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SIQILUVCHAN SUYUQLIK TO'LDIRILGAN YUPQA DEVORLI SILINDRIK QOBIQLARNING ERKIN TEBRANISHLARI TAHLILI

Annotatsiya. *Siqiluvchan suyuqlik to'ldirilgan yupqa devorli silindrik qobiqning erkin tebranishlari tadqiq etildi. Tizim parametrlarining ba'zi qiymatlarida xususiy tebranish chastotalari aniqlandi, shuningdek, "silindrik qobiq–suyuqlik" tizimining geometrik va fizik parametrlarining silindrning erkin tebranishiga ta'siri o'rganildi.*

Kalit so'zlar: *kuchlanish, tebranishlar, to'lqin, chastota, zichlik, qobiq.*

АНАЛИЗ СВОБОДНЫХ КОЛЕБАНИЙ ТОНКОСТЕННЫХ ЦИЛИНДРИЧЕСКИХ ОБОЛОЧЕК, ЗАПОЛНЕННЫХ СЖИМАЕМОЙ ЖИДКОСТЬЮ

Аннотация. *Исследованы свободные колебания тонкостенной цилиндрической оболочки, заполненной сжимаемой жидкостью. Определены собственные частоты колебаний при некоторых значениях параметров системы, а также изучено влияние геометрических и физических параметров системы «цилиндрическая оболочка – жидкость» на свободные колебания цилиндра.*

Ключевые слова: *напряжение, колебания, волна, частота, плотность, оболочка.*

ANALYSIS OF FREE VIBRATIONS OF THIN-WALLED CYLINDRICAL SHELLS FILLED WITH COMPRESSIBLE FLUID

Annotation. *Free vibrations of a thin-walled cylindrical shell filled with a compressible fluid have been investigated. Natural frequencies of the system were determined for certain parameter values, and the influence of the geometric and physical parameters of the "cylindrical shell–fluid" system on the free vibrations of the cylinder was studied.*

Keywords: *stress, vibrations, wave, frequency, density, shell.*

Kirish. Qobiqlar mashina va inshootlarning elementlari sifatida aviatsiya, kemasozlik va boshqa sohalarda keng qo'llaniladi. Shu sababli oxirgi vaqtlarda ish sharoitida tashqi muhit bilan kontaktda bo'lgan yupqa devorli konstruksiyalarning dinamik holati bilan bog'liq masalalar tadqiqotchilarda katta qiziqish uyg'otmoqda. Qobiqlar nazariyasining dinamik kontakt masalalari orasida elastik qattiq muhit va suyuqlik bilan kontaktda bo'lgan elastik yupqa qobiqlarning erkin tebranishlari haqidagi masalalar muhim o'rin tutadi.

Elastik va suyuq muhitlar bilan kontaktda bo'lgan sferik hamda silindrik qobiqlarning erkin tebranishlar chastotalari va shakllari tadqiq etilgan. Asimptotik metodlar yordamida ko'rilayotgan tizimlarning tebranish shakllarini aniqlash va chastotasini hisoblash uchun soddalashtirilgan yaqinlashgan formulalar olingan bo'lib, bu olingan natijalardan foydalanishni cheklaydi, chunki bir qator muhim holatlarda o'rganilayotgan jarayonlarni sifat jihatidan tahlil qilish imkoniyatini istisno etadi [1,2].

Tadqiqot metodologiyasi. Ushbu ishda siqiluvchan suyuqlik to'ldirilgan yupqa devorli cheksiz silindrik qobiqning erkin aksial simmetrik (o'qqa nisbatan simmetrik) tebranishlari ko'rib chiqiladi. "Silindrik qobiq–suyuqlik" tizimining xususiy chastotalarini topish transsendent tenglamalarni yechish bilan bog'liqligi sababli, suyuqliksiz qobiqning tebranish chastotasi tizim tebranish chastotasi orqali oshkor ko'rinishda ifodalanadi. Bu esa tizim chastotalar spektrini ham tahliliy, ham grafik usulda tadqiq etish imkonini beradi.

Silindrik qobiqlarning radial tebranish tenglamalari quyidagi ko'rinishga ega [3]:

$$\frac{\partial^2 u}{\partial\phi^2}-\frac{1-\mu}{2}\frac{\partial^2 u}{\partial\theta\partial\phi}-\left(\frac{1+\mu}{2}-\frac{1-\mu}{2}\beta^2\right)\frac{\partial^2 v}{\partial\theta\partial\phi}-\frac{\partial W}{\partial\theta}-\frac{1-\mu}{2}\beta^2\frac{\partial^3 W}{\partial\theta\partial\phi^2}-\frac{\rho r^2(1-\mu^2)}{2Eh}\frac{\partial^2 u}{\partial t^2}$$

$$\frac{1+\mu}{2}\frac{\partial^2 u}{\partial\theta\partial\phi}+\frac{\partial^2 v}{\partial\theta^2}-\left(\frac{1-\mu}{2}-(1-\beta^2)\right)\frac{\partial^2 v}{\partial\phi^2}+(1+\beta^2)\frac{\partial^3 v}{\partial\theta^2\partial\phi^2}+$$

$$+\frac{\partial W}{\partial\phi}+\frac{\beta^2}{3}\frac{\partial^3 W}{\partial\phi^3}-\frac{3-\mu}{2}\beta^2\frac{\partial^3 W}{\partial\theta^2\partial\phi}-\frac{\rho r^2(1-\mu^2)}{2Eh}\frac{\partial^2 v}{\partial t^2}$$

$$\mu\frac{\partial u}{\partial\phi}-\frac{\partial V}{\partial\theta}-\beta^2\frac{\partial^3 v}{\partial\theta\partial\phi^2}-2\frac{\partial^2 W}{\partial\phi^2}-\frac{\beta^2}{3}\frac{\partial^4 W}{\partial\phi^4}-\frac{\rho r^2(1-\mu^2)}{2Eh}\left(\frac{\partial^2 W}{\partial t^2}-p\right)$$

bunda

$$\xi = \frac{x}{r}, \quad \beta^2 = \frac{h^2}{r^2}. \tag{1}$$

Suyuqlik harakatini potensialli deb hisoblab va suyuqlik harakati tenglamalaridagi konvektiv hadlarni e'tiborsiz qoldirib (inkor etib), quyidagilarni qabul qilish mumkin:

$$p = -\rho_{liq}\frac{\partial \Phi}{\partial t} \tag{2}$$

Bunda: ρ_{liq} –suyuqlik zichligi, kg/m^3; p –qobiq sirtining birligiga nisbatan olingan tashqi yuklama (bosim), Pa; Φ –suyuqlik tezligi potensiali (o'lchamsiz).

Suyuqlik dinamikasi akustik qo'yilishda ko'rib chiqiladi. Suyuqlikning potensialli harakati holatida, tezliklar maydonini tavsiflash uchun faqat bitta skalyar to'lqin tenglamasiga ega bo'lamiz:

$$\Delta\Phi - \frac{1}{a^2}\frac{\partial^2 \Phi}{\partial t^2} = 0 \tag{3}$$

Potensial to'lqin tenglamasini qanoatlantirgan holatda, (3)-tenglamani silindrik koordinatalarda quyidagicha ifodalaymiz:

$$\frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r}\frac{\partial \Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \varphi^2} - \frac{1}{a^2}\frac{\partial^2 \Phi}{\partial t^2} = 0 \tag{4}$$

Silindr va suyuqlik birgalikda (ajralmasdan) harakatlanadi deb faraz qilinadi. (1)-formuladagi suyuqlik bosimi, suyuqlik tezlik potensiali mavjudligi farazidan kelib chiqib, (2)-tenglikdan aniqlanadi; bu potensial suyuqlik va qobiq chegarasida harakatning birgalikda bo'lish shartiga (moslik shartiga) javob beradi:

$$\frac{\partial \Phi}{\partial r}\Big|_{r=a} = \frac{\partial W}{\partial t} \tag{5}$$

Silindrik qobiq yopiq deb qabul qilamiz. Ikkita parallel aylana bo'ylab tayanchga ega bo'lgan qobiqni ko'rib chiqamiz: $\zeta = 0, \frac{\partial \zeta}{\partial x} = 0$. Ushbu holatda, tayanchdagi sirpanishni hamda deformatsiya va eguvchi momentning yo'qligini hisobga olib, quyidagi shartlarga ega bo'lamiz:

$$\frac{\partial u}{\partial z} = 0, \quad V = 0, \quad W = 0, \quad \frac{\partial^2 W}{\partial z^2} = 0$$

U holda (1) tenglamalar tizimining yechimi quyidagi ko'rinishda ifodalanishi mumkin:

$$u = A\cos m\vartheta \sin n\varphi \sin \omega t, \quad V = B\sin m\vartheta \cos n\varphi \sin \omega t, \quad W = C\sin m\vartheta \sin n\varphi \sin \omega t \tag{6}$$

$$\Phi = D(r)\sin m\vartheta \sin n\varphi \cos \omega t \tag{7}$$

bunda

$$v = n\frac{r}{I}\pi\left(\frac{n}{I}x - v\zeta\right)$$

(2)ga muvofiq, (7)ni hisobga olgan holda, p bosimi quyidagi ko'rinishni oladi:

$$p = \rho_{liq}D(r)\sin m\vartheta \sin n\varphi \sin \omega t \tag{8}$$

(7)ni (4)ga qo'yib, quyidagini hosil qilamiz:

$$D''(r) + \frac{1}{r}D'(r) - \left(\frac{\omega^2}{a^2} - \frac{n^2}{r^2}\right)D(r) = 0 \tag{9}$$

Silindr ichida (9)-tenglamaning yechimi quyidagi ko'rinishga ega:

$$D(r) = D_c(r_m)J_1\left(\frac{\omega_l r_m}{a}\right) \tag{10}$$

(10)ni (7)da hisobga olib,

$$\Phi = D_c(r_m)J_1\left(\frac{\omega_l r_m}{a}\right)\sin m\vartheta \sin n\varphi \cos \omega t \tag{11}$$

va (5)da (6) hamda (11)ni qo'llab, quyidagini hosil qilamiz:

$$D_c = \frac{aC}{J_1\left(\frac{\omega_l r_m}{a}\right)} \tag{12}$$

(6) va (11)ni (1)ga qo‘yib, quyidagiga ega bo‘lamiz:

$$(m^2v^2 + \frac{1-\mu}{2}n^2)A + mvn\left(\frac{1+\mu}{2} - \frac{1-\mu}{2}\beta^2\right)B + \left(\mu mv - \frac{1-\mu}{3}\beta^3 mvn^2\right)C = -\frac{\omega^2}{b^2}A$$

$$\frac{1+\mu}{2}mvn + \left[\frac{1-\mu}{2}(1+\beta^2) + \left(1+\frac{\beta^3}{3}\right)m^2v^2\right]B + \left[n + \frac{\beta^3}{3}n^3 - \frac{3-\mu}{2}\beta^2 mvn\right]C - \frac{\omega^2}{b^2}B$$

$$mvn + \left[n + \frac{\beta^3}{3}n^3 - \frac{2-\mu}{2}\beta^2\frac{\mu}{3}m^2v^2n\right]B +$$

$$+\left(\frac{2}{3}\beta^2m^2v^2n^2 - \frac{1}{3}\beta^2m^2v^2 - 1 - \frac{1}{3}\beta^2n^4\right)C - \frac{\omega^2 + \frac{\cos\rho_{liq}}{I\rho}J_1\left(\frac{\omega l y_m}{a}\right)}{b^2 J_1\left(\frac{\omega l y_m}{a}\right)}C$$

$$\frac{2Eh}{\rho\gamma^2(1-\mu^2)} = b^2 \tag{13}$$

Ushbu qiymatlarni (1) tenglamaga qo‘ygandan so‘ng, A, B, C noma’lum konstantalariga nisbatan tenglamalar sistemasini hosil qilamiz. Ushbu sistemaning determinanti ω^2 ga nisbatan uchinchi darajali chastota tenglamasini beradi.

Ushbu tenglamadan berilgan parametrlar uchun tayanchga ega bo‘lgan qobiqning ikkita ko‘ndalang va ikkita bo‘ylama tebranishlarining mos toni (garmonikasi) uchun chastotalarni olamiz. (13) ifodani soddalashtirish uchun quyidagi belgilashlarni kiritamiz:

$$R_{11} = -m^2v^2 + \frac{1-\mu}{2}\kappa^2, \qquad R_{12} = -\left(\frac{1+\mu}{2} - \frac{1-\mu}{3}\beta^2\right)\tau v, \qquad R_{13} = -\mu\tau v - \frac{1-\mu}{2}\beta^2 mv^2,$$

$$R_{21} = -\frac{1+\mu}{2}\tau v, \qquad R_{22} = -\frac{1-\mu}{2}(1+\beta^2) + \left(1+\frac{\beta^2}{3}\right)m^2v^2, \qquad R_{23} = -\kappa + \frac{\beta^3}{3} + \frac{3-\mu}{2}\beta^2 mv^2,$$

$$R_{31} = -\kappa v, \qquad R_{32} = -\kappa + \frac{\beta^3}{3} + \frac{2-\mu}{2}\beta^2\mu^2m^2v^2\kappa, \qquad R_{33} = -\frac{2}{3}\beta^2m^2v^2\kappa + \frac{1}{3}\beta^2\kappa^4 - \frac{\omega\alpha\rho_{liq}}{b^2\rho}\frac{J_1\left(\frac{\omega l v_m}{a}\right)}{J_{1'}\left(\frac{\omega l v_m}{a}\right)}. \tag{14}$$

Shuningdek, quyidagi matritsani kiritamiz:

$$R - R_0 = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}, \qquad E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{15}$$

(13)-tizim yechimining no-trivial (nolga teng bo‘lmagan) bo‘lish shartini quyidagilarga nisbatan yozib chiqamiz:

$$A, B, C:$$

$$\left|R - \frac{\omega^2}{b^2}E\right| = 0. \tag{16}$$

Suyuqlik mavjud bo‘lmagan holda, ($\rho_{liq} = 0$), tenglama quyidagi ko‘rinishni oladi:

$$\left|R^0 - \frac{\omega^2}{b^2}E\right| = 0, \qquad R^0 = R\big|_{\rho_{liq}=0}. \tag{17}$$

Tenglama ω^2 ga nisbatan kubik (uchinchi darajali) tenglamani ifodalaydi:

$$\Omega_0^3 + i_1^0\Omega_0^2 + i_2^0\Omega_0 - i_3^0 = 0, \qquad \Omega_0 = \frac{\omega_0^2}{b^2}. \tag{18}$$

bunda

$$i_1^0 = -R_{11}^0 - R_{22}^0 - R_{33}^0, \qquad i_2^0 = -(R_{11}^0R_{33}^0 - R_{12}^0R_{23}^0 + R_{13}^0R_{22}^0 - R_{23}^0 - R_{12}^0 - R_{13}^0).$$

$$i_3^0 = -R_{11}^0R_{22}^0R_{33}^0 + 2R_{12}^0R_{23}^0R_{31}^0 - R_{11}^0R_{23}^0R_{32}^0 - R_{22}^0R_{13}^0R_{31}^0 - R_{33}^0R_{12}^0R_{21}^0.$$

$$i_1^0 = R_{ii}^0, \quad i_2^0 = -\begin{vmatrix} R_{11}^0 & R_{13}^0 \\ R_{31}^0 & R_{33}^0 \end{vmatrix} - \begin{vmatrix} R_{22}^0 & R_{23}^0 \\ R_{32}^0 & R_{33}^0 \end{vmatrix} - \begin{vmatrix} R_{11}^0 & R_{12}^0 \\ R_{21}^0 & R_{22}^0 \end{vmatrix}, \quad i_3^0 = \begin{vmatrix} R_{11}^0 & R_{12}^0 & R_{13}^0 \\ R_{21}^0 & R_{22}^0 & R_{23}^0 \\ R_{31}^0 & R_{32}^0 & R_{33}^0 \end{vmatrix}$$

(18)dan Ω_0 ni aniqlaymiz:

$$\Omega_0 = x_k - \frac{i_1^0}{3}, \qquad k = 1,2,3,$$

$$x_1 = A_0 + B_0, \qquad x_{2,3} = -\frac{A_0 + B_0}{2} \pm i\frac{A_0 - B_0}{2}\sqrt{3}.$$

$$A_0 = \sqrt[3]{-\frac{q_0}{2} + \sqrt{Q_0}}, \qquad B_0 = \sqrt[3]{-\frac{q_0}{2} - \sqrt{Q_0}}, \qquad Q_0 = -\left(\frac{p_0}{3}\right)^3 + \left(\frac{q_0}{2}\right)^2.$$

$$p_0 = -\frac{(i_1^0)^2}{3} + i_2^0, \qquad q_0 = -2\left(\frac{i_1^0}{3}\right)^3 + \frac{i_1^0 i_2^0}{3} + i_3^0.$$

ni ifodalab (ifodalab olib),

$$b^2 = \frac{\omega_0^2}{\Omega_0}$$

ni ifodalab va (17)ga qo‘yib, quyidagi shartni hosil qilamiz:

$$\left|R - \frac{\Omega_0\omega^2}{\omega_0^2}E\right| = 0.$$

Oxirgi tenglama o‘zgaruvchiga nisbatan kubik (uchinchi darajali) tenglamadir.

$$\Omega^3 + i_1\Omega^2 + i_2\Omega + i_3 = 0, \qquad \Omega = \frac{\Omega_0\omega^2}{\omega_0^2}.$$

Tenglamaning yechimi quyidagi formulalar bilan beriladi:

$$\Omega = y - \frac{i_1}{3}, \qquad y_1 = A_1 + B_1, \qquad y_{2,3} = \frac{A_1 + B_1}{2} \pm i\frac{A_1 - B_1}{2}\sqrt{3},$$

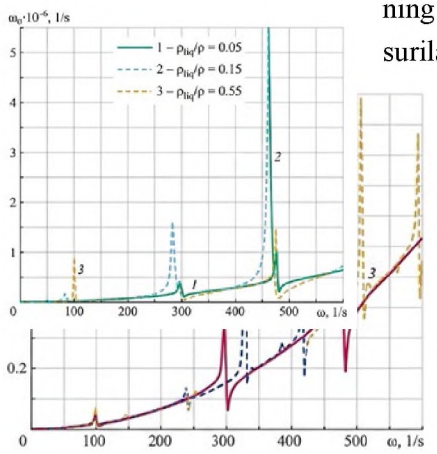
$$A_1 = \sqrt[3]{-\frac{q}{2} + \sqrt{Q}}, \qquad B_1 = \sqrt[3]{-\frac{q}{2} - \sqrt{Q}}, \qquad Q = -\left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2,$$

$$p = -\frac{i_1^2}{3} + i_2, \qquad q = -2\left(\frac{i_1}{3}\right)^3 + \frac{i_1 i_2}{3} + i_3.$$

(23)-formula ω_0 ning ω ga bog‘liqligini ifodalaydi. (17)-tenglama tizimning erkin tebranish chastotasini suyuqlik mavjud bo‘lmagan holatdagi qobiqning erkin tebranish chastotasi bilan bog‘laydi. Umumiy holda tizimning erkin tebranish chastotalarini topish (16)-transsendent tenglamani yechish bilan bog‘liq bo‘lib, uni yechishda mualliflar, ko‘pincha, yaqinlashgan (xususan, asimptotik) metodlarga murojaat qiladilar. Teskari masalaning yechimi tizimning turli modalari uchun tebranish chastotalarining bo‘sh qobiq chastotasiga bog‘liqlik grafiklarini qurish imkonini beradi. Bu esa tadqiqotni, jumladan, tizimning erkin tebranish chastotalarini aniqlashni soddalashtiradi.

Tahlil va natijalar. 1–3-rasmlardan ko‘rinib turibdiki, ω_0 uchun $0–6\cdot10^6$ va ω uchun 0–600 oraliqlarida qurilgan grafiklar tasvirlangan. 1-rasmda suyuqlik zichligining qobiq zichligiga nisbatining uch

xil qiymati uchun $\omega - \omega_0$ chastota spektrining uchta fragmenti ko‘rsatilgan; ko‘rinib turibdiki, suyuqlikning nisbiy zichligi ortishi bilan ω_0 ning ω ga bog‘liqlik grafigi o‘ngga suriladi.

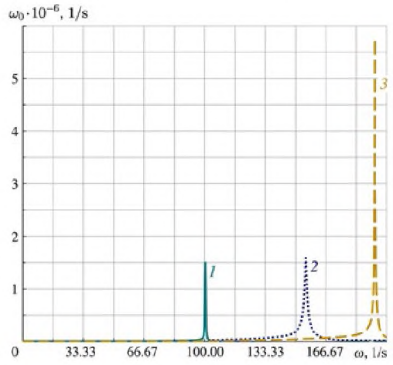


1-rasm. Suyuqlik zichligining qobiq zichligiga nisbatining turli qiymatlarida $\omega_0 = C(\omega)$ (1), $D(\omega)$ (2) va $K(\omega)$ (3) chastota spektrining fragmenti.

2-rasmda silindr qalinligining radiusga nisbatining uch xil qiymati uchun $\omega - \omega_0$ chastota spektrining fragmentlari keltirilgan. Ko‘rinib turibdiki, silindr o‘lchami kamayishi bilan ω_0 ning ω ga bog‘liqlik grafiklari suriladi.

2-rasm. Silindr qobig‘i qalinligining uning radiusiga nisbatining turli qiymatlarida $\omega_0 = C(\omega)$ (1), $D(\omega)$ (2) va $K(\omega)$ (3) chastota spektrining fragmenti.

har bir moda uchun o‘ngga siljiydi. 3-rasmda suyuqlikning siqiluvchanlik koeffitsientining uch xil qiymati uchun $\omega - \omega_0$ chastota spektrining uchta fragmenti tasvirlangan bo‘lib, undan suyuqlikda g‘alayonlarning tarqalish tezligi ortishi bilan ω_0 ning ω ga bog‘liqlik grafiklari ω o‘qi bo‘ylab o‘ngga surilishi ko‘rinadi.



3-rasmda tizimning turli modalari uchun tebranish chastotalarining bo‘sh qobiq tebranish chastotasiga bog‘liqligi keltirilgan bo‘lib, unda tizim tebranish chastotalarining ham ortish, ham pasayish xarakteriga ega sohalari yaqqol ko‘zga tashlanadi. 1-rasmdan ko‘rinib turibdiki, bo‘sh qobiqning tebranish chastotasi ortishi bilan tizimning tebranish chastotasi ham ortadi. Pasayish sohalari suyuqlikda qobiqqa qarama-qarshi yo‘nalgan harakat mavjudligiga mos keladi. Grafikdagi asimptotalar mos keladi.

3-rasm. $\omega_0 = C(\omega)$ (1), $D(\omega)$ (2) va $K(\omega)$ (3) chastota spektrining fragmenti, siqiluvchi suyuqlik qattiqligining silindrsimon qobiqning erkin tebranishlariga nisbatining turli qiymatlarida: $1 - a = 2800$ m/s; $2 - 2400$; $3 - 1400$.

Xulosa va takliflar. Tizim parametrlarining ayrim qiymatlarida uning xususiy tebranish chastotalari analitik usulda aniqlandi, shuningdek, tizimning turli modalari uchun tebranish chastotalarining bo‘sh qobiq chastotasiga bog‘liqlik grafiklari qurildi. Geometrik va fizik parametrlarning silindrning erkin tebranishiga ta’siri tadqiq qilindi.

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