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VIBRATIONS OF A HETEROGENEOUS CYLINDRICAL SHELL STIFFENED WITH RINGS AND DYNAMICALLY CONTACTING WITH FLOWING FLUID

R.N. Agayev

Azerbaijan University of Architecture and Civil Engineering, Baku, Azerbaijan, rufat.83@mail.ru

Abstract- In the present paper we study natural vibrations of a cylindrical shell heterogeneous in thickness, stiffened with rings and dynamically contacting with flowing fluid. Using the Hamilton-Ostrogradsky variational principle when solving the probem a system of equations is structured for studying natural vibrations of a cylindrical shell heterogeneous in thickness, stiffened with rings and dynamically contacting with flowing fluid. The heterogeneity of the cylindrical shell along the thickness was taken into account by accepting the Young modulus and material density as a function of coordinate changing along the thickness. When studying joint vibrations of a cylindrical shell heterogeneous along the thickness, stiffened with circular ribs and dynamically contacting with flowing fluid, two cases were considered: a) fluid is in stationary state; b) fluid moves at a constant speed. In both cases, a frequency equation was constructed and its roots were found. In the calculation process, linear and parabolic cases of change of the heterogeneous function with respect to the coordinate were considered.

Keywords: Cylindrical Shell, Liquid, Free Vibrations, Vibration Frequency.

1. INTRODUCTION

In connection with increase of velocity of motion, pressure, temperature and other factors, study of vibration processes occurring in machines and mechanisms used in modern engineering is of great importance. In the course of operation these constructions are in contact with various media. Therefore, vibration processes occurring in a construction or structural elements should be studied with regard to influence of external factors. In the paper we research natural vibrations of the system a shell stiffened with ribs in the direction of the heterogeneous generatrix along the thickness and fluid. The heterogeneity of the cylindrical shell along the thickness may be taken into account by two various methods. By introducing a multilayer [1] and heterogeneity function. In the paper, the heterogeneity was taken into account by accepting the Young modulus and material density as a function of a coordinate changing along the thickness.

Natural vibrations of an isotropic cylindrical shell stiffened with crossed ribs and fluid moving in infinite elastic medium were considered in [2]. Natural vibrations of an isotropic cylindrical shell stiffened only with rings and fluid moving in an elastic medium were researched in [3]. The papers [4-6] study parameter vibrations of smooth cylindrical shells with regard to heterogeneity along the thickness. Using the variational principle in the solution of the problem, for finding frequency of vibrations of the system under consideration, a frequency equation was constructed and researched depending on physical-geometrical parameters characterizing the system, the characteristic curves on the force-frequency plane were drawn. Stability of cylindrical shells exposed to the action of time-varying force was studied in [7]. Free vibrations of an isotropic inhomogeneous, moving fluid-contacting cylindrical shell stiffened with cross system of ribs were studied in [8].

In the paper [9] natural vibrations of flowing fluid interacting, cylindrical shell inhomogeneous in thickness, are studied. Using the Hamilton-Ostrogradsky variation principle in the solution of the problem, for studying free vibrations of a flowing-fluid-contacting cylindrical shell inhomogeneous in thickness and stiffened with rings, a system of equations was constructed. Homogeneity of the thickness of the cylindrical shell was taking into account accepting the Young modulus and density of the material as a function of coordinate alternating along thickness.

When studying vibrations of a cylindrical shell inhomogeneous along the thickness and stiffened with annular ribs and dynamically interacting with flowing fluid, we considered two cases: a) fluid is at rest inside the cylindrical shell b) fluid moves with constant velocity inside the cylindrical shell. In both cases, the frequency equation was structured and its roots were found. In the calculation process, linear and parabolic cases of alternation of inhomogeneity function with respect to the coordinate were considered.

2. PROBLEM STATEMENT

We will use a three-dimensional functional by taking into account the heterogeneity of a cylindrical shell along the thickness. In this case, the total energy of the cylindrical shell is in the following form:

$$U=\frac{1}{2}\iint\int_{-\frac{h}{2}}^{\frac{h}{2}}\left(\sigma_\alpha e_\alpha+\sigma_\beta e_\beta+\tau_{\alpha\beta}e_{\alpha\beta}+\right.$$
$$\left.+\rho(z)\left(\left(\frac{\partial u}{\partial t}\right)^2+\left(\frac{\partial \vartheta}{\partial t}\right)^2+\left(\frac{\partial w}{\partial t}\right)^2\right)\right)d\alpha d\beta dz \quad (1)$$

where,

$$\sigma_\alpha=\frac{T_1}{h}+\frac{12M_1}{h^3}Z$$
$$\sigma_\beta=\frac{T_2}{h}+\frac{12M_2}{h^3}Z \quad (2)$$
$$\tau_{\alpha\beta}=\frac{S}{h}+\frac{12H}{h^3}Z$$

There are various ways for taking into account heterogeneity. One of them is to accept the Young modulus and material's density as a function of a coordinate changing along the thickness [1]: $E=E(z),\ \rho=\rho(z)$. We assume that the Poisson ratio is constant. In this case, the stress-strain relations are written as:

$$e_\alpha=\frac{1}{E(z)}\left(\sigma_\alpha-v\sigma_\beta\right)$$
$$e_\beta=\frac{1}{E(z)}\left(\sigma_\beta-v\sigma_\alpha\right) \quad (3)$$
$$e_{\alpha\beta}=\frac{2(1+v)}{E(z)}\sigma_{\alpha\beta}$$

Taking into account expressions (2)-(3) and the equality

$$\iint\int_{-\frac{h}{2}}^{\frac{h}{2}}\left(\rho(z)\left(\frac{\partial u}{\partial t}\right)^2+\left(\frac{\partial \vartheta}{\partial t}\right)^2+\left(\frac{\partial w}{\partial t}\right)^2\right)d\alpha d\beta dz=$$
$$=\iint\left(\rho_0\left(\left(\frac{\partial u}{\partial t}\right)^2+\left(\frac{\partial \vartheta}{\partial t}\right)^2+\left(\frac{\partial w}{\partial t}\right)^2\right)-\right.$$
$$-2\rho_1\left(\frac{\partial^2 w}{\partial x\partial t}\cdot\frac{\partial u}{\partial t}+\frac{\partial^2 w}{\partial y\partial t}\cdot\frac{\partial \vartheta}{\partial t}\right)+$$
$$\left.+\rho_2\left(\left(\frac{\partial^2 w}{\partial x\partial t}\right)^2+\left(\frac{\partial^2 w}{\partial y\partial t}\right)^2\right)\right)d\alpha d\beta$$

in (1), we can write:

$$V=\frac{1}{h}\iint\left\{T_1\left[\frac{1}{E_0}\left(2T_2-vT_1\right)+\frac{12}{E_1h^3}\left(M_2-vM_1\right)\right]+\right.$$
$$+T_2\left[-\frac{vT_2}{E_0}+\frac{12}{E_1h^3}\left(M_1-vM_2\right)\right]+$$
$$+2(1+v)S\left(\frac{S}{E_0}+\frac{12H}{E_1h^3}\right)+\frac{72}{E_2h^6}\times \quad (4)$$
$$\left.\times\left(2M_1M_2-vM_1^2-vM_2^2+2(1+v)H^2\right)\right\}d\alpha d\beta$$

We write the total energy of the system of rings:

$$V_1=\frac{1}{2}\sum_{j=1}^{k_2}\int_{y_1}^{y_2}\left[E_jF_j\left(\frac{\partial \vartheta_j}{\partial y}-\frac{w_j}{R}\right)^2+\right.$$
$$+E_jJ_{xj}\left(\frac{\partial^2 w_j}{\partial x^2}+\frac{w_j}{R^2}\right)^2+E_jJ_{zj}\left(\frac{\partial^2 u_i}{\partial y^2}-\frac{\varphi_{kpj}}{R}\right)^2+$$
$$+\sum_{j=1}^{k_2}\rho_jF_j\int_{y_1}^{y_2}\left[\left(\frac{\partial u_j}{\partial t}\right)^2+\left(\frac{\partial \vartheta_j}{\partial t}\right)^2+\right. \quad (5)$$
$$\left.+\left(\frac{\partial w_j}{\partial t}\right)^2+\frac{J_{kp.j}}{F_j}\left(\frac{\partial \phi_{kp.j}}{\partial t}\right)^2\right]dy$$

Since the fluid is ideal, the conditions $q_x=0,\ q_y=0$ are satisfied for the forces acting on the cylindrical shell. The work done by forces acting on a cylindrical shell in displacements of the points of the shell as viewed from fluid is:

$$A_0=-\int_0^{x_1}\int_0^{2\pi}q_z w dx dy$$

The total energy of the system under consideration will consist of the sum

$$W=V+V_1+A_0 \quad (6)$$

In expressions (1)-(6) u,ϑ,w are displacements of the points of the cylindrical shell, u_j,ϑ_j,w_j are displacements of the points of the ring, E,v are modulus of elasticity of the material of the cylindrical shell and the Poisson ratio, respectively, R,h are the radius and thickness of the cylindrical shell, respectively, E_j is elasticity modulus of the ring, F_j is the area of the cross section of the ring; $I_{zj},\ I_{xj},I_{kp.j}$ are inertia moments of the cross-section of the ring; k_2 is the amount of rings, q_z are the components of pressure force acting on the cylindrical shell as viewed from fluid and $\rho_i=\int_{-h}^{h}\rho(z)z^i dz$, $\frac{1}{E_i}=\int_{-h}^{h}\frac{z^j dz}{E(z)}$.

It is considered that hard contact conditions between the cylindrical shell and rings are satisfied:

$$u_j(y)=u(x_j,y)+h_j\varphi_1(x_j,y)$$
$$\vartheta_j(y)=\vartheta(x_j,y)+h_j\varphi_2(x_j,y)$$
$$\vartheta_j(y)=\varphi_2(x_j,y)$$
$$\varphi_{kp.j}=\varphi_1(x_j,y) \quad (7)$$
$$w_j(y)=w(x_j,y)$$
$$h_j=0.5h+H_j^1$$

The movement of fluid moving with velocity U with respect to the potential φ is in form [10]:

$$\Delta\varphi-\frac{1}{a_0^2}\left(\frac{\partial^2\varphi}{\partial t^2}+2U\frac{\partial^2\varphi}{R\partial\xi\partial t}+U^2\frac{\partial^2\varphi}{R^2\partial\xi^2}\right)=0 \quad (8)$$

In the radial direction the equality of velocity and pressure in the contact of a shell-fluid satisfied:

$$\vartheta_r\big|_{r=R} = \frac{\partial \varphi}{\partial r}\bigg|_{r=R} = -\left(\omega_0 \frac{\partial w}{\partial t_1} + U\frac{\partial w}{R\partial \xi}\right)\bigg|_{r=R} \quad (9)$$

$$q_z = -p\big|_{r=R} \quad (10)$$

We look for the potential φ of disturbances in the following form:

$$\varphi(\xi, r, \theta, t_1) = f(r)\cos n\varphi \sin kx \sin \omega t \quad (11)$$

Using (9) and (10), form (11) we get [10, 11]:

$$\varphi = -\Phi_{\alpha n}\left(\omega_0 \frac{\partial w}{\partial t_1} + U\frac{\partial w}{R\partial \xi}\right)$$
$$p = \Phi_{\alpha n}\rho_m\left(\omega_0^2 \frac{\partial^2 w}{\partial t_1^2} + 2U\omega_0 \frac{\partial^2 w}{R\partial \xi \partial t_1} + U^2 \frac{\partial^2 w}{R^2 \partial \xi^2}\right) \quad (12)$$

where,

$$\Phi_{\alpha n} = \begin{cases} \dfrac{I_n(\beta r)}{I_n'(\beta R)}, M_1 < 1 \\ \dfrac{J_n(\beta r)}{J_n'(\beta R)}, M_1 > 1 \\ \dfrac{r^n}{nR^{n-1}}, M_1 = 1 \end{cases} \quad (13)$$

In equalities (13) $M_1 = \dfrac{U + \omega_0 R\omega_1 / a}{a_0}$, $\beta^2 = R^{-2}(1 - M_1^2)\chi^2$, $\beta_1^2 = R^{-2}(M_1^2 - 1)\chi^2$, I_n is an nth order modified first kind Bessel function, $U^* = U/c$, c is sound propagation speed in the cylindrical shell, J_n is an nth order first kind Bessel function.

So, the solution of the stated problem is reduced to joint integration of the total energy (6), the system of motion equations of fluid (8) of a cylindrical shell with flowing fluid in its interior domain and strengthened with discretely distributed rings within the boundary conditions (12).

3.PROBLEM SOLUTION

In the expression (6) the quantities are $u, \vartheta, w, T_1, T_2, M_1, M_2, S, H$. Let us determine stationary value of the function (6). For that we use the Riets method. We will look for the unknown quantities in the following form:

$$u = \cos\frac{\pi x}{l}\sin(k\varphi)(u_0\cos\omega t + u_1\sin\omega t)$$
$$\vartheta = \sin\frac{\pi x}{l}\cos(k\varphi)(\vartheta_0\cos\omega t + \vartheta_1\sin\omega t)$$
$$w = \sin\frac{\pi x}{l}\sin(k\varphi)(w_0\cos\omega t + w_1\sin\omega t)$$
$$T_1 = \sin\frac{\pi x}{l}\sin(k\varphi)(T_{10}\cos\omega t + T_{11}\sin\omega t)$$
$$T_2 = \cos\frac{\pi x}{l}\cos(k\varphi)(T_{20}\cos\omega t + T_{21}\sin\omega t)$$
$$S = \sin\frac{\pi x}{l}\sin(k\varphi)(S_{10}\cos\omega t + S_{11}\sin\omega t) \quad (14)$$
$$M_1 = \cos\frac{\pi x}{l}\sin(k\varphi)(M_{10}\cos\omega t + M_{11}\sin\omega t)$$
$$M_2 = \sin\frac{\pi x}{l}\sin(k\varphi)(M_{20}\cos\omega t + M_{21}\sin\omega t)$$
$$H = \cos\frac{\pi x}{l}\cos(k\varphi)(H_{10}\cos\omega t + H_{11}\sin\omega t)$$

Writing expressions (14) in functional (6), we get a function dependent on the variables $u_0, u_1, \vartheta_0, \vartheta_1$, $w_0, w_1, T_{10}, T_{11}, T_{20}, T_{21}, S_{10}, S_{11}, M_{10}, M_{12}, M_{20}, M_{22}$, H_{10}, H_{11}. The stationarity condition of the obtained function is determined from the following system:

$$1)\frac{\partial J}{\partial u_0} = 0;\ 2)\frac{\partial J}{\partial u_1} = 0;\ 3)\frac{\partial J}{\partial \vartheta_0} = 0;\ 4)\frac{\partial J}{\partial \vartheta_1} = 0$$
$$5)\frac{\partial J}{\partial w_0} = 0;\ 6)\frac{\partial J}{\partial w_1} = 0;\ 7)\frac{\partial J}{\partial T_{10}} = 0;\ 8)\frac{\partial J}{\partial T_{11}} = 0$$
$$9)\frac{\partial J}{\partial T_{20}} = 0;\ 10)\frac{\partial J}{\partial T_{21}} = 0;\ 11)\frac{\partial J}{\partial S_{10}} = 0;\ 12)\frac{\partial J}{\partial S_{11}} = 0 \quad (15)$$
$$13)\frac{\partial J}{\partial M_{10}} = 0;\ 14)\frac{\partial J}{\partial M_{11}} = 0;\ 15)\frac{\partial J}{\partial M_{20}} = 0;\ 16)\frac{\partial J}{\partial M_{21}} = 0$$
$$17)\frac{\partial J}{\partial H_{10}} = 0;\ 18)\frac{\partial J}{\partial H_{11}} = 0$$

Since the system (15) is homogeneous, for the existence of its non-zero solution the principle determinant should equal zero. As a result, we get the frequency equation:

$$\det\|a_{ij}\| = 0,\ i, j = 1,18 \quad (16)$$

where,

$$a_{11} = \frac{\pi^2 l\rho_0}{2\omega} + \frac{\pi^3}{2\omega l^2}\sum_{i=1}^{k_1}\tilde{E}_i F_i \sin^2 k\varphi_i + $$
$$+\frac{\pi\omega l}{2}\sum_{i=1}^{k_1}\tilde{\rho}_i F_i \sin^2 k\varphi_i - \frac{\pi^2}{2\omega}\left(\frac{k}{R}\right)^4$$

$$a_{15} = \frac{\rho_1\omega\pi^3}{2};\ a_{22} = a_{11};\ a_{26} = a_{15}$$

$$a_{33} = \frac{\pi^2 l\rho_0}{2\omega} + \frac{\pi^3}{2\omega l^2}\sum_{i=1}^{k_1}\tilde{E}_i F_i \sin^2 k\varphi_i + $$
$$+\frac{\pi^3}{4\omega R^2 l}\sum_{i=1}^{k_1}G_i J_{kp,i}\cos^2 k\varphi_i + \frac{\pi l\omega}{2}\sum_{i=1}^{k_1}\tilde{\rho}_i F_i \cos^2 k\varphi_i + $$
$$+\frac{\pi l\omega}{4}\sum_{i=1}^{k_1}\tilde{\rho}_i J_{kp.i}\cos^2 k\varphi_i$$

$$a_{35} = \frac{\omega\pi^2 lk\rho_0}{2R} + \frac{\pi^3}{2\omega R^2 l}\sum_{i=1}^{k_1}G_i J_{kp.i}\cos^2 k\varphi_i + $$
$$+\frac{\pi l\omega k}{4R^2}\sum_{i=1}^{k_1}\tilde{\rho}_i F_i \sin 2k\varphi_i$$

$$a_{44} = a_{33};\ a_{46} = a_{35};\ a_{51} = \frac{\rho_1\omega\pi^3}{2}$$

$$a_{53} = \frac{\omega\pi^2 lk\rho_1}{2R} +$$

$$+\frac{\pi^3 k}{4\omega R^2 l}\sum_{i=1}^{k_1} G_i J_{kp.i}\cos^2 k\varphi_i + \frac{\pi l\omega k}{4R^2}\sum_{i=1}^{k_1}\tilde{\rho}_i I_{kp.i}\sin 2k\varphi_i$$

$$a_{55} = \frac{\pi^2 l\rho_0}{2\omega} - \pi\rho_2\omega\left(\left(\frac{\pi}{l}\right)^2 + k^2\right) +$$

$$+\frac{\pi^5}{2\omega l^4}\sum_{i=1}^{k_1}\tilde{E}_i I_{zi}\sin^2 k\varphi_i + \frac{\pi^3 k^2}{4\omega R^2 l}\sum_{i=1}^{k_1} G_i J_{kp.i}\cos^2 k\varphi_i +$$

$$+\frac{\pi l}{2\omega}\sum_{i=1}^{k_1}\tilde{\rho}_i F_i\sin^2 k\varphi_i + \frac{\pi l\omega k^2}{2R^2}\sum_{i=1}^{k_1}\tilde{\rho}_i J_{kp.i}\sin^2 k\varphi_i -$$

$$\left. -\pi l\Phi_{\alpha n}(R)\rho_m\omega^2 + \frac{2\pi U\omega}{l} + \left(\frac{\pi}{l}\right)^2 U^2\right)$$

$$a_{64} = a_{52};\ a_{66} = a_{55};\ a_{77} = -\frac{\nu\pi^2 l}{2\omega E_0}$$

$$a_{713} == -\frac{3\nu\pi^2 l}{2\omega E_1 h^3};\ a_{715} = \frac{3\pi^2 l}{\omega E_1 h^3};\ a_{88} = a_{77}$$

$$a_{814} = a_{813};\ a_{816} = a_{815};\ a_{99} = \frac{\nu\pi^2 l}{2\omega E_0};\ a_{1010} = a_{99}$$

$$a_{1111} = \frac{(1+\nu)\pi^2 l}{\omega E_0};\ a_{1212} = a_{1111}$$

$$a_{137} = -\frac{3\nu\pi^2 l}{2\omega E_1 h^3};\ a_{1313} = a_{137}$$

$$a_{148} = a_{137};\ a_{1414} = a_{1313};\ a_{157} = -\frac{3\pi^2 l}{\omega E_1 h^3}$$

$$a_{1515} = -\frac{36\nu\pi^2 l}{E_2 h^6};\ a_{168} = a_{157};\ a_{1616} = a_{1515}$$

$$a_{1717} = \frac{36(1+\nu)\pi^2 l}{E_2 h^6};\ a_{1818} = a_{1717}$$

4. CONCLUSIONS

Equation (16) was studied by the numerical method. The following estimations were taken for the medium and shell parameters:

$$h^* = \frac{h}{R} = 0.25\times 10^{-2};\ \nu = 0.3;\ E_i = E = 6.67\times 10^9\ \text{N/m}^2$$

$$\alpha = 0.5;\ h_i = 1.39\ \text{mm};\ F_i = 5.75\ \text{mm}^2$$

$$J_{xi} = 19.9\ \text{mm}^4;\ \rho_i = 0.26\times 10^4\ \text{N}\times\text{san}^2/\text{m}^4$$

$$E_0 = E;\ \rho_0 = \rho_i;\ \frac{J_{zi}}{2\pi R^3 h} = 0.23\times 10^{-6}$$

$$J_{kp.i} = 0.48\ \text{mm}^4;\ U^* = 0.005$$

The two cases of heterogeneity functions are considered: the liner

$$E(z) = E_0\left[1+\alpha\left(\frac{z}{h}\right)\right];\ \rho_z = \rho_0\left[1+\alpha\left(\frac{z}{h}\right)\right]$$

and parabolic

$$E(z) = E_0\left[1+\alpha\left(\frac{z}{h}\right)^2\right];\rho_z = \rho_0\left[1+\alpha\left(\frac{z}{h}\right)^2\right]$$

where the Young modulus α is a homogeneity parameter. Note that in the case of a liner function $|\alpha| < 1$, in the case of parabolic law α is any number and

$$\omega_1 = \sqrt{\frac{(1-\nu^2)\rho_0 R^2\omega^2}{E}}.$$

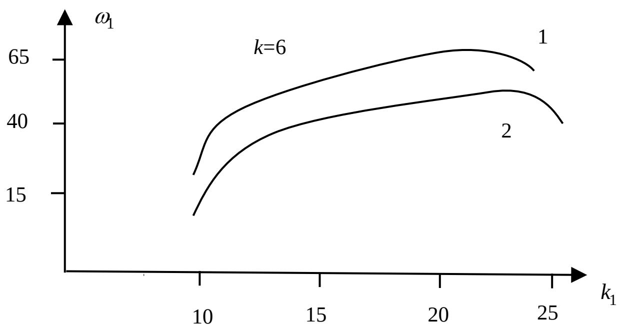

Figure 1. Dependence of frequency parameter on the amount of rings, 1 is a linear law, 2 is a parabolic law

The result of calculations was given in Figure 1 in the form of dependence of the frequency parameter on the amount of rings, in Figure 2 in the form of dependence of frequency parameter on the fluid motion speed. The linear case of heterogeneity laws correspond to curve 1, parabolic change cases of heterogeneity laws correspond to curve 2.

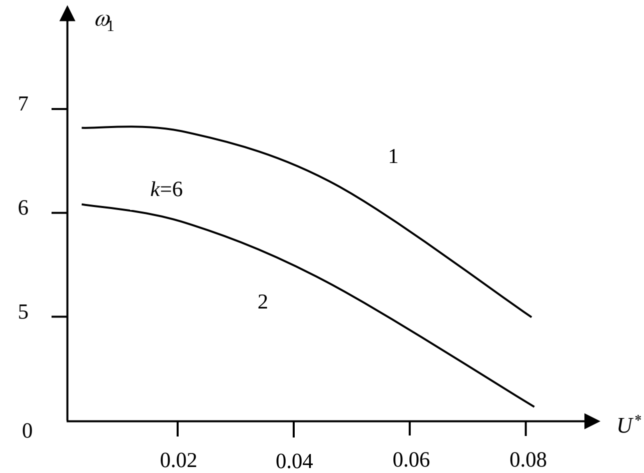

Figure 2. Dependence of frequency parameter on the fluid movement speed, 1 is a linear law, 2 is a parabolic law

Calculations show that vibration frequencies corresponding to the linear case of heterogeneity laws are greater than vibration frequencies corresponding to the parabolic change case. As can be seen from the figure, increasing the amount of rings, vibration frequencies of the system at first increase, and after certain value when the inertia effect of ribs intensifies, they decrease. As can be seen from Figure 2, increasing fluid movement speed, vibration frequencies of the system decrease.

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BIOGRAPHY

Rufat Nadir Agayev was born in Baku, Azerbaijan, 1983. He received the B.Sc. degree in degree in Construction and Civil Engineering Municipalities and the M.Sc. degree in Technical Exploitation and Reconstruction of Buildings and Constructions from Azerbaijan University of Architecture and Construction, Baku, Azerbaijan in 2004 and 2008, respectively. He entered the Ph.D. program in Construction Mechanics at the same university in 2014. In 2005-2007, he worked at the Heat Systems Service Centre, Baku, Azerbaijan as a Project Engineer. He worked at the Aztechproject Construction LLC, Baku, Azerbaijan in 2007-208 as a Head Project Engineer. During 2009-2010 and 2011-2013, he worked at the Baku State Project Institute, Baku, Azerbaijan as a Senior Specialist. In 2010-2011 he worked as the Head of the Group in Oil and Gas Scientific-Research Project Institute, Baku, Azerbaijan. Currently, he has received a grant from the Ministry of Civil Aviation and Architecture, Baku, Azerbaijan and works in a labor activity as a physical person. He is the author of 3 scientific articles.