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FLEXURAL–GRAVITATIONAL WAVES FROM MOVING DISTURBANCES

A. E. Bukatov, L. V. Cherkesov, and A. A. Yaroshenko

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We investigate propagating flexural–gravitational waves, generated under the action of a load moving over the surface of a floating elastic plate, found in a state of uniform extension or compression. Without account of extension or compression stresses, flexural–gravitational propagating waves were considered in [1, 2]. Planar waves were investigated in [3, 4] under conditions of longitudinal compression.

1. Let a thin, isotropic, elastic plate float on the surface of an ideal, incompressible liquid of finite depth H. The plate and the liquid are not restricted in their horizontal stresses. The plate is displaced across the surface with a velocity v of the loading $p = p_0 f(x_1, y)$, $x_1 = x + vt$. Consider the effect of a uniform extension on the generated flexural–gravitational marine wave, assuming that the liquid motion is a potential flow, and that the velocities of the liquid particle motion and of the plate deflection ζ are low.

Taking into account uniform extension [5-7] in a coordinate system x_1, y, related to the moving pressure region, the problem reduces to solving the Laplace equation for the velocity potential φ

$$\Delta\varphi = 0, \quad -H < z < 0, \quad -\infty < x, \; y < \infty \tag{1.1}$$

with boundary conditions

$$D_1\nabla^4\zeta - Q_1\Delta_1\zeta + \varkappa_1 v^2\frac{\partial^2\zeta}{\partial x^2} + \zeta + \frac{v}{g}\frac{\partial\varphi}{\partial x} = -p_1 f(x, y) \quad \text{at} \quad z = 0, \tag{1.2}$$

$$\partial\varphi/\partial z = 0 \quad \text{at} \quad z = -H,$$

where

$$D_1 = D/\rho g, \; Q_1 = Q/\rho g, \; \varkappa_1 = \rho_1 h/\rho g, \; D = Eh^3/[12(1-\mu^2)], \; p_1 = p_0/\rho g,$$
$$\nabla^4 = \Delta_1^2, \quad \Delta_1 = \partial^2/\partial x^2 + \partial^2/\partial y^2,$$

ρ, liquid density; E, h, ρ_1, and μ, respectively, the normal elastic modulus, the width, density, and Poisson coefficient of the plate; Q, extension stress; ζ and φ, related by the mathematical condition $\varphi_z = v\zeta_x$ at z = 0. From here on the subscript 1 of x_1 will be omitted.

Applying a Fourier transform in horizontal coordinates to solve the problem (1.1), (1.2), we obtain, in the case of an axisymmetric load, an integral representation for the plate deflection (raising the plate-liquid surface):

$$\zeta = \frac{1}{2\pi}p_1 \operatorname{Re}\left\{\int_0^\infty \frac{r}{\tau}\bar{f}(r)\,M(r)\,J(r, R, \gamma)\,dr\right\}; \tag{1.3}$$

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$$J=\frac{1}{2\pi}\int_{-\pi/2}^{3\pi/2}\frac{1}{k_0}\exp\left[irR\cos(\theta-\gamma)\right]d\theta, \tag{1.4}$$

where $M(r) = rg(1+\varkappa_1 rg\tanh rH)^{-1}\tanh rH$, $k_0 = rv\cos\theta - \tau$, $\tau = [(1+Q_1r^2+D_1r^4)M(r)]^{1/2}$, $r = (m^2+n^2)^{1/2}$, $x = R\cos\gamma$, $y = R\sin\gamma$, $m = r\cos\theta$, $n = r\sin\theta$, $R = (x^2+y^2)^{1/2}$, $\bar{f}(r)$ is the Fourier transform of the function $f(R)$.

Consider three regions of variation of the displacement velocity of the disturbance region:

$$0<v<v_0,\ v_0<v<\sqrt{gH},\ v>\sqrt{gH}.$$

The integrand in (1.4) has for $0 < v < v_0$ no singularities on the path of integration and, under the conditions $v_0 < v < \sqrt{gH}$, $r_1 \leq r \leq r_2$ or $v > \sqrt{gH}$, $0 < r < r_2$ has poles $\theta_{1,2} = \mp \arccos\tau_0$. Here, $\tau_0 = (rv)^{-1}\tau$, $v_0 = \tau(r_0)/r_0$, where r_0 is the unique positive root of the equation $\tau'_0(r) = 0$, the prime denotes differentiation with respect to r, and $r_{1,2}$ are the real roots of the equation $\tau_0(r) = 1$. In this case, $\tau'_0 < 0$ for $0 < r < r_0$ and $\tau'_0 > 0$ for $r_0 < r < \infty$. Besides, $\tau_0(0) = \sqrt{gH}/v$, $\lim_{r\to\infty}\tau_0 = \infty$, $\tau'_0(0) = \tau'_0(r_0) = 0$. In the case $rH \gg 1$,

$$v_0=\sqrt{g/r_0}\left[(1+Q_1r_0^2+D_1r_0^4)/(1+\varkappa_1 r_0 g)\right]^{1/2}, \tag{1.5}$$

where r_0 is the positive root of the equation

$$2\varkappa_1 gD_1r^5+3D_1r^4+Q_1r^2-2\varkappa_1 rg-1=0.$$

If $rH \ll 1$, then

$$v_0=\sqrt{gH}\left[(1+Q_1r_0^2+D_1r_0^4)/(1+\varkappa_1 gHr_0^2)\right]^{1/2}, \tag{1.6}$$

and r_0 satisfies the equation

$$\varkappa_1 gHD_1r^4+2D_1r^2+Q_1-\varkappa_1 gH=0.$$

Satisfying the condition of [8], we choose the path of integration in (1.4) on the contour L, traversing on the real axis from $\theta = -\pi/2$ to $\theta = 3\pi/2$ with bypass points $\theta = \theta_1$ and $\theta = \theta_2$ in the complex θ plane with small semicircles below and above, respectively.

2. If $0 < v < v_0$, applying to (1.4) the stationary-phase method and integrating consequently (1.3) by parts, we obtain that ζ has for large R order not lower than $O(R^{-1})$.

Let $v_0 < v < \sqrt{gH}$. In this case we represent integral (1.3) in the form of a sum of three integrals over the intervals $[0, r_1]$, $[r_1, r_2]$, $[r_2, \infty]$. Since the integrand in (1.4) has no singularities on the segments $[0, r_1]$, $[r_2, \infty]$, subsequent application of the stationary phase method and integration by parts shows that the given integrals, corresponding to the first and third segments, are of order $O(R^{-1})$. Consequently,

$$\zeta=\frac{1}{2\pi}p_1\,\mathrm{Re}\left\{\int_{r_1}^{r_2}r\tau^{-1}\bar{f}(r)M(r)J\,dr\right\}+O(R^{-1}); \tag{2.1}$$

$$J=\frac{1}{2\pi}\int_L k_0^{-1}\exp\left[irR\cos(\theta-\gamma)\right]d\theta. \tag{2.2}$$

Calculating the contour integral (2.2) with account of the signs of the expressions $\mathrm{Re}[i\cos\cdot(\theta-\gamma)]$ on the small semicircles and the bypass points $\theta = \theta_{1,2}$, and substituting into (2.1) the expression obtained for J, we find

$$\zeta=\frac{1}{2\pi}p_1\,\mathrm{Re}\sum_{j=1}^{5}\eta_j+O(R^{-1}), \tag{2.3}$$

$$\eta_1=\int_{r_1}^{r_2}B_1e^{iR\Phi_1}dr,\quad 0\leqslant\gamma\leqslant\bar{\gamma};\quad \eta_2=\int_{r_1}^{n_1}B_1e^{iR\Phi_1}dr,\quad \bar{\gamma}<\gamma\leqslant\pi;$$

$$\eta_3 = \int_{n_2}^{r_2} B_1 e^{iR\Phi_1} dr, \quad \bar{\gamma} < \gamma \leqslant \pi; \quad \eta_4 = \int_{n_3}^{n_4} B_2 e^{iR\Phi_2} dr, \quad 0 \leqslant \gamma \leqslant \pi - \bar{\gamma}; \tag{2.3}$$

$$\eta_5 = R^{-1/2} \int_{r_1}^{r_2} B_3 \cos(rR - \pi/4)\, dr; \quad r_1 < n_1 < n_2 < r_2,$$

$$B_{1,2} = ir\bar{f}(r) M(r) \tau^{-1} \left(vr \sqrt{1-\tau_0^2}\right)^{-1}, \quad \bar{\gamma} = \pi - \operatorname{arctg} \max \tau_1(r),$$

$$B_3 = qr\bar{f}(r) M(r) \tau^{-1}, \quad \Phi_{1,2} = r\left(\tau_0 \cos\gamma \mp \sqrt{1-\tau_0^2} \sin\gamma\right),$$

$$q = 2\left[\sqrt{2\pi r}\,(v^2 r^2 \cos^2\gamma - \tau^2)\right]^{-1}, \quad \tau_1 = \tau_0^{-1}\left(1-\tau_0^2\right)^{1/2},$$

where $n_{1,2}$ are the real roots of the equation $\tau_1 = -\tan\gamma$, and $n_{3,4}$ are the real roots of the equation $\tau_1 = \tan\gamma$.

The phase functions Φ_1 and Φ_2 of the integrals η_2 and η_4 have no stationary points, while $\eta_5 = O(R^{-1})$. Consequently, $\eta_2 + \eta_4 + \eta_5 = O(R^{-1})$.

The stationary points of the phase function Φ_1 in the intervals η_1 and η_3 are roots of the equations

$$\operatorname{tg}\gamma = \tau_2(r), \quad \tau_2 = (r\tau_0)'\left(1-\tau_0^2\right)^{1/2}\left[1 - \tau_0 (r\tau_0)'\right]^{-1}. \tag{2.4}$$

For $v_0 < v < v_1$ this equation has one γ-dependent real root $r = \alpha_3$ in the regions of r variations under consideration. Here,

$$v_1 = \tau_3(r_3), \quad \tau_3 = \left[\tau_{01}^2 - \frac{(\tau_{01}')^2 r\left(\tau_{01} + r\tau_{01}'\right)}{(r\tau_{01})''}\right]^{1/2},$$

where r_3 is the real root of the equation $\tau''_2(r) = 0$, $r_3 < r_0$, $\tau_{01} = \tau/r$.

Equation (2.4) has one root for $v_1 < v < \sqrt{gH}$ if $0 < \gamma < \gamma_2$ or $\gamma_1 < \gamma < \pi$. We denote this root by α_1 in the first case and by α_3 in the second. If also $v_1 < v < \sqrt{gH}$, but $\gamma_2 < \gamma < \gamma_1$, then there exist three roots $\alpha_1 < \alpha_2 < \alpha_3$. In this case,

$$\gamma_1 = \operatorname{arctg}\tau_2(\alpha_4), \quad \gamma_2 = \operatorname{arctg}\tau_2(\alpha_5), \quad \alpha_1 < \alpha_4 < \alpha_2 < \alpha_5 < \alpha_3,$$

where $\alpha_{4,5}$ are the real roots of the equation $\tau'_2(r) = 0$. We note that $\alpha_1 = \alpha_4 = \alpha_2$ for $\gamma = \gamma_1$ and $\alpha_2 = \alpha_5 = \alpha_3$ for $\gamma = \gamma_2$.

Based on the analysis performed of the location of the stationary points of the phase functions of the integrals η_1 and η_3, we obtain from (2.3)

$$\zeta = \zeta_3 + O(R^{-1}) \text{ for } 0 < |\gamma| < \pi,$$

if $v_0 < v < v_1$. If $v_1 < v < \sqrt{gH}$, then

$$\zeta = \begin{cases} \zeta_1 + O(R^{-1}) & \text{for } 0 < |\gamma| < \gamma_2, \\ \zeta_1 + \zeta_2 + \zeta_3 + O(R^{-1}) & \text{for } \gamma_2 < |\gamma| < \gamma_1, \\ \zeta_3 + O(R^{-1}) & \text{for } \gamma_1 < |\gamma| < \pi. \end{cases} \tag{2.5}$$

Here, $\zeta_k = R^{-1/2}\psi(\alpha_k)\cos\left[R\Phi_1(\alpha_k, \gamma) - (-1)^k \frac{\pi}{4}\right]$, $\psi = -f_1(r) M(r) \left[v\tau\sqrt{1-\tau_0^2}\right]^{-1}\left(2\pi\left|\Phi_1''\right|\right)^{-1/2}$, $f_1(r) = \bar{f}(r) p_1$.

It is seen that for velocities $v_0 < v < v_1$ of moving disturbances only one wave system ζ_3 is generated, being damped with distance as $1/R^{1/2}$. These waves cover the whole surface of the plate (plate–liquid boundary). The paddle direction of these waves at a large distance from the x axis is determined by the angle

$$\gamma_0 = \operatorname{arctg}[(v/v_0)^2 - 1]^{-1/2}.$$

The distance between neighboring paddle waves on the rays $\gamma = 0$ and $\gamma = \pi$ equals, respectively, $\lambda_1 = 2\pi/r_1$, $\lambda_2 = 2\pi/r_2$. The distance from the moving disturbance to the wave paddle, following the disturbance, equals $l_1 = \pi/4r_1$, and up to the wave paddle, traveling in advance, $l_2 = 3\pi/4r_2$.

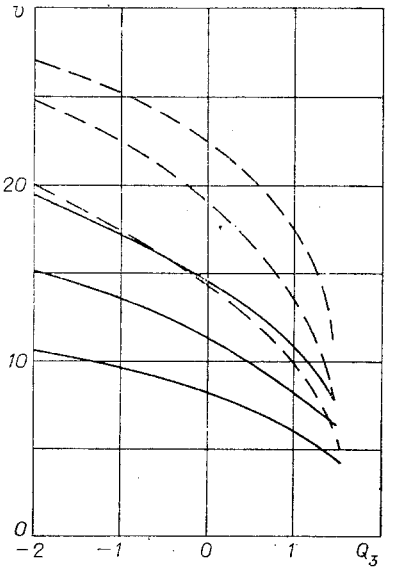

Fig. 1

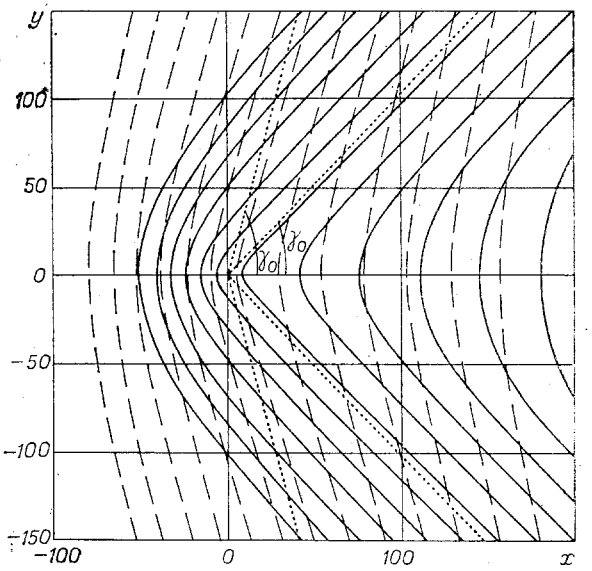

Fig. 2

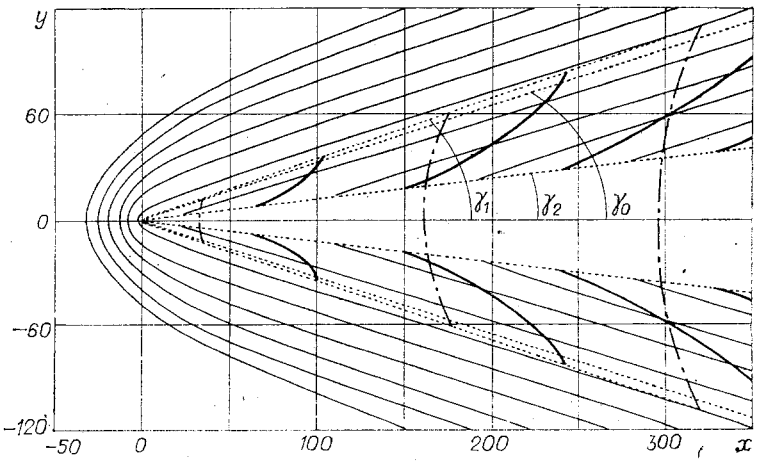

Fig. 3

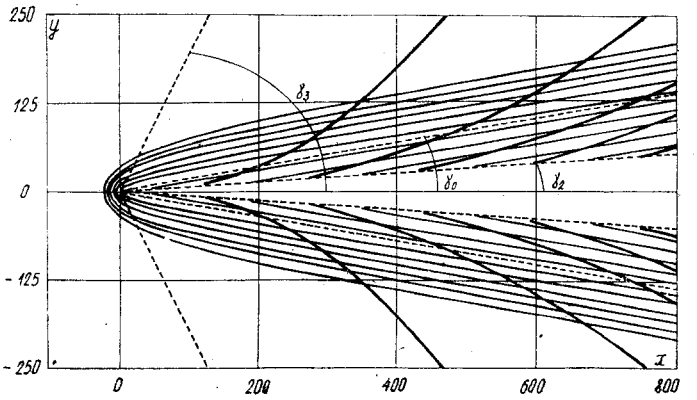

Fig. 4

Three wave systems are formed for velocities $v_1 < v < \sqrt{gH}$: ζ_1, ζ_2, and ζ_3. The wave system ζ_1 has the nature of transverse waves, while ζ_2 has that of longitudinal gravitational marine waves [2, 9, 10], deformed due to extensions, elastic, and mass forces on the plate. The waves ζ_3, formed in this case in the region $\gamma_2 < |\gamma| < \pi$, are due, as in the case $v_0 < v < v_1$, to exclusively elastic plate forces, and their paddle direction is also characterized by the angle γ_0.

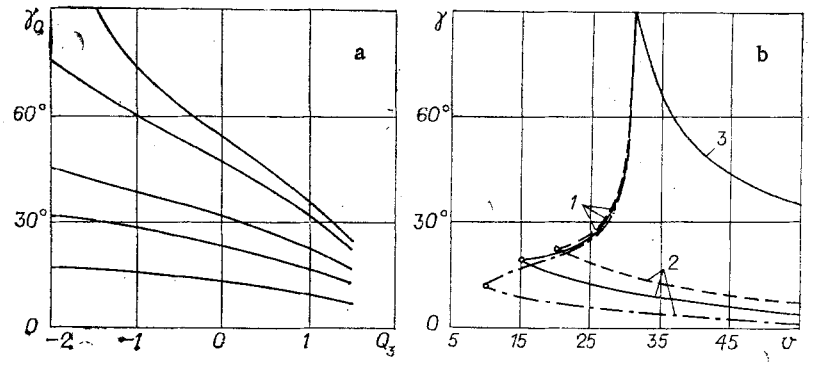

Fig. 5

Now let $v > \sqrt{gH}$. In this case, $r_1 = 0$, and the equation $\tau'_2(r) = 0$ has only one real root α_5. The phase function of the integrals η_1 and η_3 has for $0 < \gamma < \gamma_2$ no stationary points, namely real roots of Eq. (2.4). For $\gamma_2 < \gamma < \gamma_3$, where $\gamma_3 = \arctan[v^2(gH)^{-1} - 1]^{-1/2}$, there are two stationary points α_2 and α_3, and for $\gamma_3 < \gamma < \pi$ — only one α_3. Taking this into account, we find from (2.3)

$$\zeta = \begin{cases} O(R^{-1}) & \text{for} \quad 0 < |\gamma| < \gamma_2, \\ \zeta_2 + \zeta_3 + O(R^{-1}) & \text{for} \quad \gamma_2 < |\gamma| < \gamma_3, \\ \zeta_3 + O(R^{-1}) & \text{for} \quad \gamma_3 < |\gamma| < \pi, \end{cases}$$

where ζ_2 and ζ_3 are the same as in (2.5).

Consequently, the disturbances displaced with velocity $v > \sqrt{gH}$ excite two wave systems: ζ_2 and ζ_3. The waves ζ_3 form above the angle $\gamma < |\gamma_2|$. Inside it, following the moving disturbances, waves with an amplitude decaying as $1/R^{1/2}$ are generally not generated. The waves ζ_2 are generated inside the angular zone $\gamma_2 < |\gamma| < \gamma_3$.

3. The wave motion generated in the case of a uniformly compressed plate in the presence of a compressing stress, satisfying the equation

$$Q_1 < Q_2 = \tau_4(r_4),$$
$$\tau_4 = [(1 + D_1 r^4)\tau_5(r) + 4D_1 r^4 \tau_6(r)][\tau_5(r) + 2\tau_6(r)]r^{-2},$$
$$\tau_5 = \operatorname{th} rH + rH \operatorname{ch}^{-2} rH, \quad \tau_6 = (1 + \varkappa_1 rg \operatorname{th} rH) \operatorname{th} rH,$$

is described by the same equation as in the case of uniform extension, if Q_1 is replaced by $-Q_1$.

4. For quantitative estimates of the effect of uniform compression and extension on the waves generated, we performed numerical calculations in the case of an icy plate of width 0.2, 0.5, and 1 m for the parameter values [6, 11]:

$$E = 3 \cdot 10^9 \text{ N/m}^2, \ \rho_1 = 870 \text{ kg/m}^3, \ \mu = 0{,}34, \ \rho = 10^3 \text{ kg/m}^3, \ H = 10^2 \text{ m}. \tag{4.1}$$

The magnitude of the extension stress varied in the region $[0.2\rho g\sqrt{D_1}]$, and of the compressing one — in the range $(0, \rho g Q_2)$. Here Q_2 for h = 0.2, 0.5, and 1 m is equal to $1.479\sqrt{D_1}$, $1.478\sqrt{D_1}$, and $1.476\sqrt{D_1}$, respectively. The calculation results are presented in Figs. 1-6, where $Q_3 = Q_1/\sqrt{D_1}$. Negative Q_3 values characterize extension, and positive ones — compression. The value $Q_3 = 0$ corresponds to the case of absence of compression and extension stresses [1, 2]. The Q_3-dependence of v_0 and v_1 (m/sec) is illustrated in Fig. 1. The solid (v_0) and dashed (v_1) lines correspond, from above downward, to the plate thicknesses of 1, 0.5, and 0.2 m. It is seen that the values of the critical velocities v_0 and v_1, near which the nature of the wave motion varies slowly, increase with increasing extension stresses, and decrease with increasing compression stresses. These changes may well be significant. For example, for plate thickness 1 m the values of v_0 and v_1 equal, respectively, 18.3 and 26.2 m/sec at $Q_3 = -1.476$, 14.6, and 22.5 m/sec for $Q_3 = 0$, 7.9, and 11.0 m/sec at $Q_3 = 1.476$.

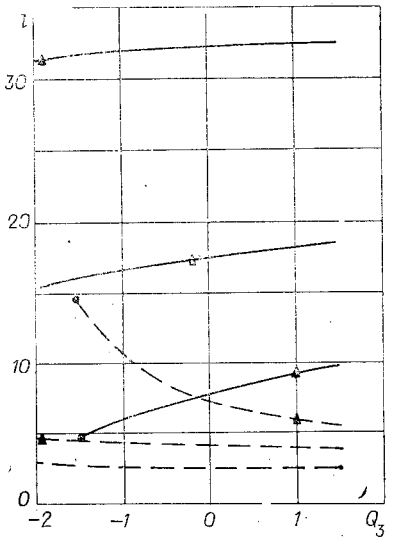

Fig. 6

The phase contours of the waves formed are illustrated in Figs. 2-4 for h = 0.2 m for disturbance displacement velocities equal to 10 (Fig. 2), 20 (Fig. 3), and 35 m/sec (Fig. 4) of the regions $v_0 < v < v_1$, $v_1 < v < \sqrt{gH}$, and $v > \sqrt{gH}$, respectively.

The solid ($Q_3 = 0.5$) and dashed ($Q_3 = -1$) curves in Fig. 2 are node lines of ζ_3 waves. The node lines of ζ_3, ζ_2, and ζ_1 waves in the case $Q_3 = 1$ correspond to the thin solid, boldface solid, and dash-dotted curves on Figs. 3 and 4. Qualitatively, the same wave patterns are also formed in the absence of compression and extension stresses ($Q_3 = 0$). However, the regions of velocity variation v, for which they occur, vary with Q. The angular zone values where the ζ_1, ζ_2, and ζ_3 waves are generated also change. The effect of compression and extension stresses on the value of the angle γ_0 is characterized by the dependences shown in Fig. 5a, and on the values of the angles γ_1, γ_2, and γ_3 in Fig. 5b. The curve order from up downward in Fig. 5a corresponds to disturbance displacement velocities equal to 10, 11, 15, 20, and 35 m/sec. The dashed ($Q_3 = -1.9$), solid ($Q_3 = 0$), and dash-dotted ($Q_3 = 1$) curves 1-3 correspond on Fig. 5b to the angles γ_1, γ_2, and γ_3. The circles mark $\gamma_{1,2}$ values corresponding to the velocity v_1. We note in this case that $\gamma_1 = \gamma_3 = \pi/2$ for $v = \sqrt{gH}$, $\gamma_0 = \pi/2$ for $v = v_0$.

It follows from the curves given that the angle γ_0 is larger for extension than for compression, even for $Q_3 = 0$. The value of the angle γ_3 is practically independent of variations in Q_3. As to the angles γ_1 and γ_2, they increase with extension stress, and decrease with increasing compression stress. Consequently, for $v > \sqrt{gH}$ a large compression (extension) stress corresponds to a small (large) angular zone following the moving disturbances, in which the wave amplitude has an order not less than R^{-1}. The region $\gamma_3 < |\gamma| < \gamma_2$, where ζ_2 waves are generated simultaneously with ζ_3, decreases for increasing extension stress, and broadens with increasing compression stress.

If $v_0 < v < \sqrt{gH}$, an increase in extension (compression) stress leads to a broadening (narrowing) of the formation region of transverse waves ζ_1. In this case, the region $\gamma_1 < |\gamma| < \gamma_2$, in which are formed transverse ζ_1, longitudinal ζ_2, and flexural ζ_3 waves, decreases with increasing extension stress, and increases with increasing compression stress.

With varying Q_3 the distance l along the x axis from the disturbance region to the first paddle ahead of the traveling wave ζ_3 and behind the traveling wave ζ_1 also changes. For h = 0.2 m this is illustrated, respectively, by the dashed and solid lines in Fig. 6. Ordered from top downward, the solid lines correspond to disturbance displacement velocities 20, 15, and 10 m/sec, and the dashed ones — to velocities of 10, 20, and 35 m/sec. The l values marked by triangles and circles characterize the distances at which the quantity Q_3 corresponds to the velocities v_1 and v_0. It is seen that with increasing compressing stress the distance from the first wave paddle ζ_1 to the disturbance region increases, while with increasing extension stress it decreases. The distance from the first wave paddle ζ_3 to the disturbance region has an opposite dependence on the change in Q.

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CONTACT INTERACTION BETWEEN A CYLINDRICAL PANEL AND A HALF-PLANE

É. M. Kim and V. P. Ol'shanskii

UDC 539.3

FORMULATION OF THE PROBLEM AND METHOD OF SOLUTION

Let an external load be applied to a shell and directed parallel to the edge of a semi-infinite plate, as is shown in Fig. 1. The bodies are joined in sections whose width h_0 is small compared to the length $2l$, so that the contact domain can be considered a straight-line segment $\{x \in [-l, l], y = 0\}$. We take the density of the tangential contact forces $\tau(x)$ as the principal unknown. We set the normal component equal to zero. This is justified physically by the fact that the bending stiffness of a thin-walled panel is considerably less than the tension–compression stiffness. An analogous simplification is used in [1] in analyzing the contact interaction between shells and is, in mathematical respects, that we have one singular integral equation in place of a system of two. To obtain it we take the equality of the strains $(u_0)'_x$ in the plate and u'_x in the shell as the contact condition. Using the Green's function from [1, 2], we have

$$\int_{-l}^{l} \tau(\xi)\, \Phi(x-\xi)\, d\xi = f(x), \tag{1}$$

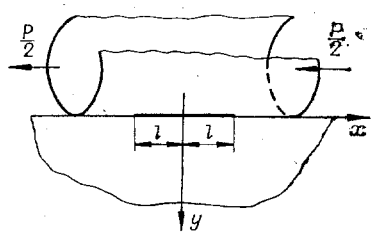

Fig. 1

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