534

. .

.   *2/10,*   *, 61046,*   *; e-mail: avramov@nas.gov.ua* ,

The model of geometrically nonlinear behavior of functionally graded composite cylindrical shell with nanotubes reinforcements is derived. The simply supported cylindrical shell is treated. The Reddy high-order shear deformation theory is used. Three projections of the displacements and two rotations angles of middle surface normal are the main unknowns of this problem. The potential energy of the cylindrical shell geometrically nonlinear deformation is derived with account of shear. Three displacements projections and two rotation angles of the middle surface normal is expanded using the eigenmodes of the cylindrical shell vibrations. The axisymmetric eigenmodes are accounted in these expansions too. High dimension nonlinear system of ordinary differential equation is obtained to describe the structure nonlinear vibrations using the assumed-mode method. The piston theory is used to describe the supersonic gas theory. The extended rule of mixture is used to obtain the mechanical features of nano composites. The calculation of the characteristic exponents and the direct numerical integrations of the motions equations are used to analyze the dynamic stability of the trivial equilibrium. As a result of the numerical analysis, it is obtained, that the trivial equilibrium loses stability due to the Hopf bifurcation. The limit

cycle is originated due to the Hopf bifurcation. This cycle describes the travelling waves of the cylindrical shell. The harmonic balanced method is used to analyze the limit cycle behavior, when the flow pressure is varied. The mono harmonic approximation of the self-sustained vibrations is used. The data, which are obtained by the harmonic balanced method, are compared with the results of the direct numerical integrations. The results, which are obtained by two methods, are close. Therefore, the harmonic balanced method are true for self- sustained vibrations analysis.

:   -   ,

   ,   ,   .

          .   -

                              ,   .   -

                                                   ,   -

                  [1].   -

          ,   -   -

      .   .   -

      −   [2].   -

                  [3].

                                          .   -

                                                      .   -

                                                            .   -

                                  [4],   -

                      .   [5]   -

                                                                  .

                                  .   -

                                                              [6 − 10].   -

              [11 − 13].

                                      -   -

                                  .

                                      .   -

                  .   -

          .   -

              .   -

              .

          .   -

                  ,   .

      1.   .   -

                              h   .

                  -

                      (x, θ, z) (. 1).

                                                                                  -

,

, ,
.

u, v, w — .
.
.
.

x (. 1). , -
. 2. UD
.

FGV, FGΛ, FGX FGO . 2.

. -
- . -
( ) , , -

V_{CNT}^* .
, ,
1.

. 1

. 2

1. , , z
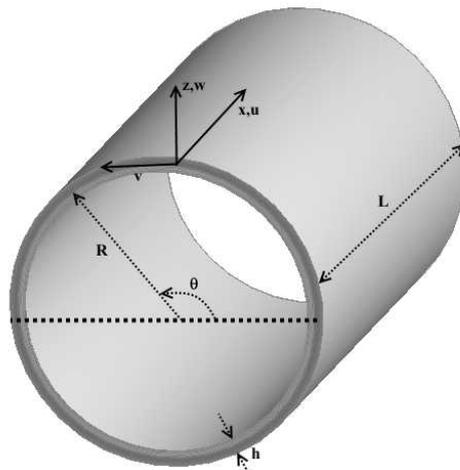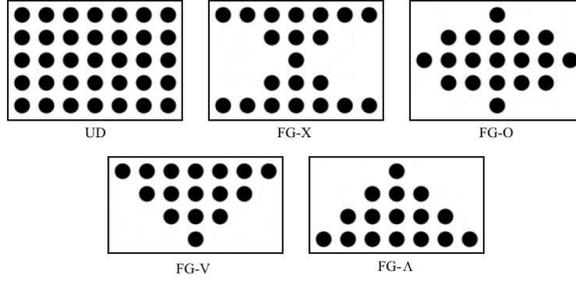
	,
UD-CNT	$V_{CNT}(z) \equiv V_{CNT}^*;$
FGV-CNT	$V_{CNT}(z) = \left(1 + \dfrac{2z}{h}\right)V_{CNT}^*;$
FGΛ-CNT	$V_{CNT}(z) = \left(1 - \dfrac{2z}{h}\right)V_{CNT}^*;$
FGX-CNT	$V_{CNT}(z) = \dfrac{4|z|}{h}V_{CNT}^*;$
FGO-CNT	$V_{CNT}(z) = 2\left(1 - \dfrac{2|z|}{h}\right)V_{CNT}^*.$

\- -

z . :

$$E_{11}(z) = \eta_1 V_{CNT}(z)E_{11}^{CNT} + V_m(z)E^m; \quad E_{22}(z) = \frac{\eta_2 E_{22}^{CNT}E^m}{V_{CNT}(z)E^m + V_m(z)E_{22}^{CNT}}; \quad G_{12}(z) = \frac{\eta_3 G_{12}^{CNT}G^m}{V_{CNT}(z)G^m + V_m(z)G_{12}^{CNT}};$$

$E_{11}^{CNT}, E_{22}^{CNT}, G_{12}^{CNT} -$; $\mu_{12}^{CNT} -$
; $\eta_1, \eta_2, \eta_3 -$, -
; $E^m, G^m -$
; $\rho^{CNT}, \rho^m -$.
, -
. -
:

$$\begin{bmatrix} \sigma_{XX} \\ \sigma_{\theta\theta} \end{bmatrix} = \begin{bmatrix} Q_{11}(z) & Q_{12}(z) \\ Q_{12}(z) & Q_{22}(z) \end{bmatrix} \begin{bmatrix} \varepsilon_{XX} \\ \varepsilon_{\theta\theta} \end{bmatrix}; \qquad (2)$$

$$\sigma_{\theta Z} = G_{23}(z)\gamma_{\theta Z}; \sigma_{XZ} = G_{13}(z)\gamma_{XZ}; \sigma_{X\theta} = G_{12}(z)\gamma_{X\theta}.$$

$$Q_{11}(z)\frac{E_{11}(z)}{1 - \mu_{12}(z)\mu_{21}(z)}; \quad Q_{22}(z)\frac{E_{22}(z)}{1 - \mu_{12}(z)\mu_{21}(z)}; \quad Q_{12}(z)\frac{\mu_{21}(z)E_{11}(z)}{1 - \mu_{12}(z)\mu_{21}(z)}.$$

$\gamma_{XZ}, \gamma_{\theta Z}$ —   ; $\varepsilon_{XX}, \varepsilon_{\theta\theta}, \gamma_{\theta Z}, \gamma_{XZ}, \gamma_{X\theta}$ —

                    ; $\sigma_{XZ}, \sigma_{\theta Z}$ —   ; $\sigma_{XX}, \sigma_{\theta\theta}, \sigma_{X\theta}$ —   -

.

,

            z x, θ z

$u_x(x, \theta, t, z), u_\theta(x, \theta, t, z)$ $u_z(x, \theta, t, z)$,   .   -

        :

$$u_x(x, \theta, t, z) = u(x, \theta, t) + z\phi_1(x, \theta, t) + z^2\psi_1(x, \theta, t) + z^3\gamma_1(x, \theta, t); \quad (3)$$
$$u_\theta(x, \theta, t, z) = \left(1 + \frac{z}{R}\right)v(x, \theta, t) + z\phi_2(x, \theta, t) + z^2\psi_2(x, \theta, t) + z^3\gamma_2(x, \theta, t);$$
$$u_z(x, \theta, t, z) = w(x, \theta, t),$$

R —   ; ϕ_1, ϕ_1 —   -

                                                        θ, x ,   .   -

                                                                                            :

$u(x, \theta, t), v(x, \theta, t), w(x, \theta, t), \phi_1(x, \theta, t), \phi_2(x, \theta, t)$.   -
$\psi_1(x, \theta, t), \gamma_1(x, \theta, t), \psi_2(x, \theta, t), \gamma_2(x, \theta, t)$ (3)

                                        :

$$\gamma_{XZ}\Big|_{Z=\pm 0.5h} = 0; \quad \gamma_{\theta Z}\Big|_{Z=\pm 0.5h} = 0. \qquad (4)$$

            (4),   (3)   -

        :

            -

        :

$$T = 0.5 \int_0^{2\pi} \int_0^L \int_{-0.5h}^{0.5h} \rho(z)\left(\dot{u}_x^2 + \dot{u}_\theta^2 + \dot{u}_z^2\right)\left(1 + \frac{z}{R}\right) dz\, dx\, R\, d\theta, \qquad (6)$$

    L —   .   (3)

(6).   :

$$T = 0.5 \int_0^{2\pi} \int_0^L \left\{ r_0(\dot{u}^2 + \dot{v}^2 + \dot{w}^2) + 2r_1\left(\frac{\dot{v}^2}{R} + \dot{u}\dot{\phi}_1 + \dot{v}\dot{\phi}_2\right) + \right.$$
$$+ r_2\left(\frac{\dot{v}^2}{R^2} + \dot{\phi}_1^2 + \dot{\phi}_2^2 + \frac{2}{R}\dot{v}\dot{\phi}_2 + 2\dot{v}\dot{\psi}_2\right) + 2r_3\left(\dot{u}\dot{\gamma}_1 + \frac{\dot{v}\dot{\psi}_2}{R} + \dot{\gamma}_2\dot{v} + \dot{\phi}_2\dot{\psi}_2\right) +$$

$$r_i = \int_{-0.5h}^{0.5h} z^i \rho(z)\, dz; \quad i = 0, \dots, 6. \qquad (7)$$

            .

        :

$$2\prod = \int_0^L \int_0^{2\pi} \int_{-0.5h}^{0.5h} (\sigma_{XX}\varepsilon_{XX} + \sigma_{\theta\theta}\varepsilon_{\theta\theta} + \sigma_{\theta Z}\gamma_{\theta Z} + \sigma_{XZ}\gamma_{XZ} + \sigma_{X\theta}\gamma_{X\theta})\left(1 + \frac{z}{R}\right) dz$$

52

:

$$\prod\nolimits_{\text{□}} = \frac{1}{2}\int_0^L \int_0^{2\pi} \int_{-0.5h}^{0.5h} \left(Q_{11}\varepsilon_{XX}^2 + 2Q_{12}\varepsilon_{\theta\theta}\varepsilon_{XX} + Q_{22}\varepsilon_{\theta\theta}^2 + G_{23}\gamma_{\theta Z}^2 + G_{13}\gamma_{XZ}^2 + G_{12}\gamma_{X\theta}^2\right)\left(1+\frac{z}{R}\right)dzRd\theta dx.$$

,
-

$$\varepsilon_{XX}, \varepsilon_{\theta\theta}, \gamma_{X\theta}$$

u_X, u_θ, u_Z :

$$\varepsilon_{XX} = \frac{\partial u_X}{\partial x} + 0.5\left[\left(\frac{\partial u_X}{\partial x}\right)^2 + \left(\frac{\partial u_\theta}{\partial x}\right)^2 + \left(\frac{\partial u_Z}{\partial x}\right)^2\right];$$

$$\varepsilon_{\theta\theta} = \frac{1}{R(1+zR^{-1})}\left(\frac{\partial u_\theta}{\partial\theta} + u_Z\right)+$$

$$\gamma_{X\theta} = \frac{1}{R(1+zR^{-1})}\frac{\partial u_X}{\partial\theta} + \frac{\partial u_\theta}{\partial x} + \frac{1}{R(1+zR^{-1})}\left\{\frac{\partial u_X}{\partial\theta}\frac{\partial u_X}{\partial x} + \right.$$
$$\left. +\left(\frac{\partial u_\theta}{\partial\theta} + u_Z\right)\frac{\partial u_\theta}{\partial x} - \frac{\partial u_Z}{\partial x}\left(-\frac{\partial u_Z}{\partial\theta} + u_\theta\right)\right\}. \qquad (10)$$

Z :

$$\varepsilon_{XX} = \varepsilon_{XX,0} + zk_{XX}^{(0)} + z^2 k_{XX}^{(1)} + z^3 k_{XX}^{(2)};$$
$$\varepsilon_{\theta\theta} = \varepsilon_{\theta\theta,0} + zk_{\theta\theta}^{(0)} + z^2 k_{\theta\theta}^{(1)} + z^3 k_{\theta\theta}^{(2)};$$
$$\gamma_{X\theta} = \gamma_{X\theta,0} + zk_{X\theta}^{(0)} + z^2 k_{X\theta}^{(1)} + z^3 k_{X\theta}^{(2)}; \quad \gamma_{XZ} = \gamma_{XZ,0} + zk_{XZ}^{(0)} + z^2 k_{XZ}^{(1)} + z^3 k_{XZ}^{(2)};$$
$$\gamma_{\theta Z} = \gamma_{\theta Z,0} + zk_{\theta Z}^{(0)} + z^2 k_{\theta Z}^{(1)} + z^3 k_{\theta Z}^{(2)}, \qquad (11)$$

:

$$\varepsilon_{XX,0} = \frac{\partial u}{\partial x} + 0.5\left[\left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right]; \quad k_{XX}^{(0)} = \frac{\partial\phi_1}{\partial x}; \quad k_{XX}^{(1)} = 0;$$

$$k_{XX}^{(2)} = -\frac{4}{3h^2}\left(\frac{\partial\phi_1}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right); \quad \varepsilon_{\theta\theta,0} = \frac{1}{R}\left(\frac{\partial v}{\partial\theta} + w\right) + \frac{1}{2R^2}\left\{\left(\frac{\partial u}{\partial\theta}\right)^2 + \left(\frac{\partial v}{\partial\theta} + w\right)^2 + \left(v - \frac{\partial w}{\partial\theta}\right)^2\right\};$$

$$k_{\theta\theta}^{(0)} = -\frac{w}{R^2} + \frac{1}{R}\frac{\partial\phi_2}{\partial\theta}; \quad k_{\theta\theta}^{(1)} = \frac{1}{2R^3}\frac{\partial^2 w}{\partial\theta^2} - \frac{1}{2R^2}\frac{\partial\phi_2}{\partial\theta} - \frac{1}{R^3}\frac{\partial v}{\partial\theta};$$

$$k_{\theta\theta}^{(2)} = -\frac{4R^2 + h^2}{3R^4 h^2}\frac{\partial^2 w}{\partial\theta^2} - \frac{4R^2 + 2h^2}{3R^3 h^2}\frac{\partial\phi_2}{\partial\theta} - \frac{1}{3R^4}\frac{\partial v}{\partial\theta};$$

$$\gamma_{X\theta,0} = \frac{\partial u}{R\partial\theta} + \frac{\partial v}{\partial x} + \frac{1}{R}\left\{\frac{\partial u}{\partial\theta}\frac{\partial u}{\partial x} + \left(\frac{\partial v}{\partial\theta} + w\right)\frac{\partial v}{\partial x} - \left(v - \frac{\partial w}{\partial\theta}\right)\frac{\partial w}{\partial x}\right\};$$

$$k_{X\theta}^{(0)} = \frac{\partial\phi_1}{R\partial\theta} - \frac{1}{R^2}\frac{\partial u}{\partial\theta} + \frac{\partial v}{R\partial x} + \frac{\partial\phi_2}{\partial x}; \quad k_{X\theta}^{(1)} = -\frac{\partial\phi_1}{R^2\partial\theta} + \frac{1}{2R^2}\frac{\partial^2 w}{\partial\theta\partial x} + \frac{\partial\phi_2}{2R\partial x}.$$

Z .

:

-

$$\prod\square = 0.5 \int_0^L \int_0^{2\pi} \left(\sum_{v=0}^{6} \prod \tilde{\square}_v \right) dx R d\theta, \qquad (12)$$

$\Pi\tilde{\square}_0 = Q_{11}^{(0)} \varepsilon_{XX,0}^2 + 2Q_{12}^{(0)} \varepsilon_{\theta\theta,0} \varepsilon_{XX,0} + Q_{22}^{(0)} \varepsilon_{\theta\theta,0}^2 + G_{23}^{(0)} \gamma_{\theta Z,0}^2 + G_{12}^{(0)} \gamma_{X\theta,0}^2 + G_{13}^{(0)} \gamma_{XZ,0}^2 ;$

$\Pi\tilde{\square}_1 = 2Q_{11}^{(1)} \varepsilon_{XX,0} k_{XX}^{(0)} + 2Q_{22}^{(1)} \varepsilon_{\theta\theta,0} k_{\theta\theta}^{(0)} + 2Q_{12}^{(1)} \varepsilon_{\theta\theta,0} k_{XX}^{(0)} +$

$\Pi\tilde{\square}_2 = 2Q_{12}^{(2)} k_{\theta\theta}^{(0)} k_{XX}^{(0)} + 2G_{12}^{(2)} \gamma_{X\theta,0} k_{X\theta}^{(1)} + Q_{22}^{(2)} k_{\theta\theta}^{(0)2} + 2G_{13}^{(2)} \gamma_{XZ,0} k_{XZ}^{(1)} +$

$\Pi\tilde{\square}_3 = 2G_{12}^{(3)} \gamma_{X\theta,0} k_{X\theta}^{(2)} + 2G_{12}^{(3)} k_{X\theta}^{(0)} k_{X\theta}^{(1)} + 2G_{23}^{(3)} \gamma_{\theta z,0} k_{\theta Z}^{(2)} + 2Q_{12}^{(3)} k_{\theta\theta}^{(2)} \varepsilon_{XX,0} +$

$\Pi\tilde{\square}_4 = Q_{22}^{(4)} k_{\theta\theta}^{(1)2} + G_{23}^{(4)} k_{\theta Z}^{(1)2} + 2Q_{12}^{(4)} k_{\theta\theta}^{(2)} k_{XX}^{(0)} + 2G_{12}^{(4)} k_{X\theta}^{(0)} k_{X\theta}^{(2)} + 2Q_{22}^{(4)} k_{\theta\theta}^{(0)} k_{\theta\theta}^{(2)} +$
$+ G_{13}^{(4)} k_{XZ}^{(1)2} + G_{12}^{(4)} k_{X\theta}^{(1)2} + 2Q_{12}^{(4)} k_{\theta\theta}^{(0)} k_{XX}^{(2)} + 2Q_{11}^{(4)} k_{XX}^{(0)} k_{XX}^{(2)}.$

(12),   :

$$\left(Q_{11}^{(i)}, Q_{12}^{(i)}, Q_{22}^{(i)}, G_{23}^{(i)}, G_{13}^{(i)}, G_{12}^{(i)} \right) = \int_{-0,5h}^{0,5h} z^i (Q_{11}, Q_{12}, Q_{22}, G_{23}, G_{13}, G_{12}) dz. \quad (13)$$

,   .

,

,   [17]:

$$p = - \frac{\gamma p_\infty M^2}{\sqrt{M^2 - 1}} \left[\frac{\partial w}{\partial x} + \frac{M^2 - 2}{M a_\infty (M^2 - 1)} \frac{\partial w}{\partial t} - \frac{w}{2R\sqrt{M^2 - 1}} \right], \qquad (14)$$

$\gamma -$ $; p_\infty -$
$; M -$ $; a_\infty -$.

$$w(x,\theta,t) \sum_{m=1}^{N_1} [A_m \cos(n\theta) + B_m(t) \sin(n\theta)] \sin(\lambda_m x) +$$

$$+ \sum_{m=1}^{N_2} C_{}(t) \sin(\lambda_{} x);$$

$$u = \sum_{m=1}^{N_1} [A_{N_1+m} \cos(n\theta) + B_{N_1+m} \sin(n\theta)] \cos(\lambda_m x) + \sum_{m=1}^{N_2} C_{N_2+m} \cos(\lambda_{2m-1} x);$$

$$v(x,\theta,t) = \sum_{m=1}^{N_1} [A_{2N_1+m}(t) \cos(n\theta) + B_{2N_1+m}(t) \sin(n\theta)] \sin(\lambda_m x);$$

$$\phi_1 = \sum_{m=1}^{N_1} \begin{bmatrix} A_{3N_1+m}\cos(n\theta) \\ +B_{3N_1+m}\sin(n\theta) \end{bmatrix} \cos(\lambda_m x) \sum_{m=1}^{N_2} C_{2N_2+m}\cos(\lambda_{2m-1}x), \qquad (15)$$

$$\mathbf{q} = [A_1, ..., B_1, ..., C_1, ..., A_{3N_1+1}, ..., B_{3N_1+1}, ..., C_{2N_2+1}, ..., C_{3N_2}] \equiv [q_1, ..., q_{N_\bullet}]$$
$$N_\bullet = 10N_1 + 3N_2.$$

(15)

[43],   (15)

(7)

$$T = T(q_1, ..., q_{N_\bullet}).$$ (15)

(12).

$$\prod \Box = \Pi(q_1, ..., q_{N_\bullet}).$$

$$\sum_{j=1}^{N_\bullet}(m_{ij}\ddot{q}_j + K_{ij}q_j) = \sum_{\nu=1}^{N_\bullet}\sum_{j=1}^{j\le\nu}\alpha_{\nu j}^{(i)}q_\nu q_j + \sum_{\nu=1}^{N_\bullet}\sum_{j=1}^{j\le\nu}\sum_{j_1=1}^{j_1\le j}\beta_{\nu j j_1}^{(i)}q_\nu q_j q_{j_1} + Q_i; \quad (16)$$

$$\mathbf{M} = \{m_{ij}\}_{i=1,...,N_\bullet}^{j=1,...,N_\bullet}; \ \mathbf{K} = \{K_{ij}\}_{i=1,...,N_\bullet}^{j=1,...,N_\bullet}$$
$$\alpha_{\nu j}^{(i)}, \beta_{\nu j j_1}^{(i)} -$$
$$\mathbf{Q} = [Q_1, ..., Q_{N_\bullet}] -$$

$$Q_\nu = \sum_{m=1}^{N_1}(\lambda_{\nu m}q_m + \eta_{\nu m}\dot{q}_m); \ Q_{3N_1+\nu} \sum_{m=1}^{N_1}(\lambda_{\nu m}q_{3N_1+m} + \eta_{\nu m}\dot{q}_{3N_1+m}). \quad (17)$$

(16).
[14].

(16)

[14].

55

2.

η_1, η_2, η_3.

[15].

n (15).

p_∞.

$p_\infty^{(CR)}$.

$$R = 0.25 \text{ м}; h = 5 \cdot 10^{-3} \text{ м}; \frac{h}{R} = 0.02; L = 1 \text{ м},\tag{18}$$

FGV (. 2) $V_{CNT}^* = 0{,}12$.

$M = 5; M = 3$ $M = 1{,}5$.

(15) $N_1 = 2; N_2 = 1$.

(16) $N_* = 23$.

(14)

. 3.

$M = 3$ $M = 5$. $M = 3$ $M = 5$

n

$n = 6$.

$M = 3$

(18)

. 2.

2.

;

,

$n = 5$ $n = 6$.

3,

.

3.

p_∞.

(16).

UD

$V_{CNT}^* = 0{,}12$. (18),

$;\ M = 3$. n
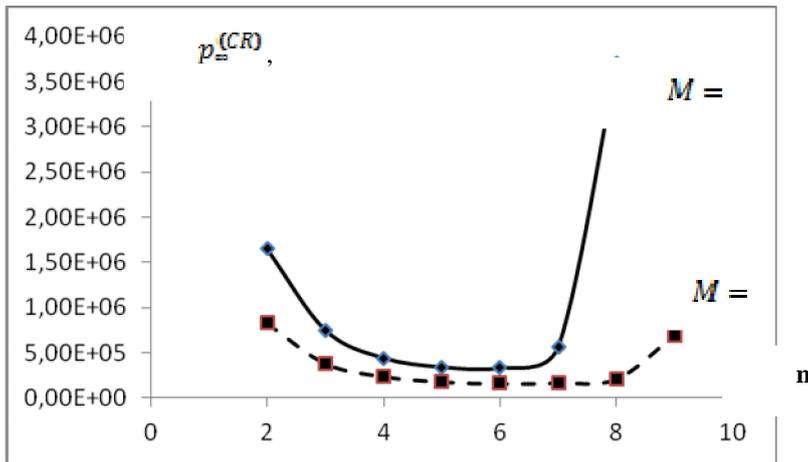
(15) $n = 6$ . . 4,

$q_1 - A_1$

p_∞. $p_\infty < 0{,}32\,\text{МПа}$

$p_\infty = 0{,}32\,\text{МПа}$

,

(. 4) ,

. 4.

,
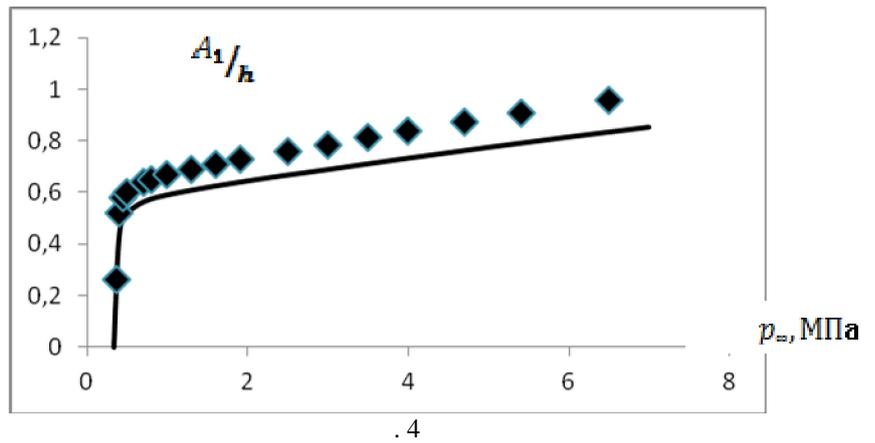
. 3

2.

$$M = 3$$

	V_{CNT}^{*}	n	$p_{\infty}^{(CR)}$, МПа
FGV- NT	0,12	6	0,33
	0,17	5	0,68
	0,28	5	0,97
FGX-CNT	0,12	5	0,38
	0,17	5	0,76
	0,28	5	1,21
FGO-CNT	0,12	6	0,27
	0,17	5	0,56
	0,28	5	0,71

. 4

.

$$n = 5; 6$$

-

$$n = 27$$

-

$\phi_2'(x, \theta, t)$,

-

.

1. *Seidel G. D., Lagoudas D. C.* Micromechanical analysis of the effective elastic properties of carbon nanotube reinforced composites. Mechanics of Materials. 2006. Vol. 38. P. 884–907.
2. *Liu Y. J., Chen X. L.* Evaluations of the effective material properties of carbon nanotube-based composites using a nanoscale representative volume element. Mechanics of Materials. 2003. Vol. 35. 69–81.
3. *Odegard G. M., Gates T. S., Wise K. E., Park C., Siochi E. J.* Constitutive modeling of nanotube–reinforced polymer composites. Composites Science and Technology. 2003. Vol. 63. . 1671–1687.
4. *Allaoui A., Bai S., Cheng H. M., Bai J. B.* Mechanical and electrical properties of a MWNT/epoxy composite/. Composites Science and Technology. 2002.Vol. 62. .1993–1998.
5. *Ci L., Bai J. B.* The reinforcement role of carbon nanotubes in epoxy composites with different matrix stiffness. Composites Science and Technology. 2006. Vol. 66. . 599–603.
6. *Mehrabadi S. J., Aragh B. S.* Stress analysis of functionally graded open cylindrical shell reinforced by agglomerated carbon nanotubes. Thin-Walled Structures. 2014. Vol. 80. .130–141.
7. *Zhang L.W., Lei Z. X., Liew K. M., Yu J. L.* Static and dynamic of carbon nanotube reinforced functionally graded cylindrical panels. Composite Structures. 2014. 111. . 205–212.
8. *Song Z. G., Zhang L. W., Liew K. M.* Vibration analysis of CNT-reinforced functionally graded composite cylindrical shells in thermal environments. International Journal of Mechanical Sciences. 2016. Vol. 115–116. . 339–347.
9. *Sobhaniaragh B., Batra R. C., Mansur W. J., Peters F. C.* Thermal response of ceramic matrix nanocomposite cylindrical shells using Eshelby-Mori-Tanaka homogenization scheme. Composites Part B: Engineering. 2017. Vol. 118. . 41–53.
10. *Yaser K., Rossana D., Francesco T.* Free vibration of FG-CNT reinforced composite skew cylindrical shells using the Chebyshev-Ritz formulation. Composites Part B: Engineering. 2018. Vol. 147. . 169–177.
11. *Lei Z. X., Liew K. M., Yu J. L.* Free vibration analysis of functionally graded carbon nanotube-reinforced composite plates using the element-free kp-Ritz method in thermal environment. Composite Structures. 2013. Vol. 106. . 128–138.
12. *Lei Z. X. Zhang L .W. , Liew K. M.* Elastodynamic analysis of carbon nanotube-reinforced functionally graded plates. International Journal of Mechanical Sciences. 2015. Vol. 99. . 208–217.
13. *García-Macías E., Rodríguez-Tembleque L., Sáez A.* Bending and free vibration analysis of functionally graded graphene vs. carbon nanotube reinforced composite plates. Composite Structures. 2018. Vol. 186. . 123–138.
14. . . . . . .1. , , . 2- . : , 2015. 716 .
15. *Mehri M., Asadi H., Wang Q.* On dynamic instability of a pressurized functionally graded carbon nanotube reinforced truncated conical shell subjected to yawed supersonic airflow. Composite Structures. 2016. Vol. 153. 938–951.

02.04.2019,
10.06.2019