complex task, which requires investigation at the various frequencies and signal processing methods.

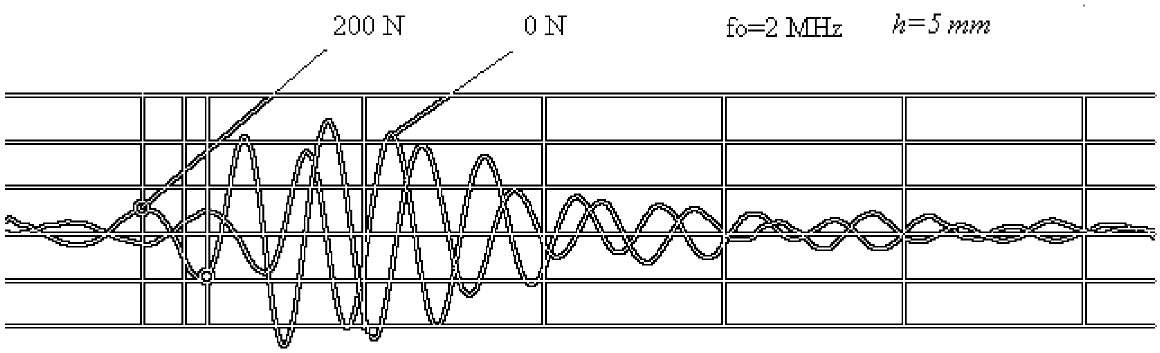


Fig.5a) Signals before and after loading of the sample with *h*=5 mm, frequency 2 MHz

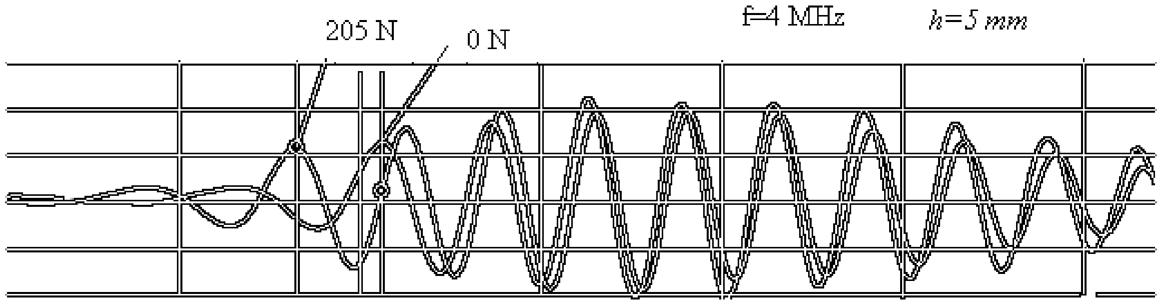


Fig.5b) Signals before and after loading of the sample with *h*=5 mm, frequency 4 MHz

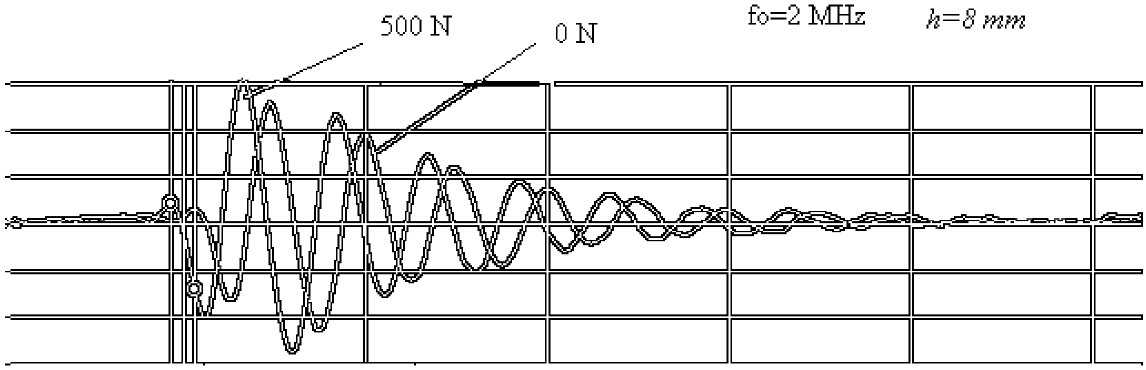


Fig.5c) Signals before and after loading of the sample with *h*=8 mm, frequency 2 MHz

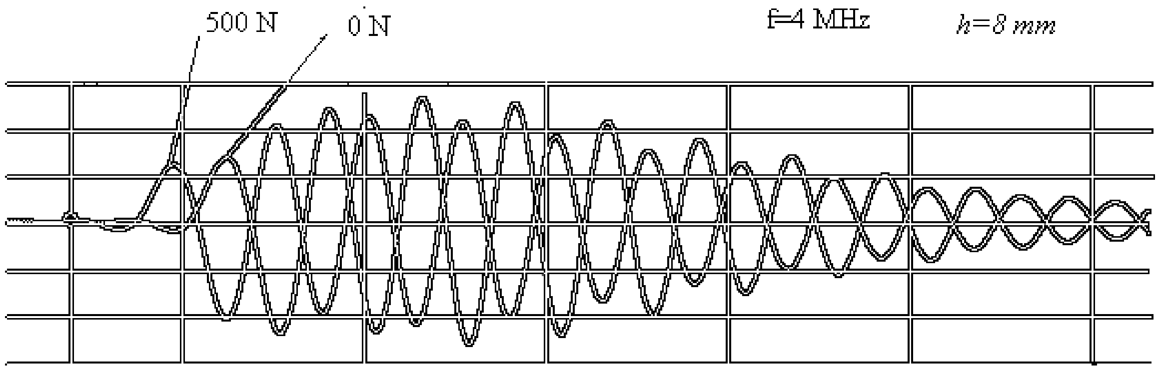


Fig.5d) Signals before and after loading of the sample beam with *h*=8 mm, frequency 4 MHz

Fig.5

4. Signal processing

The registered signals from surface acoustic ultrasonic waves are processed as described in [7]. The procedure includes smoothing, filtering, applying a Fourier transformation and determination of the spectrum parameter (real and imaginary part, phases and amplitudes, respectively) [9]. To assess difference between signals coming from an unloaded specimens and these ones with mechanical stresses, we use a cross-spectrum analysis [10,11]. It enables us to find correlations between signals obtained for one and the same distance and shifted with respect to time. We can also estimate the phase difference between those signals [10].

The complex frequency spectrum of signal x(t) is found after performing Fourier transformation

(4.1) $G(\omega) = \int_{t_0}^{t_0+T} x(t)e^{-i\omega t}dt = S(\omega)e^{-i\varphi(\omega)}$, where $S(\omega)$ is the amplitude frequency spectrum given by (4.2)

(4.2) $S(\omega) = |G(\omega)| = \sqrt{[\mathrm{Re}\,G(\omega)]^2 + [\mathrm{Im}\,G(\omega)]^2}$.

The phase frequency spectrum is expressed by

(4.3) $\phi\ (\omega) = \arg G(\omega) = arctg(\frac{\mathrm{Im}\,G(\omega)}{\mathrm{Re}\,G(\omega)})$,where $\mathrm{Im}(G(\omega)) = \int_{t_0}^{t_0+T} x(t)\sin\omega t dt$ and $\mathrm{Re}(G(\omega)) = \int_{t_0}^{t_0+T} x(t)\cos\omega t dt$.

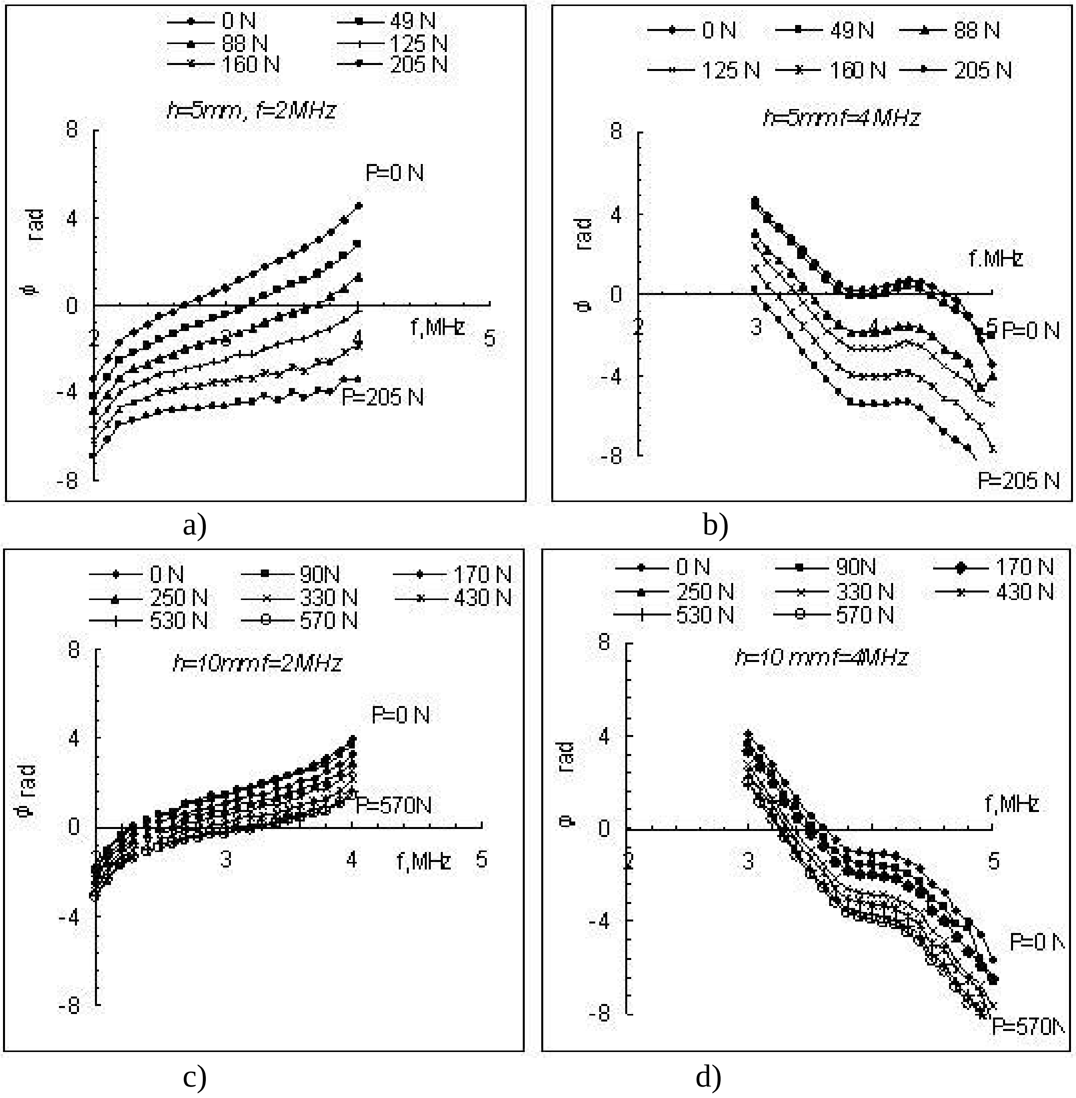


Fig.6. Phase spectra of ultrasonic signals

The phases of the ultrasonic signals obtained from thinner sample *h*=5mm with high stress gradient are shown in fig. 6 a,b. at 2 and 4 MHz. The phases of the signals obtained for different loading are well distinguished. Figure 6 c,d show the phase spectra from sample with small stress gradient and thickness *h*=10 mm. The increasing of the loading causes the change in the phases curves. For the materials with higher stress gradient the distances between phases are larger than these obtained in lower stress gradient.

5. Cross-spectrum analysis

We look for change of the shape of signals, spectra and phase differences along each material, using for that purpose a cross-correlation function (5.1).

The cross-correlation function $CRF(\tau)$ characterizes the change of a specific signal x(t) as compared to another one $y(t+\tau)$, shifted in time τ (5.1)

(5.1) $$CRF_{xy}(\tau) = \frac{1}{T}\int_{t_0}^{t_o+T} x(t)y(t+\tau)dt,$$

where $x(t)$ is the signal recorded at a distance x and time t, $y(t)$ is another signal recorded at the same distance but shifted in time τ.

To assess the interrelation between the spectral components of the two signals, we use a cross-spectral density or a cross-spectrum. Its is a Fourier image of the cross-correlation function being expressed by the relation

(5.2) $$CS_{xy}(f) = \int_{-\infty}^{\infty} CRF_{xy}(t)e^{-j2\pi f\tau}d\tau$$

The cross-spectrum is found as follows (5.3) [11]

(5.3) $CS_{xy}(f) = F[x^*(t)y(t+\tau)] = S_x{}^*(f)S_y(f)$, where $S_x(f)$ is the Fourier image of $x(t)$, $S_x{}^*(f)$ is an image complex-conjugated to $S_x(f)$, and $S_y(f)$ is the Fourier image of $y(t)$ respectively.

(5.4) $CS_{xy}(f) = CO(f) + iQ(f) = |CS_{xy}|\exp\{i\Phi_x\}$, where $CO(f)$ is the real part, $Q(f)$ is the imaginary one, and Φ is the phase of the cross-spectral function.

The phase Φ_{xy} of the cross-spectrum CS(f) is found as in [10,11] and it determines the phase differences between the studied signals $x(t)$ and $y(t)$ in the specified frequency range.

(5.5) $$\Phi_{xy}(f) = arctg\left(\frac{\mathrm{Im}(CS_{xy}(f))}{\mathrm{Re}(CS_{xy}(f))}\right).$$

For comparing the ultrasonic signals at different loads the spectrum of signal of unloaded materials S0 is correlated with the spectrum of loaded materials Si . The symbols are Φ0i, where i=1,2...8 are corresponding loads 0N, 50N,90N,170,205N,330N,430N,520N. The phases differences are determined in the frequency region 1-4 MHz and are shown in the figure 7 . The results from cross spectral analysis show that the stress-state causes the variation in the cross-spectrum phase Φ.

The coefficient S is the slope of the cross-spectrum phase Φ and is determined by (5.6).

(5.6) $$\Phi(f) = S(f - f_o)$$

The dependences of the cross-spectrum phase Φ on the frequency f from samples with *h*=5mm and *h*=10 mm are shown in the fig.7. The curves are different and the differences are considerable for the increasing stress. The slope of Φ(f) can be used as the information parameter for identification of different loads.

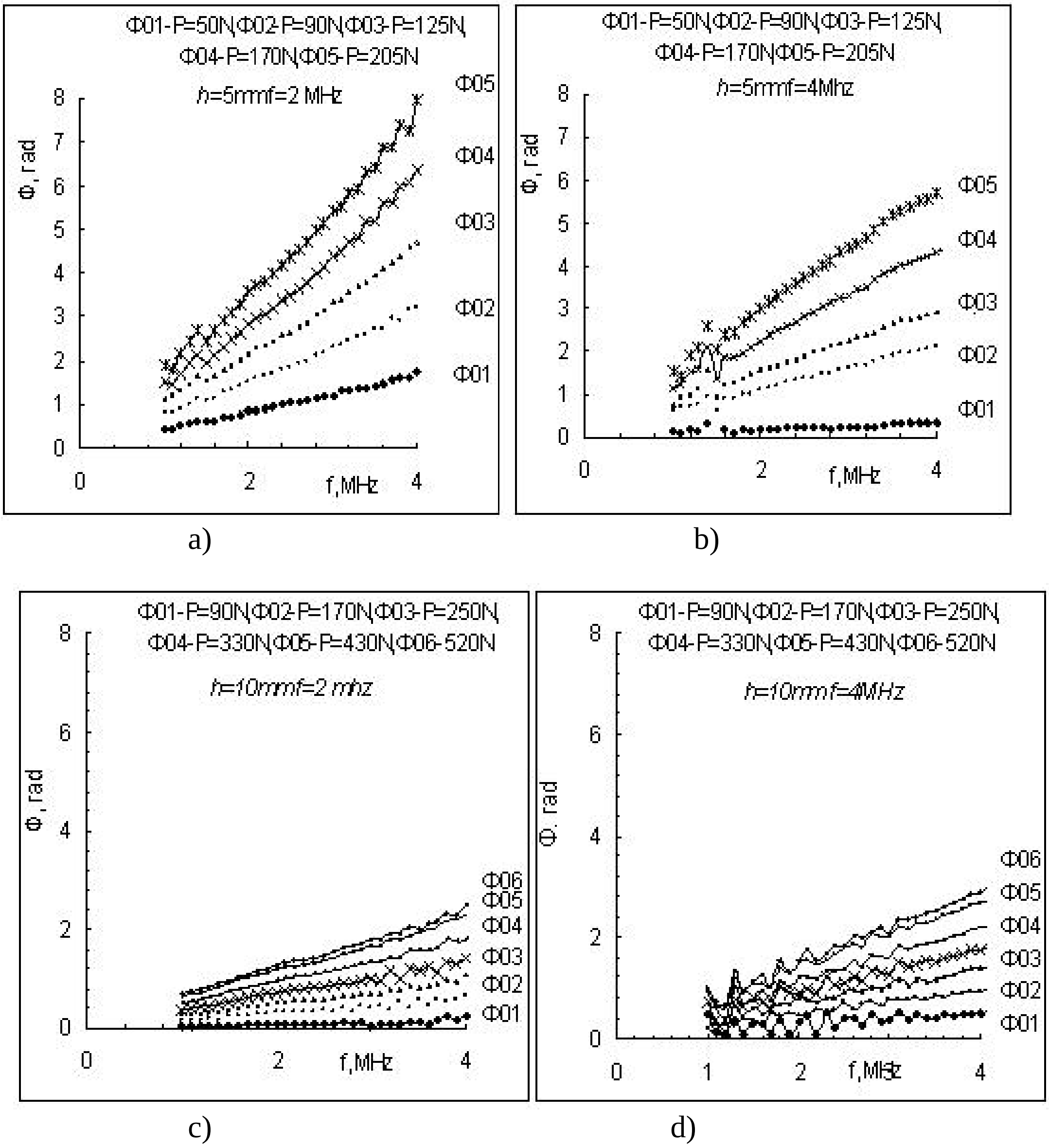
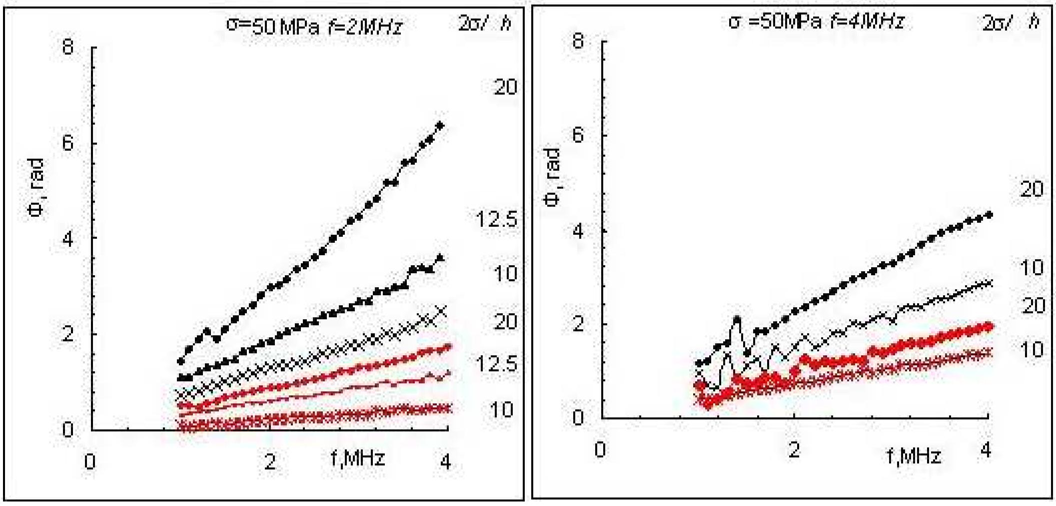


Fig.7. Dependence of cross-spectrum phase Φ on the frequency f from sample with *h*=5mm (a) - 2 MHz, (b) - 4 MHz and sample with *h*=10 mm (c) - 2 MHz, (d) - 4 MHz

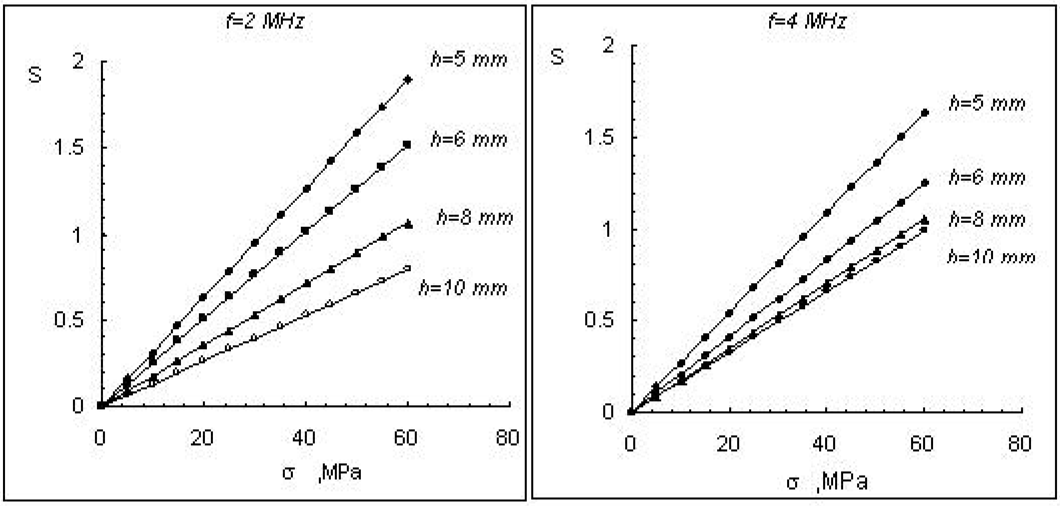
The figure 8(a), (b) show Φ(f) for materials with the stress σ =50 MPa and stress gradient ratio $2\sigma / h$ from 10 [MPa/mm] to 20 [MPa/mm]. The higher stress gradient causes greater slope. This tendency is registered in the distances between emitting and receiving transducers about $20\lambda_R$ and $40\lambda_R$ and marked in red colour. The slopes of the curves are vastly higher at the 7 times larger distances (marked in black colour). The changes are accumulated with the rising of the acoustical path. The results at frequency 2 MHz where the penetration of ultrasonic wave is deeper show the higher values of the slope.



a) b)

Fig.8. Φ(f) for materials with the stress σ =50 MPa and stress gradient ratio $2\sigma / h$ 10, 12.5 , 20

The figures 9(a) and 9(b) are illustrative for the change in the slopes (S) of the Φ(f) in dependence of the stress-state in materials with different stress gradient.



a) b)

Fig.9. The slope S vs maximum stress σ

Conclusion

The performed study shows the capability of the available ultrasonic apparatus and equipment to estimate the acoustical properties of elastically deformed materials. The small changes of the surface wave velocities in stressed materials are registered and measured. The use of a through transmission technique with emitting and receiving transducers for Rayleigh waves and a digital ultrasonic flaw detector is perspective approach for stress-state evaluation of the constructions.

The obtained results conform to the results of modeling in [2]. In the recent work it is proved again that the spectral analysis of ultrasonic waves is exclusively suitable for analyzing mechanical stresses by ultrasound. The mechanical stress causes a change of the shape and spectra of the ultrasonic pulses. For recognition and identification of different loads a cross-spectra technique and phase analyses are recommended. A new information parameter is pointed out namely the slope of curve Φ(f).

The initial anisotropy of the metal sheets is of great importance for the stress and stress gradient influence and ultrasonic waves propagation and their parameters. In order to achieve proper results it is necessary to study the situations with different configuration and mutual position of the vectors of gradients (transversal and longitudinal), principal axes of the anisotropy and wave directing vector. Such a study is a quite complex task that requires the stress to be with exactly defined shape and suitable signal processing method.

The materials used in the present work are taken from the serial production. The samples made from low carbon steel sheets have anisotropy and deviation of structure parameters. The cutting of the samples is done with a water jet device so the thermal effects and hardening of the surface are eliminated. The cleaning of the surface is carried out with a glass paper at low speed to prevent the cold peening. Thus the study demonstrates the possibility of the method for stress-state evaluation in conditions very close to the real in the practice and exploitation.

Authors should be very grateful to any researcher who carries out the similar study and shares the results.

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