UDK 539.3:534.242

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SCATTERING OF FREQUENCY-MODULATED SOUND PULSE ON CIRCULAR CYLINDRICAL THIN ELASTIC SHELL WITH A SLIT

The non-stationary problem of scattering of the plane sound wave by the elastic circular cylindrical shell empty inside and weakened by an infinitely long linear slit is studied. It is known that in this case the secondary components of the echo-pulse re-radiated by the circumferential waves of the Lamb type are very weak in comparison with the first, geometrically reflected pulse. At the same time the secondary pulses carry information about the material of shell and place location of defect in it. The sinusoidal frequency-modulated pulse of the finite duration in the incident wave and cross-correlation function are used for amplifying of the amplitudes of these components of echo-signal. The classification of arrival times of pulses re-radiated by circumferential waves after their reflection from the edges of slit in the shell is performed. The numerical calculations are carried out for the case of the stainless steel shell immersed in the sea water.

Introduction. The previous paper [10] on the plane sound pulse wave scattering from the thin circular cylindrical elastic shell empty inside and weakened by an infinite long linear slit has been concerned with the analysis of slit influence on the structure of echo-signals. The numerical results obtained for the case of stainless steel shell immersed in water showed that the pulses re-radiated by circumferential waves of the Lamb type are very weak in comparison with geometrically reflected pulse. In the case of shell with slit the new additional pulses caused circumferential waves reflection from defect are also small and therefore their identification in the practical echo-ranging applications may be very difficult. In the work [6] the linear frequency-modulated incident sound pulses was proposed for the echo location of spherical elastic shells of arbitrary thickness and cross-correlation techniques was introduced for the analysis of complicate echo structure. This method [12] allowed to define time intervals between pulses in echo primarily due to the elastic response of the shell object that resemble incident pulse.

Proposed paper is concerned with the investigation of the linear frequency-modulated echo pulses from a thin cylindrical empty shell weakened by infinite long linear slit.

1. Mathematical modeling. The mathematical statement of the problem considered here was filed in the work [10]. That is, we study 2-D scattering of a plane acoustic wave which incidences on the thin circular cylindrical elastic shell empty inside and containing the straight infinitely long slit. Dynamics of the elastic shell is described by the Kirchhoff – Love theory. The shell free from loading on the edges of slit.

The form of the acoustic pressure in the incident wave signal is described as in work [6]

$$p_{\text{inc}}(x_1,t) = p_0 \exp\left[-i\int_0^{t_1} \omega'(t')\,dt'\right][H(t_1+\Delta t) - H(t_1-\Delta t)]\,, \tag{1}$$

where p_0 is the constant pressure, $H(t)$ is the Heaviside step-function, $t_1 = t - (x_1 + a)/c$, t is the time, $x_1 = r\cos\theta$; r, θ are the polar coordinates with origin at the axis of cylindrical shell symmetry, a is the radius of shell which thickness is h, $2\Delta t$ is the duration of signal with the circular frequency ω' linearly modulated on time:

$$\omega'(t) = \frac{1}{2}\left[(\omega_1+\omega_2) + (\omega_1-\omega_2)\frac{t}{\Delta t}\right]. \tag{2}$$

Here ω_1 and ω_2 are the frequencies, respectively, at the beginning and the end of signal.

Let us introduce the dimensionless parameters and variables [6]

$$\alpha = \frac{1}{2}(\omega_1 + \omega_2)\frac{a}{c} = \bar{\omega}\frac{a}{c} = \bar{k}a = \bar{x},$$

$$\beta = \frac{1}{2}(\omega_1 - \omega_2)\left(\frac{a}{c}\right)^2 \frac{1}{\Delta t} = \Delta\omega \frac{a}{c}\frac{a}{2c\Delta t} = \Delta k a \frac{a}{2c\Delta t} = \Delta x \frac{1}{2\Delta\tau},$$

$$\tau_1 = \tau - (\xi_1 + 1), \qquad \xi_1 = \frac{x_1}{a}, \qquad \tau = \frac{ct}{a}, \tag{3}$$

where $\bar{\omega} = (\omega_1 + \omega_2)/2$ is the middle frequency, $\bar{k} = \bar{\omega}/c$ is the middle wave-number in outer fluid, $\bar{x} = \bar{k}a$ is the middle wave radius of shell, $\Delta\omega = \omega_1 - \omega_2$ is the difference frequency, $\Delta k = \Delta\omega/c$ is the difference wave-number in outer fluid, $\Delta x = \Delta ka$ is the difference wave radius of shell, $2\Delta\tau = 2c\Delta t/a$ is the dimensionless time of incident pulse duration. Then from the Eq. (1) we obtain

$$p_{\text{inc}}(x_1, t) = p_0 \exp\left[-i\left(\alpha\tau_1 + \frac{1}{2}\beta\tau_1^2\right)\right][H(\tau_1 + \Delta\tau) - H(\tau_1 - \Delta\tau)] \equiv p_0 P_i(\tau_1). \tag{4}$$

Application of the integral Fourier transform over time t to this function gives

$$p_{\text{inc}}^F(x_1, \omega) = p_0 \frac{a}{c} e^{ix(\xi_1+1)} G(x), \tag{5}$$

where

$$G(x) = \sqrt{\frac{\pi}{|\beta|}}\{C(X) + C(Y) - i\,\text{sgn}\,\beta[S(X) + S(Y)]\}\exp\left[\frac{i\beta}{2}\left(\frac{x-\alpha}{\beta}\right)^2\right],$$

$$X = \sqrt{\frac{|\beta|}{\pi}}\left(\Delta\tau - \frac{x-\alpha}{\beta}\right), \qquad Y = \sqrt{\frac{|\beta|}{\pi}}\left(\Delta\tau + \frac{x-\alpha}{\beta}\right). \tag{6}$$

Here $x = ka$ is the wave radius of shell, $k = \omega/c$ is the wave-number in outer fluid, $C(u)$ and $S(u)$ are the Fresnel integrals [1].

The spectral representation of incident wave (5) gives the solution of problem for plane wave diffraction on the cylindrical shell with a slit in the following form:

$$p_{\text{sc}}^F(r, \theta, \omega) = p_0 G(x)\frac{a}{c}\sqrt{\frac{a}{2r}} f(\theta, k) e^{ix(1+r/a)}, \qquad r \gg a, \tag{7}$$

where $f(\theta, k)$ is the scattering amplitude as function of the scattering angle θ and wave-number in fluid k, as also of the material and geometrical parameters of the system (density of fluid ρ and sound velocity c in fluid, density of shell material ρ_s, longitudinal c_L and shear c_T velocities in shell material, radius of shell middle surface a and thickness of shell h, and also angular coordinate θ_0 of slit) [10].

Then, using the inverse integral Fourier transform to the Eq. (7), the acoustical pressure in scattered non-stationary wave is obtained in the form

$$p_{\text{sc}}(r, \theta, t) = p_0 \sqrt{\frac{a}{2r}} \frac{1}{2\pi} \int_{-\infty}^{\infty} G(x) f(\theta, k) \exp\left[-ix\left(\tau - \frac{r}{a} - 1\right)\right] dx \equiv$$

$$\equiv p_0\sqrt{\frac{a}{2r}}P_{\text{sc}}\left(\theta,\tau-\frac{r}{a}-1\right),\quad r\gg a\,. \tag{8}$$

If the incident signal equals only real part of the Eq. (4):

$$P_{\text{inc,R}}(\tau)=\operatorname{Re}P_{\text{inc}}(\tau)=\cos\left(\alpha\tau_1+\frac{1}{2}\beta\tau_1^2\right)[H(\tau_1+\Delta\tau)-H(\tau_1-\Delta\tau)]\,, \tag{9}$$

also only the real part of complex signal (8) in the scattered pulse is obtained:

$$P_{\text{sc,R}}(\theta,\tau)=\operatorname{Re}P_{\text{sc}}(\theta,\tau)=\operatorname{Re}\frac{1}{2\pi}\int_{-\infty}^{\infty}G(x)f(\theta,k)e^{-ix\tau}\,dx\,. \tag{10}$$

Because the scattering amplitude $f(\theta,k)$ satisfies the symmetry condition $f(\theta,-k)=f^*(\theta,k)$ [3], where asterisk denotes complex conjugation, then Eq. (10) can be transformed to the expression

$$P_{\text{sc,R}}(\theta,\tau)=\frac{1}{2\pi}\int_0^{\infty}[C_0(\theta,x)\cos(x\tau)+S_0(\theta,x)\sin(x\tau)]\,dx\,, \tag{11}$$

where

$$\begin{aligned}
&C_0(\theta,x)=N_{\text{R}}(x)f_{\text{R}}(\theta,k)-N_{\text{I}}(x)f_{\text{I}}(\theta,k)\,,\\
&S_0(\theta,x)=N_{\text{R}}(x)f_{\text{I}}(\theta,k)+N_{\text{I}}(x)f_{\text{R}}(\theta,k)\,,\\
&N_{\text{R}}(x)=G_{\text{R}}(x)+G_{\text{R}}(-x),\qquad N_{\text{I}}(x)=G_{\text{I}}(x)-G_{\text{I}}(-x)\,,\\
&G_{\text{R}}(x)=\operatorname{Re}G(x),\qquad G_{\text{I}}(x)=\operatorname{Im}G(x)\,,\\
&f_{\text{R}}(\theta,k)=\operatorname{Re}f(\theta,k),\qquad f_{\text{I}}(\theta,k)=\operatorname{Im}f(\theta,k)\,.
\end{aligned} \tag{12}$$

Hence, the acoustic pressure in echo-signal is described by formula

$$p_{\text{sc,R}}(r,\theta,t)=\operatorname{Re}p_{\text{sc}}(r,\theta,t)=p_0\sqrt{\frac{a}{2r}}P_{\text{sc,R}}\left(\theta,\tau-\frac{r}{a}-1\right),\qquad r\gg a\,. \tag{13}$$

To analyze the components in scattered pulse we use the method of cross-correlation function [6, 8, 9, 11]. In this study the cross-correlation function is chosen in the form

$$\text{c}(\theta,\tau)=\frac{|I_2(\theta,\tau)|}{\sqrt{I_0I_1(\theta,\tau)}}\,, \tag{14}$$

where

$$\begin{aligned}
&I_0=\int_{-\Delta\tau}^{\Delta\tau}P_{\text{inc,R}}^2(\tau')\,d\tau'\,,\\
&I_1(\theta,\tau)=\int_{-\Delta\tau}^{\Delta\tau}P_{\text{sc,R}}^2(\theta,\tau+\tau')\,d\tau'\\
&I_2(\theta,\tau)=\int_{-\Delta\tau}^{\Delta\tau}P_{\text{sc,R}}(\theta,\tau+\tau')P_{\text{inc,R}}(\tau')\,d\tau'\,.
\end{aligned} \tag{15}$$

In function $c(\theta,\tau)$ the incident pulse and scanned section of echo-pulse are every normalized by the root mean square of its amplitude.

With using the formula (9) the integral I_0 is calculated as

$$I_0=\Delta\tau+\frac{1}{2}\sqrt{\frac{\pi}{2|\beta|}}\left\{[C(X_0)+C(Y_0)]\cos\left(\frac{\alpha^2}{\beta}\right)+[S(X_0)+S(Y_0)]\sin\left(\frac{\alpha^2}{\beta}\right)\right\}, \tag{16}$$

where

$$X_0 = \sqrt{\frac{2|\beta|}{\pi}}\left(\Delta\tau + \frac{\alpha}{\beta}\right),$$

$$Y_0 = \sqrt{\frac{2|\beta|}{\pi}}\left(\Delta\tau - \frac{\alpha}{\beta}\right). \tag{17}$$

Similarly, taking into consideration the Eq. (10), the integral $I_2(\theta,\tau)$ can be found in form

$$I_2(\theta,\tau) = \frac{1}{2}\int_0^{\infty}[N_R^2(x) + N_I^2(x)][f_R(\theta,k)\cos(x\tau) + f_I(\theta,k)\sin(x\tau)]\,dx\,. \tag{18}$$

2. The results of numerical calculation. The calculations were made for the case of stainless steel shell ($\rho_s = 7900\,\mathrm{kg/m^3}$, $c_L = 5240\,\mathrm{m/s}$, $c_T = 2978\,\mathrm{m/s}$ [4], $h/a = 0.025$) immersed in water ($\rho = 1000\,\mathrm{kg/m^3}$, $c = 1410\,\mathrm{m/s}$, $c_T = 2978\,\mathrm{m/s}$ [6]). The plots of form-function $|f(\theta,k)|$ for the back scattering ($\theta = 180\,°$) in the non-higher range of x, $0 \le x \le 30$, and various slit placement in the shell were represented in [10]. It was shown that in the case of shell without defect this function contains the series of quasi-periodical resonances generated by circumferential acoustic waves of the Lamb symmetrical and asymmetrical, bending (for $2kh \approx 1$) types. When the shell is weakened by a slit, the curve of form-function is changed and characterized by very complicated irregularities. These irregularities arise as the result of circumferential waves reflection on the slit and excitation of tangential, angular and radial vibrations of the free edges of the shell.

These effects are represented in the structure of echo-signals with constant carrier frequency [10] by the secondary echo-pulses significantly weaker compared to the first, geometrically reflected pulse. Therefore the surface acoustic pulses can be unnoticeable on the background of noises. For determination of these secondary echo-pulses the frequency-modulated incidence pulse is applied with the central frequency $\bar{x} = \alpha = 20$, the frequency sweep $\Delta x = 20$, and the half-pulse duration $\Delta\tau = 1$ (all values are dimensionless). The frequency of pulses is linearly increasing with time.

The Figs. 1 illustrate the incident frequency-modulated pulse (Fig. 1***a***), echo (Fig. 1***b***), and cross-correlation function (Fig. 1***c***) for $x_{\mathrm{mid}} = 20$, $\Delta\tau = 1$, $\Delta x = 20$ for the shell without slit and for frequency increasing with time ($\beta = 10$, $I_0 = 0.93295$. The Fourier integral (11) for the acoustical pressure in the echo-pulses and the integrals $I_j(\theta,\tau)$, $j = 1,2$, (15) in the cross-correlation function were calculated using the Romberg's method in Fortran-90 program [7]. In particular, for the integrals over dimensionless frequency x the infinite top limit of integration was reduced to $x = 100$. For the numerical calculation of the Fresnel integrals and the Bessel functions containing in the scattering amplitude $f(\theta,k)$ [10] the computation of special functions from the Fortran-library [13] was used.

The Figs. 2 show results for the same parameters, but for frequency decreasing with time $\beta = -10$, $I_0 = 0.99987$. The starting point of reference is the time when the incident pulse achieves the axial of symmetry of cylindrical shell. The peaks of the cross-correlation function are plotted on the same abscissa as the middle of the individual echo-pulses, i. e. the pulse directly reflected from the outer surface of the cylindrical shell and the echo-pulses re-radiated by the circumferential waves propagating on the surface of shell. The locations of these peaks indicate the time delays between individual pulses.

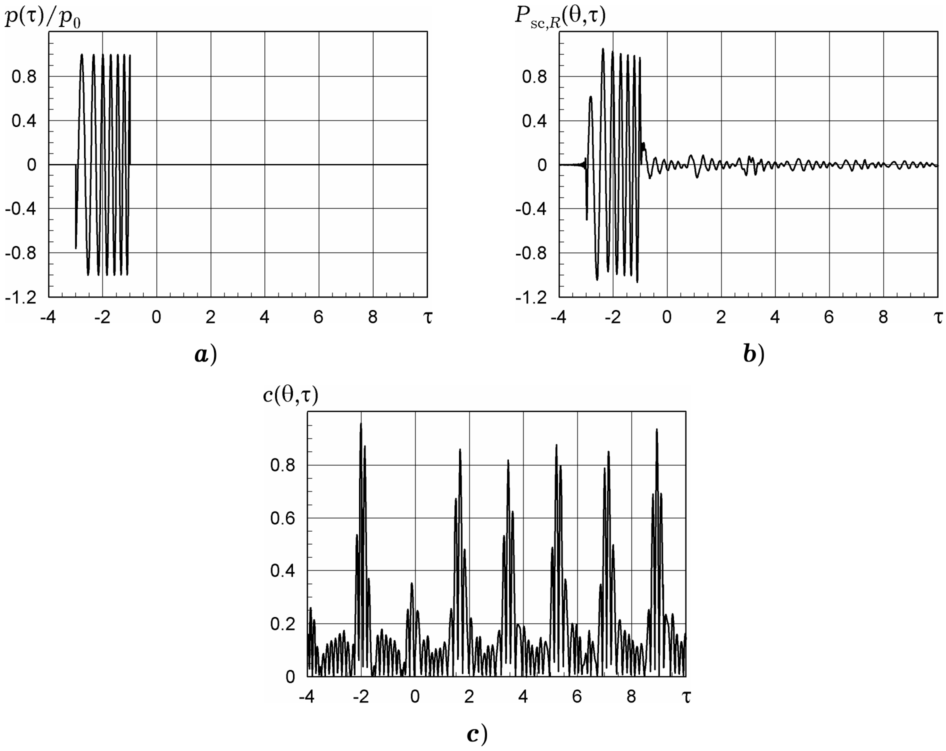


Fig. 1

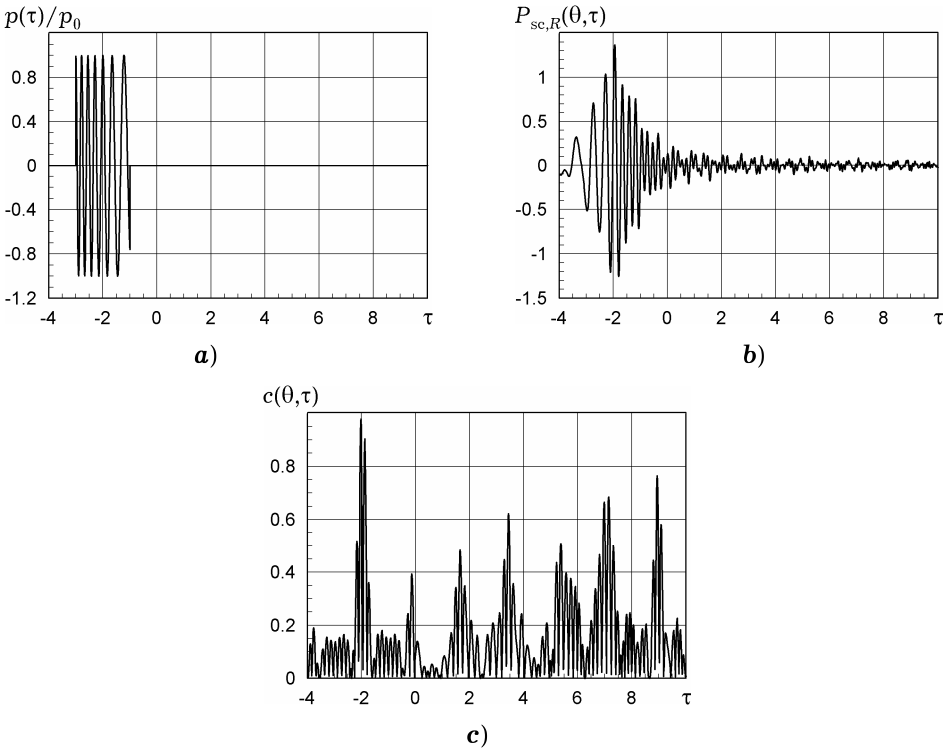


Fig. 2

Next, the information about these time delays allows to identify the velocities of circumferential waves. It must be note that width of these peaks is inversed to the frequency sweep Δx [10]. As seen the cross-correlation function with increasing frequency ($\beta > 0$) more precisely indicates the echo-pulses time locations than the cross-correlation function with decreasing frequency ($\beta < 0$). In both cases the incident pulse half-length $\Delta\tau = 1$ is sufficient for insignificant mutual superposition between the individual echo-pulses.

The results of numerical calculations of echo-pulses waves and cross-correlation functions with increasing frequency ($\beta = 10$) for the shell with slit location $\theta_0 = 0, 45, 90, 135, 180°$ are displayed, respectively, on the Figs. 3–7. In this case overlap between individual echo-pulses occurs and the peaks of the cross-correlation function diminish. But in these conditions the method of cross-correlation function becomes more effective for the identification of individual echo-pulses types.

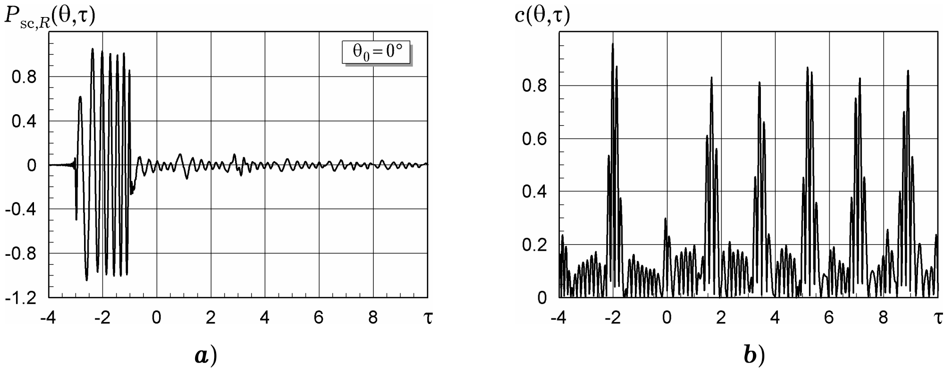


Fig. 3

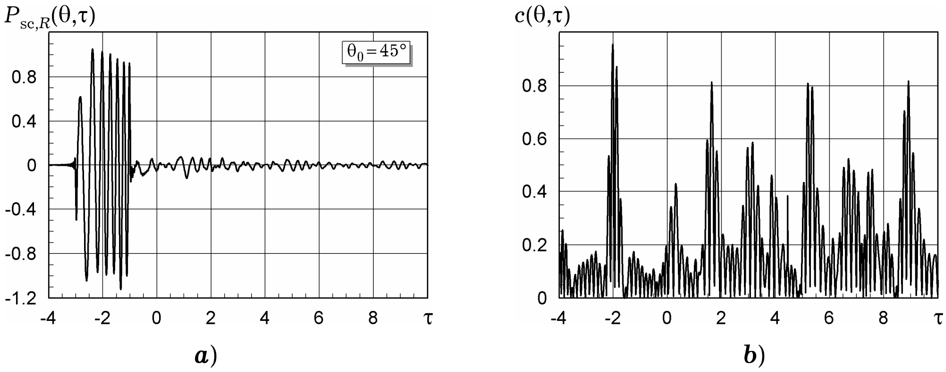


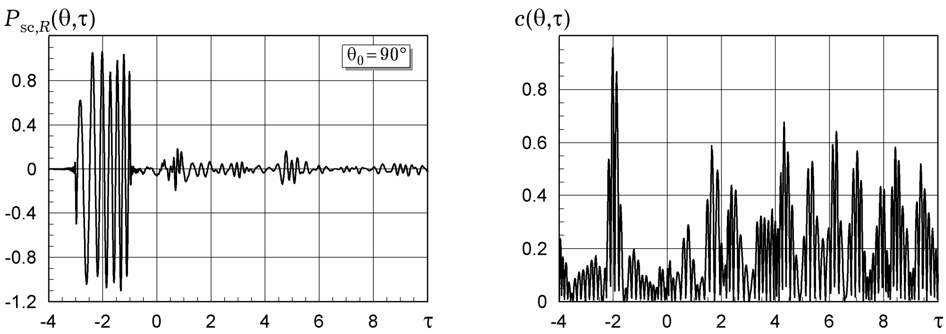
Fig. 4

From the theory of surface acoustic waves is known that circumferential waves are excite by incident sound rays in the critical points $\theta = \pi \pm \theta_{cr}$ and propagate from these points on surface of shell, respectively, clockwise and counter-clockwise with the phase velocity $c_{ph} = \dfrac{c}{\sin\theta_{cr}}$. In the case of shell without slit the individual circumferential pulses of the clockwise and counter-clockwise types arrive to point in acoustic medium in the back direction $\theta = \pi$ simultaneously. The dimensionless times of runs of the individual pulses to point of observation in acoustic medium are obtained from formula

$$\tau_j = 2(\tau_{cr} - \tau'_{cr}) - 2 + 2\pi j \sin\theta_{cr}, \qquad j = 0,1,2,\ldots,$$

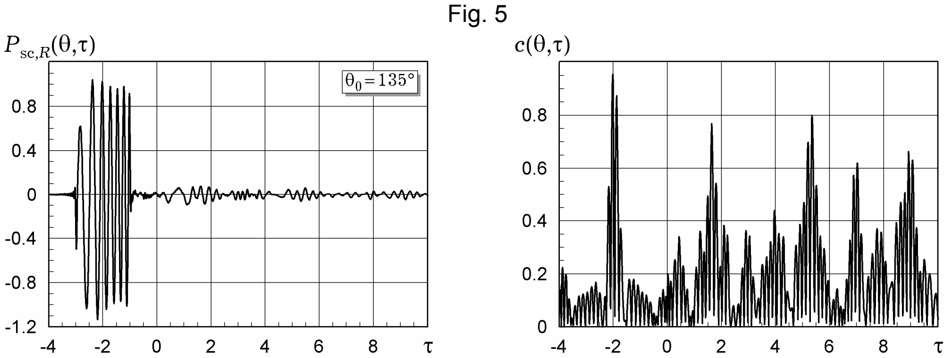
where $\tau_{cr} = 1 - \cos\theta_{cr}$, $\tau'_{cr} = (\pi - \theta_{cr})\sin\theta_{cr}$. From the locations of the cross-correlation peaks on the Fig. 2 can see that the delays between individual echo-pulses are approximately equal $\Delta\tau_j = \tau_{j+1} - \tau_j = 2\pi \sin\theta_{\rm cr} \approx 1.78 \div 1.79$, i. e. phase velocity $c_{\rm ph} \approx 4949 \div 4977$ m/s is less than the phase velocity of the Lamb circumferential acoustic wave of symmetric type in steel plate (circumferential wave pulses of plate type) $c_{10} = c_{\rm T}\sqrt{1-\left(\frac{c_{\rm T}}{c_{\rm L}}\right)^2} = 5531$ m/s [2].

If the shell is weakened by a slit, the circumferential waves reflecting from the edges of slit change their direction of propagation to opposite. The first circumferential pulse excited on the shell in the point $\theta = \pi - \theta_{\rm cr}$ runs with the phase velocity $c_{\rm ph}$ over arc $\left(\frac{\pi}{2} - \theta_{\rm cr}\right)a$ to the slit and back from it, and then re-radiates wave from the critical point $\theta = \pi - \theta_{\rm cr}$ in the outer acoustical medium on receiver ($r \gg a$, $\theta = \pi$). Similarly, the second circumferential pulse excited in the point $\theta = \pi + \theta_{\rm cr}$ on the shell runs over arc $\left(\frac{3\pi}{2} - \theta_{\rm cr}\right)a$ with the phase velocity $c_{\rm ph}$ to slit and back, and re-radiated wave from the critical point $\theta = \pi + \theta_{\rm cr}$ in the acoustical medium in the direction $\theta = \pi$. The dimensionless times of arrivals of the first and second pulses are, respectively, equal $\tau_{1,0} = 2(\tau_{\rm cr} + \tau''_{\rm cr}) - 2$ and $\tau_{2,0} = 2(\tau_{\rm cr} + \tau'''_{\rm cr}) - 2$, where $\tau''_{\rm cr} = \left(\frac{\pi}{2} - \theta_{\rm cr}\right)\sin\theta_{\rm cr}$ and $\tau'''_{\rm cr} = \left(\frac{3\pi}{2} - \theta_{\rm cr}\right)\sin\theta_{\rm cr}$.



a) ***b***)

Fig. 5



a) ***b***)

Fig. 6

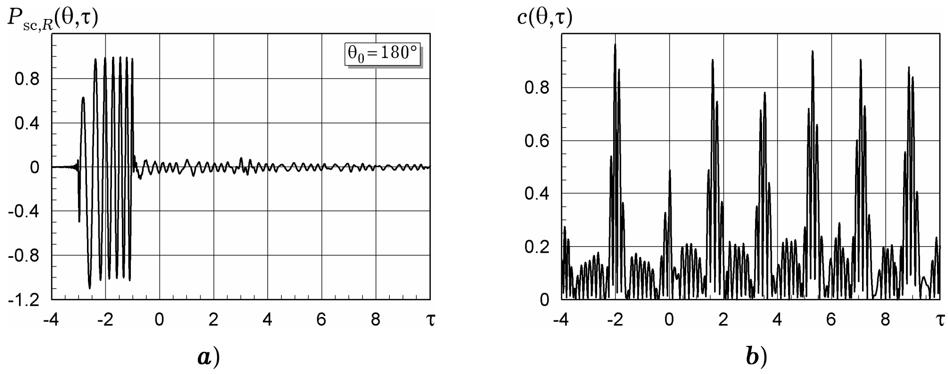


Fig. 7

The next three series of echo-pulses are re-radiated from the critical points by the circumferential waves, reflected from one edge of the shell, run whole circle around the shell and reflected from the other edge of the shell. The dimensionless times of arrivals of these series are, respectively, $\tau_{1,k+1} = \tau_{1,0} + 4\pi k \sin\theta_{\rm cr}$, $\tau_{2,k+1} = \tau_{2,0} + 4\pi k \sin\theta_{\rm cr}$, $\tau_{3,k+1} = \tau_{2,0} + 6\pi k \sin\theta_{\rm cr}$, $k = 0, 1, 2, \ldots$. It should be noted that a similar analysis was performed in [5].

The analysis of positions of the peaks of the cross-correlation functions on Figs. 3–7 shows two classes of circumferential pulses.

Each of these classes consists three series of individual echo-pulses with the dimensionless times, which are presented in Table 1 for the case of $\theta_0 = 90\,°$. The time delay of individual echo-pulses in the first and second classes are approximately $\Delta\tau_1 = 3.11$ and $\Delta\tau_2 = 5.20$. The calculation of circumferential wave velocity from the expression $\Delta\tau_n = 4\pi\sin\theta_{{\rm cr},n} = 4\pi\dfrac{c}{c_{{\rm ph},n}}$, $n = 1,2$, gives the following values: $c_{\rm ph,1} = 5697$ m/s and $c_{\rm ph,2} = 3407$ m/s. The first from these values is very closed to the circumferential wave pulses of plate type c_{10}, and the second value corresponds to the circumferential wave pulses generated by bending vibration of the shell $c_{20} = c_{\rm T}\sqrt{k_{\rm T}} = 3433$ m/s where $k_{\rm T} = 6/5$ is the numerical coefficient of shear in theory of the Timoshenko type [2].

Table 1. The times of individual echo-pulses arrival from the cylindrical shell with a slot ($\theta_0 = 90\,°$).

Classes of pulses	Series	Positions of peaks of cross-correlation function		
circumferential wave pulses of plate type	Seria 1	2.25	5.36	8.43
	Seria 2	1.64	4.76	7.88
	Seria 3	0.77	3.87	7.02
circumferential wave pulses of bending type	Seria 1	−0.780	4.315	9.51
	Seria 2	1.86	6.88	–
	Seria 3	2.91	8.12	–

Conclusions. The application of frequency-modulated incident pulse of finite length allows using the effect of passing through resonance to excite surface acoustic waves of a certain type and consequently detection of the components of echo signals coming after the specularly reflected first pulse. In the case of thin cylindrical shell such waves are surface waves of symmetric and asymmetric (bending) types. The presence of slit in the cylindrical shell and the emergence of peripheral wave reflection at the edges of the defect considerably complicate structure of the echo-signal. Moreover, in the case of an empty shell the amplitudes of the secondary echo-pulses are very small. Application of cross-correlation function allows to localize these weak signals, identify of circumferential wave types and calculate the time delay between successive pulses of established types of circumferential waves. This method also helps to classify the trajectory paths of circumferential waves from the critical points of their excitation to the edges of slit in the shell and from the edges of slit to the critical points of re-radiation of waves in the surrounding medium. Thus, based on the placement of the cross-correlation peaks can be seen on the availability and location of slit in the shell.

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РОЗСІЯННЯ ЧАСТОТНО-МОДУЛЬОВАНОГО ЗВУКОВОГО ІМПУЛЬСУ НА КРУГОВІЙ ЦИЛІНДРИЧНІЙ ТОНКІЙ ПРУЖНІЙ ОБОЛОНЦІ З ЩІЛИНОЮ

Розглядається нестаціонарна задача розсіяння плоскої звукової хвилі тонкою пружною круговою циліндричною оболонкою, порожньою всередині і послабленою безмежно довгою лінійною щілиною. Відомо, що у цьому випадку вторинні компоненти ехо-сигналу, перевипромінені периферійними хвилями типу Лемба, дуже слабкі за амплітудою порівняно з першим, геометрично відбитим імпульсом. Разом з тим вторинні імпульси несуть інформацію про матеріал оболонки і місце розташування дефекту в ній. Для підсилення амплітуд цих компонентів ехо-сигналу використано синусоїдальний частотно-модульований імпульс скінченної тривалості в набігаючій хвилі і функцію крос-кореляції. Проведено класифікацію часів приходу імпульсів, перевипромінених периферійними хвилями після їхнього відбиття від берегів розрізу в оболонці. Числові розрахунки виконано для випадку стальної оболонки, зануреної в морську воду.

РАССЕЯНИЕ ЧАСТОТНО-МОДУЛИРОВАННОГО ЗВУКОВОГО ИМПУЛЬСА НА КРУГОВОЙ ЦИЛИНДРИЧЕСКОЙ ТОНКОЙ УПРУГОЙ ОБОЛОЧКЕ СО ЩЕЛЬЮ

Рассматривается нестационарная задача рассеяния плоской звуковой волны тонкой упругой круговой цилиндрической оболочкой, пустой внутри и ослабленной неограниченно длинной линейной щелью. Известно, что в этом случае вторичные компоненты эхо-сигнала, переизлученные периферическими волнами типа Лэмба, очень слабые по амплитуде по сравнению с первым, геометрически отраженным импульсом. Вместе с тем вторичные импульсы несут информацию о материале оболочки и месторасположении дефекта в ней. Для усиления амплитуд этих компонент эхо-сигнала использованы синусоидальный частотно-модулированный импульс конечной длительности и функция кросс-корреляции. Выполнена классификация времен прибытия импульсов, переизлученных периферическими волнами после их отражения от берегов разреза в оболочке. Численные расчеты выполнены для случая стальной оболочки, погруженной в морскую воду.

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Received
18.06.17