Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2016, № 3 (83)
ISSN 1727-7108. Web: ***visnyk.tntu.edu.ua***

MECHANICS AND MATERIALS SCIENCE

МЕХАНІКА ТА МАТЕРІАЛОЗНАВСТВО

UDC 534.134

ANALYSIS OF NATURAL FREQUENCIES AND SHAPES OF STRINGER-STIFFENED CYLINDRICAL SHELLS

Petro Yasniy; Yuriy Pyndus; Mykhailo Hud

Ternopil Ivan Pul'uj National Technical University, Ternopil, Ukraine

Summary. *The linear analysis of free vibrations of horizontally oriented stringer-stiffened cylindrical shell was analyzed. The study was conducted using finite element method. The authors investigated the effects of: changes in gravitational acceleration, type of cylinder fastening, enhancement and cross-sectional area of stringer-stiffening elements on the frequencies and shapes of non-stiffened and stringer-stiffened cylindrical shell's free vibrations.*

Key words: *thin-walled shell, cylindrical shell ,free vibrations, stringers, natural frequencies*.

Received 07.09.2016

Problem setting. Stringer-stiffened cylindrical shells are widely used in missilery for production of launch vehicle fairings. The main aim of fairing is a protection of launch vehicles and satellites during boosting into orbit. The thin shells are stiffed with stringers and mating rings on the inside. Under working conditions the fairings are under stresses from surrounding gas streams and under dynamic stresses from (engines) jets. Additionally, a set of various stresses impacts the fairings during transportation to in-space launching point. Particularly, during air transportation the fairings can make both free and enforced vibrations that are caused by air turbulence, working aircraft engines, vertical acceleration (reloading). The analysis of free vibrations' properties is essential to solve the problems at assessment of stress-strain behavior and fatigue limit load of stringer-stiffened cylindrical shells during transportation, particularly air one.

Analysis of the known research results. There are known research projects devoted to dynamic of launch vehicles shells and the theory of stringer-stiffed shells [1-4], crude methods of projecting for stringer-stiffed shells [5]. Projecting of stringer-stiffed shells by means of finite elements is mentioned in [6, 7]. The latest researches [8-10] show that one of the most efficient technologies to assess the natural frequencies and forms of free vibrations of cylindrical shells is modal analysis with application of ANSYS finite-element system of stiffness modeling and mathematical physics. The listed above issues deal with comprehensive research of certain launch vehicle's construction elements and working conditions. However, the operation and transportation specifics of launch vehicles' construction requires the assessment of the natural frequencies and forms of free vibrations and, as result, their stiffness and fatigue limit load in every particular case.

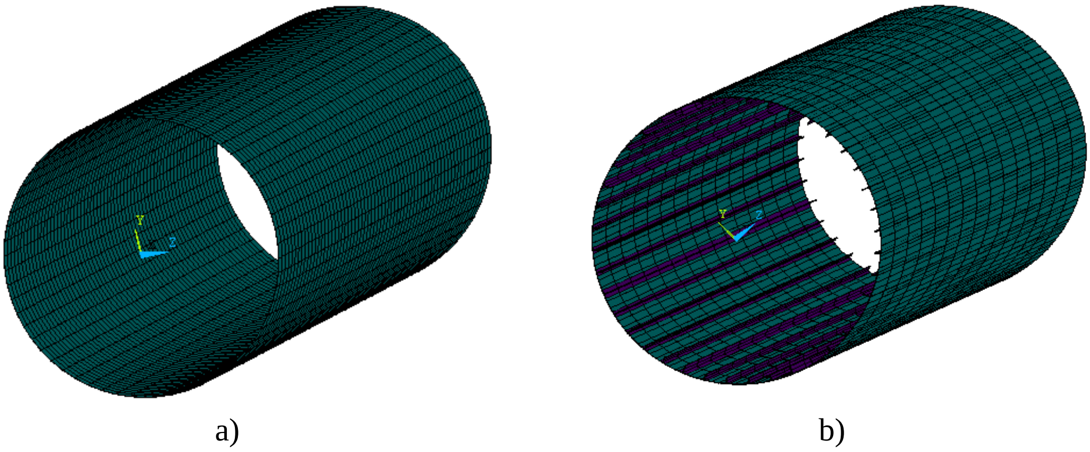
Corresponding author: Petro Yasniy; e-mail: yasniy@tu.edu.te.ua

Objectives of research project is quantitative evaluation of impact of vertical acceleration (×*g*) for shell fastening and cross-sectional area of stringers upon natural frequencies and shapes of free vibrations of stringer-stiffened cylindrical shells. The objectives are determined with necessity to assess the stress-strain behavior and fatigue limit load of stringer-stiffened cylindrical shells during air transportation.

Task setting. Using method of finite elements one has to study the impact of vertical acceleration (×*g*), type of front fastening, available enhancement and cross-sectional area of stringers and mating rings on natural frequencies and shapes of free linear vibrations of thin-walled shell.

Modeling of stringer-stiffened thin-walled shell. ANSYS APDL software complex basing on method of finite elements (MFE) was used for quantitative modeling. The authors used modal analysis for determination of frequencies and shapes of free vibrations. Modal analysis is the first step among other types of dynamic analysis like analysis of transition processes, harmonic and spectral analysis. Modal analysis assumes that the system is linear. They ignored other types of non-linearity like non-linear behavior of material, contact ultimate conditions and final translations.

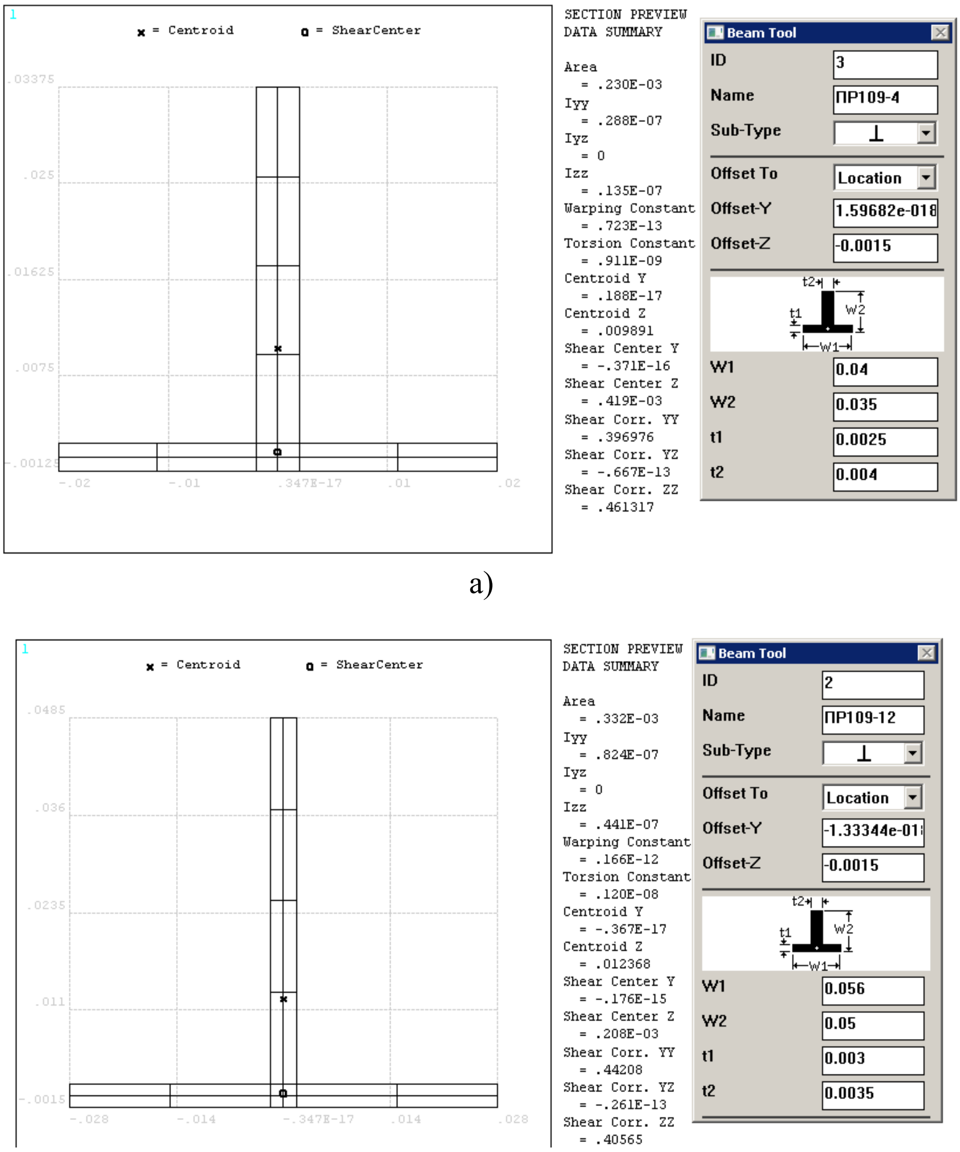
There was created the finite-element model of thin-walled cylinder without stringer stiffening in Descartes coordinates (Figure 1a) and one with enhancement (Figure 1b). The datum point is located in the center of cylinder butt end (Figure 1), in YZ plane. The axial axis of cylinder is X axis.



a) b)

Figure 1. Finite-element models of thin-walled cylinders without enhancement (a) and stringer-stiffened ones(b)

Cylinder length is 6,3 m, diameter is 1,8 m, wall thickness is 0,0015 m. We used in the stiffened model (Figure 1 b) stringers PR109-4 (32 items) (Figure 2 a) and PR109-12 (8 items) (Figure 2 b), which were located on internal surface of shell (Figure3) symmetrically and with constant step.To assess the impact of cross-sectional area of stiffening elements we used PR109-4 stringers, where we increased step-by-step the wall thickness t_1 and t_2.



```
SECTION PREVIEW
DATA SUMMARY

Area
  = .230E-03
Iyy
  = .288E-07
Iyz
  = 0
Izz
  = .135E-07
Warping Constant
  = .723E-13
Torsion Constant
  = .911E-09
Centroid Y
  = .188E-17
Centroid Z
  = .009891
Shear Center Y
  = -.371E-16
Shear Center Z
  = .419E-03
Shear Corr. YY
  = .396976
Shear Corr. YZ
  = -.667E-13
Shear Corr. ZZ
  = .461317
```

Beam Tool

ID: 3
Name: ПР109-4
Sub-Type: ⊥
Offset To: Location
Offset-Y: 1.59682e-018
Offset-Z: -0.0015
W1: 0.04
W2: 0.035
t1: 0.0025
t2: 0.004

a)

```
SECTION PREVIEW
DATA SUMMARY

Area
  = .332E-03
Iyy
  = .824E-07
Iyz
  = 0
Izz
  = .441E-07
Warping Constant
  = .166E-12
Torsion Constant
  = .120E-08
Centroid Y
  = -.367E-17
Centroid Z
  = .012368
Shear Center Y
  = -.176E-15
Shear Center Z
  = .208E-03
Shear Corr. YY
  = .44208
Shear Corr. YZ
  = -.261E-13
Shear Corr. ZZ
  = .40565
```

Beam Tool

ID: 2
Name: ПР109-12
Sub-Type: ⊥
Offset To: Location
Offset-Y: -1.33344e-01
Offset-Z: -0.0015
W1: 0.056
W2: 0.05
t1: 0.003
t2: 0.0035

b)

Figure 2. Cross section, dimensions and geometric parameters of PR109-4 (a) and PR109-12 (b) stringers

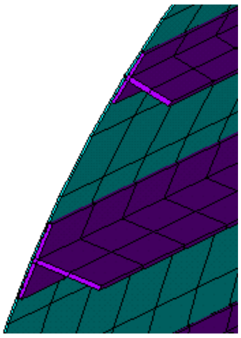


Figure 3. Shape and location of stringers inside thin-walled cylinder

During modeling of the shell and stringers we used the mechanic properties of D16AT material: Young modulus $E = 7.2 \times 10^5$ MPa; Poisson coefficient $\nu = 0{,}3$; density $\rho = 2{,}7 \cdot 10^4$ N/m^3. Gravitation acceleration was $1 \times g = 9{,}8$ м/с^2 or $0 \times g = 0$ м/с^2, according to research objectives.

To create the shell of finite-element model we used SHELL 181 element, which is applied for shells' projecting with small or moderate thickness. The element consists of four nodes and six degrees of freedom in each node: translations in the X, Y, and Z directions, and rotations about the X, Y, and Z-axes. The element can be used to solve linear and non-linear problems.

The stringers were modeled by means of linear two-node beam element BEAM 188 with six degrees of freedom in each node: translations in the X, Y, and Z directions, and rotations about them. This element can be used to solve linear and non-linear problems with large rotations and (or) large deformations.

Stringer-stiffened and unstiffened shells were fastened (i.e. restricted its translation) in space with restriction of translations for utmost front nodes from the left side in all directions (dead lock). To assess the impact of fastening type upon the shape and frequencies of free vibrations the utmost front units from the right side were restricted by two ways (if necessary): 1) with dead lock (as leftwards); 2) along axes X and Z i.e. simultaneously in vertical and diametrical translations, and axial translations along X axis were not restricted.

Research results. Lánczos block method intending to search for a large number of modes (more than 40) for big models was used for modal analysis. The mentioned method is reccomended in cases when the model contains 2d and 3d-elemennts of complicated shape. It works well if the model contains shell elements or combinations of beam elements and solids.

The number of required "expanded" modes is stipulated by problem tasks (in our case it is 100). To keep in mind the deformation under construction's own weight we predominantly made the statistic calculations and later used «Incl. prestress effects» option during modal analysis to account the effects of subsequent stressed condition.

The calculation results (sample from the first ten modes) for natural frequencies (Table 1) indicate that unstiffened and stringer-stiffened shells have multiple natural frequencies that is intrinsic for the constructions with axial symmetry. It should be mentioned that natural frequencies of stringer-stiffened shell are smaller because of increased stiffness of the construction. The enhancement effect (cross-sectional area of reinforcing elements) on natural frequencies will be described later.

Table № 1

Natural frequencies of stringer-stiffened and unstiffened shells

№	Unstiffened shell	Stringer-stiffened shell
1	18,8	14,2
2	18,8	14,2
3	19,4	14,9
4	19,4	14,9
5	23,5	16,5
6	23,5	16,5
7	24,2	19,9
8	24,2	20,2
9	29,8	20,2
10	29,8	20,7

All forms of frequencies have a number of semi-waves along a circle and cylinder generator. Figure 4 displays the form of vibrations at first mode, which has five semi-waves along the circle and one semi-wave along cylinder generator. Figures 5 a, b display the forms of natural vibrations of unstiffened cylinder at the first and second modes at frequency of 18,8 Hz. The vibration forms, being intrinsic to multiple frequencies, are shifted on quarter of wave length around the circle against each other. The same regularities are intrinsic to stringer-stiffened cylindrical shell (Figure 6, Figure 7).

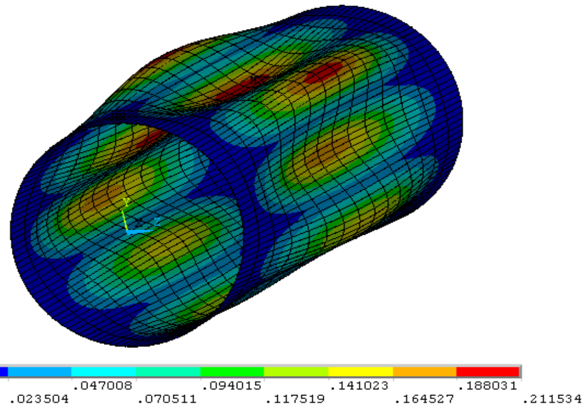
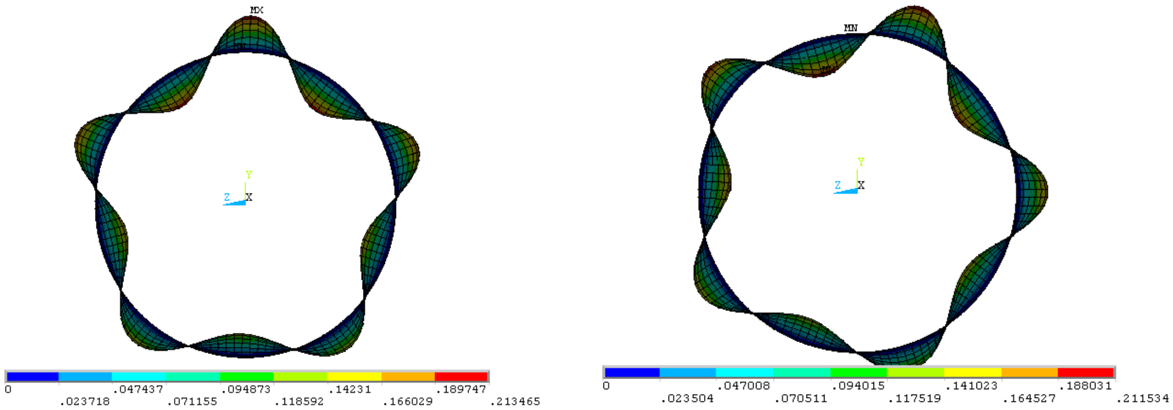


Figure 4. Form of vibrations of unstiffened cylindrical shell at 2nd mode with frequency 18,8 Hz



a) b)

Figure 5. Shifted on a quarter of wave length for vibrations of unstiffened cylindrical shell at frequency18,8 Hz

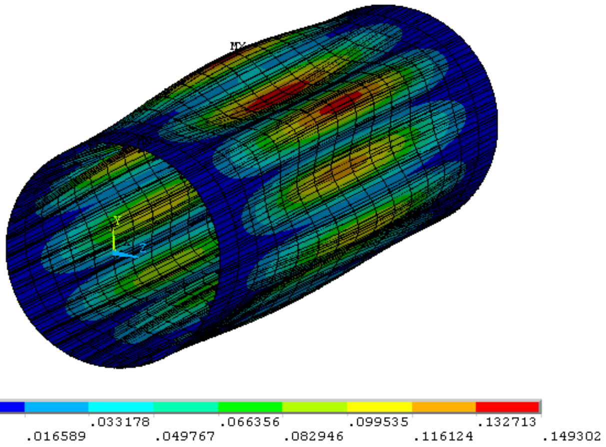
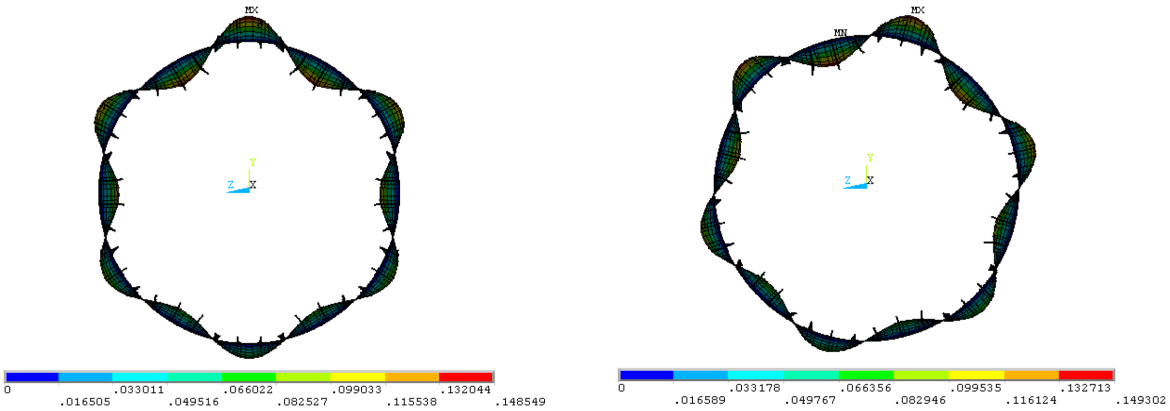


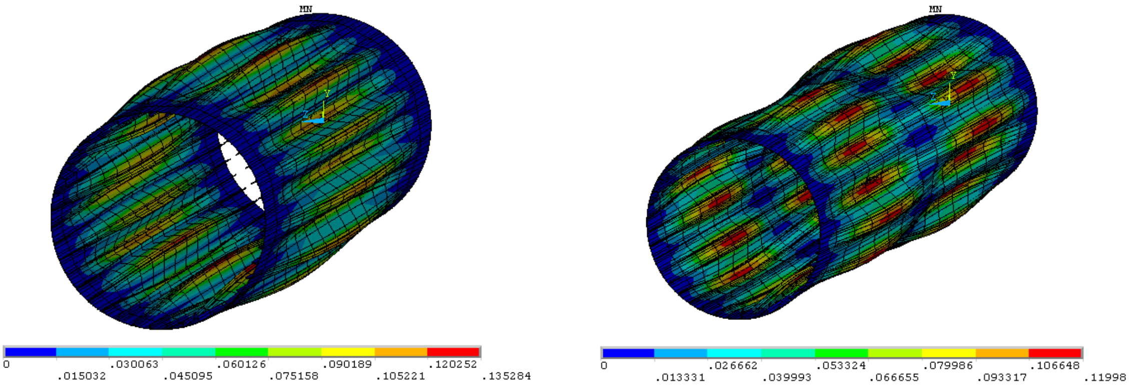
Figure 6. Form of vibrations of stringer-stiffened cylindrical shell at 2nd mode at frequency14,2 Hz



a) b)

Figure 7. Shifted on a quarter of wave length for vibrations of stringer–stiffened cylindrical shell at frequency14,2 Hz

Increasing of natural frequencies is followed with increasing of semi-waves number around cylinder circle as well as around cylinder generator (Figure 8).



a) b)

Figure 8. Form of vibrations of stringer – stiffened cylindrical shell at frequency a) 49,5 Hz and b) 59,4 Hz

Assessment of impact of vertical accelerations (×*g*) and the way of fastening on natural frequencies of unstiffened cylindrical shell is displayed on Figure 9. If the units are deadlocked from both butt ends, the natural frequencies of cylinder are a bit smaller (Figure 9, curve # 1) comparing to non-restricted in axial (along X axis) translations on cylindrical shell (Figure 9, curve # 2). Both curves here, which were produced at vertical acceleration $1\times g = 9{,}8 m/s^2$, are identical to the curves produced by analogically fastened cylinders at vertical acceleration (0×*g*). It shows that constant gravitation force does not impact on natural frequencies of cylindrical shell. The same regularity is inherent to stringer-stiffened cylindrical shell.

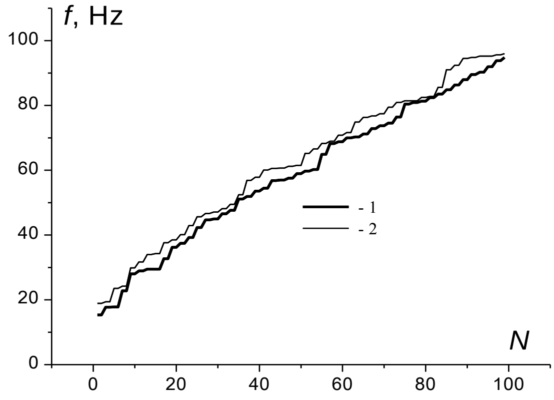


Figure 9. Natural frequencies of unstiffened cylindrical shell at vertical accelerations
1×*g* = 9,8 m/s^2 and 0×*g*:
1 – deadlocked from both butt ends;
2 –non-restricted in axial (along X axis) translations

Figure 10 displays the natural frequencies of unstiffened and stringer-stiffened thin-walled cylinders. The values of natural frequencies for stringer-stiffened cylindrical shell (Figure 10, curve # 1) are a bit smaller comparing to unstiffened one (Figure 10, curve # 2).

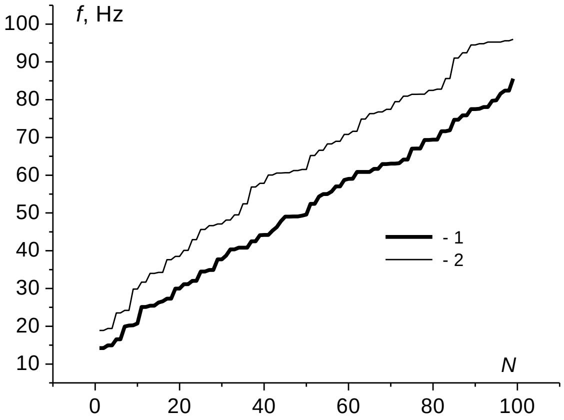


Figure 10. Natural frequencies of stringer-stiffened 1) unstiffened
2) thin-walled cylindrical shells

Figure 11 displays the impact of enhancement rate (cross-sectional area (*S*) of stringers) on natural frequencies of stringer-stiffened cylindrical shell. Obviously, the increasing of cross-sectional area of stringers is followed with decreasing of its natural frequencies in the area higher than 40 Hz. In the section, being lower than 40 Hz, the increase of cross-sectional area up to0,54×10^{-3} m^2 is followed with the decrease of natural frequencies. However, at $S >$ 0,54×10^{-3} m^2 in the area up to 40 Hz the natural frequencies start growing.

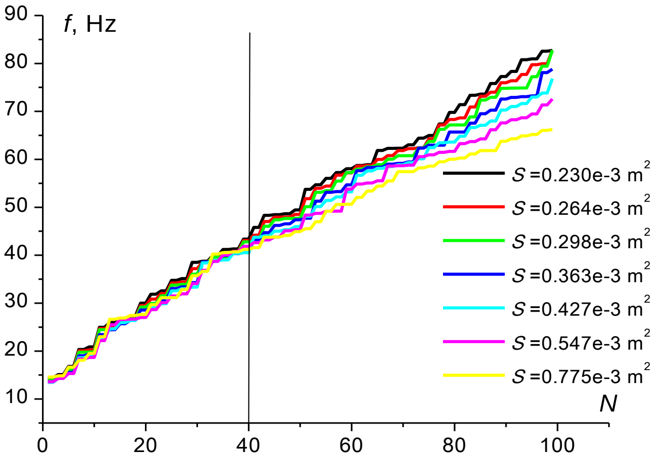


Figure 11. Impact of cross-sectional area of stringers on natural frequencies of stiffened thin-walled cylinder

Conclusions. The project deals with the comprehensive quantitative research concerning the impact of fastening, enhancement and cross-sectional area of stringer-stiffening elements on the frequencies and shapes of natural free vibrations of thin-walled cylindrical shell. It was revealed that constant gravitation acceleration (×*g*) does not impact on the values and number of natural frequencies of unstiffened and stiffened thin-walled cylinders; the values of natural frequencies of stringer-stiffened cylindrical shell are smaller comparing to the unstiffened one; the values of natural frequencies are under the influence of fastening type for cylindrical shell at its butt ends; the increase of cross-sectional area of stringers is followed with decrease of its natural frequencies in the area more than 40 Hz. In the area less than 40 Hz the increase of cross-sectional area more than $0{,}54\times10^{-3}\text{m}^2$ is followed with an increase of natural frequencies.

References

1. Mossakovskiy V.I., Makarenkov A.G., Nikitin P.I., Savin Yu. I., Spiridonov I.N. Prochnost raketnyih konstruktsiy. Moskva, Vyisshaya shkola, 1990, 358 p. [In Russian].
2. Amiro I. Ya., Zarutskiy V.A. Teoriya rebristyih obolochek. Kiev, Naukova dumka, 1980, 367 p. [In Russian].
3. Amiro I.Ya., Grachev O.A., Zarutskiy V.A., Palchevskiy A.S., Sannikov Yu.A. Ustoychivost rebristyih obolochek vrascheniya. Kiev, Naukova dumka, 1987, 180 p. [In Russian].
4. Andrianov I.V., Lesnichaya V.A., Loboda V.V., Manevich L.I. Raschet prochnosti rebristyih obolochek inzhenernyih konstruktsiy. Kiev, Vischa shkola, 1986, 167 p. [In Russian].
5. Lizin V.T., Pyatkin V.A. Proektirovanie tonkostennyih konstruktsiy. Moskva, Mashinostroenie, 1994, 247 p. [In Russian].
6. Raschetyi mashinostroitelnyih konstruktsiy metodom konechnyih elementov. Spravochnik. Pod obschey redaktsiey V.I. Myachenkova. Moskva, Mashinostroenie, 1989, 456 p. [In Russian].
7. Karmishin A.V., Lyaskovets V.A., Myachenkov V.I., Frolov A.N. Statika i dinamika tonkostennyih obolochechnyih konstruktsiy. Moskva, Mashinostroenie, 1975, 280 p. [In Russian].
8. Chernobryivko M.V., Avramov K.V., Romanenko V.N., Kochurov R.E., Batutina T.Ya. Sobstvennyie kolebaniya parabolicheskih obtekateley raket-nositeley. Mehanika ta mashinobuduvannya. Harkiv,: NTU "HPI", 2013, No 1, pp. 38 – 47. [In Russian].
9. Kazachenko A.L. i dr. Chislennyiy podhod k raschetu dinamicheskoy neustoychivosti parabolicheskih obtekateley raketonositeley. Voprosyi proektirovaniya i proizvodstva konstruktsiy letatelnyih apparatov. Harkiv, HAI, 2014, No. 4, P. 44 – 54. [In Russian].
10. Avramov K.V., Zholos O.V. Svobodnyie kolebaniya orebrennyih tonkostennyih tsilindricheskih obtekateley raketonositeley. Visnik NTU "HPI", 2015, No. 55, P. 13 – 15. [In Russian].

11. Leont'ev N.V. Primenenie sistemy ANSYS k resheniju zadach modal'nogo i garmonicheskogo analiza. Nizhnij Novgorod, 2006, 101 p. [In Russian].

Список використаної літератури

1. Моссаковский, В.И. Прочность ракетных конструкций [Текст] / В.И. Моссаковский, А.Г. Макаренков, П.И. Никитин, Ю.И. Савин, И.Н. Спиридонов. – М.: Высшая школа, 1990. – 358 с.
2. Амиро И.Я. Теория ребристых оболочек [Текст] / И.Я. Амиро, В.А. Заруцкий. – К.: Наукова думка, 1980. – 367 с. 3.
3. Амиро, И.Я. Устойчивость ребристых оболочек вращения [Текст] / И.Я. Амиро, О.А. Грачев, В.А. Заруцкий, А.С. Пальчевский, Ю.А. Санников. – К.: Наукова думка, 1987. – 180 с.
4. Андрианов, И.В. Расчет прочности ребристых оболочек инженерных конструкций [Текст] / И.В. Андрианов, В.А. Лесничая, В.В. Лобода, Л.И. Маневич. – Киев – Донецк: Вища школа, 1986. – 167 с.
5. Лизин, В.Т. Проектирование тонкостенных конструкций [Текст] / В.Т. Лизин, В.А. Пяткин. – М.: Машиностроение, 1994. – 247 с.
6. Расчеты машиностроительных конструкций методом конечных элементов: справочник; под общей редакцией В.И. Мяченкова [Текст] / М.: Машиностроение, 1989. – 456 с.
7. Кармишин, А.В. Статика и динамика тонкостенных оболочечных конструкций [Текст] / А.В. Кармишин, В.А. Лясковец, В.И. Мяченков, А.Н. Фролов. – М.: Машиностроение, 1975. – 280 с.
8. Чернобрывко, М.В. Собственные колебания параболических обтекателей ракет-носителей [Текст] / М.В. Чернобрывко, К.В. Аврамов, В.Н. Романенко, Р.Е. Кочуров, Т.Я. Батутина // Механіка та машинобудування. – Харків: НТУ «ХПІ», 2013. – № 1. – С. 38 – 47.
9. Казаченко, А.Л. Численный подход к расчету динамической неустойчивости параболических обтекателей ракетоносителей [Текст] А.Л. Казаченко / Вопросы проектирования и производства конструкций летательных аппаратов: зб. наук. пр. – Нац. аерокосм. ун-т ім. Н.Е. Жуковського «ХАІ». – Харків: В-во ХАІ. – 2014. – №. 4. – С. 44 – 54.
10. Аврамов, К.В. Свободные колебания оребренных тонкостенных цилиндрических обтекателей ракетоносителей [Текст] / К.В. Аврамов, О.В. Жолос. – Вісник НТУ «ХПІ». – 2015. – №. 55. – С. 13 – 15.
11. Леонтьев, Н.В. Применение системы ANSYS к решению задач модального и гармонического анализа [Текст] / Н.В. Леонтьев. – Нижний Новгород, 2006. – 101 с.

УДК 534.134

АНАЛІЗ ЧАСТОТ І ФОРМ ВЛАСНИХ КОЛИВАНЬ ПІДСИЛЕНИХ ЦИЛІНДРИЧНИХ ОБОЛОНОК

Петро Ясній; Юрій Пиндус; Михайло Гудь

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Виконано аналіз вільних коливань горизонтально орієнтованої циліндричної оболонки, яка підсилена з середини стрингерами. Для оцінювання коливань застосовували метод скінченних елементів. Досліджували вплив підсилення та площі поперечного перерізу підкріплюючих елементів на частоти і форми власних лінійних коливань оболонки.*

Ключові слова: *тонкостінна оболонка, циліндрична оболонка, власні коливання, стрингери.*

Отримано 07.09.2016