що процес наводнювання поверхні лопатки має місце в будь-якому випадку і для електрично заряджених крапель, і для нейтральних. Однак в разі нейтральних крапель інтенсивність процесу незначна. Проведено експериментальне дослідження поверхні робочої лопатки з ерозійним пошкодженням з останнього ступеня турбіни ВК-50 ЛМЗ, яка відпрацювала свій ресурс. Визначено кількісний вміст хрому у вирізаному з лопатки зразку сталі. Виявлено зменшення вмісту хрому в пошкодженому ерозією поверхневому шарі лопатки. Для перевірки гіпотези про схожість процесу анодного електротравлення з процесом руйнування поверхні під дією негативно заряджених крапель проведено електрохімічний експеримент на модельному зразку хромової сталі 20Х13. Показано, що рельєфи пошкоджених ділянок на модельному зразку після анодного травлення і на досліджуваній лопатці в зоні дії негативно заряджених крапель подібні. Проведені експериментальні дослідження підтвердили наявність комплексного механо-хіміко-електрохімічного процесу руйнування лопатки. На основі отриманих даних сформульовані рекомендації щодо продовження ресурсу лопаток турбомашин.

Ключові слова: *електризація пари, наводнення, ерозія лопаток.*

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OPTIMAL DESIGN OF SINGLE-LAYERED REINFORCED CYLINDRICAL SHELLS

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This paper discusses the application of the random search method for the optimal design of single-layered reinforced cylindrical shells operating in a neutral environment. When setting a mathematical programming problem, the minimum shell weight is considered as an objective function. The critical stresses are determined according to the linear theory in the elastic region of the material. As the constraints imposed on the feasible region, the constraints on the strength, general buckling and partial buckling of a shell are accepted. The aim of this paper is to study the weight efficiency of various types of shell reinforcements and the influence of an optimum-weight shell on the parameters of an axially-compressed one. A numerical experiment was carried out. Dependencies of shell weight, wall thickness, and reinforcement parameters on the magnitude of a compressive load were investigated for shells with different types of reinforcement. As a result of the numerical experiment performed, it was found that with an increase in compressive load magnitude, there is a tendency to an increase in the wall thickness of an optimal shell, with an increase in the thickness of longitudinal stiffeners (stringers) and a slight decrease in the number of ribs. In addition, it should be noted that the general case of buckling and the first special one turned out to be decisive in choosing optimal shell parameters.

Keywords: *reinforced cylindrical shell, optimal design, random search method.*

Introduction

The experience of research, design, and operation shows that thin-walled rib-reinforced shells are the most rational ones in terms of weight. The load-bearing capacity of such shells is much higher than that of smooth, non-reinforced shells with the same wall thickness. However, the calculation of rib-reinforced shells is much more complicated. The critical stresses arising in optimal compressed reinforced cylindrical shells are a function of not only sheathing and reinforcement parameters, but also the number of half-waves in the circumferential and meridional directions that are formed in the case of buckling. In this work, the problem of optimal design of a reinforced shell was solved using the approximate dependence of the critical stresses on sheathing and reinforcement parameters. The region of application of the equations for the parameters of the critical stresses was determined as a result of the comparative calculations that were carried out in [1]. In the dependence noted, the parameters of wave formation were excluded through appropriate transformations and hypotheses.

Among modern methods for solving problems of optimal structural design, in addition to analytical ones, there are numerous variational methods for seeking the extremum of a multivariable function, the decomposition method, and genetic methods based on the simulation of the evolutionary process with a special emphasis on genetic mechanisms [2]. The solution obtained on their basis is suboptimal, but this does not prevent them from being used to search for global extrema in the optimization of building structures. These methods are based on the Monte Carlo method used to generate the initial population. With this method, which uses a uniform distribution of random numbers, one can determine the extremum of the objective function only by a search through an infinite number of possible options, and one can only "reconnoiter" the region of feasible parameters. But with this method, one cannot organize a targeted search. In this regard, for the optimal design of structures, it is proposed to use random search algorithms [3] from the class of independent ones, for example, the independent global search algorithm with adapted sample distribution or from the class of wandering algorithms, such as, for example, the algorithm with a guiding sphere or with a guiding cone. In this paper, for the optimal design of a stringer-reinforced shell, is proposed a stochastic algorithm for seeking the global extremum of a function with controllable boundaries of the interval of the parameters being optimized [4].

Optimal Design of Elastic Axially-compressed Cylindrical Stringer Shells

Consider a circular cylindrical shell of radius R and length L, simply supported on the edges, reinforced with longitudinal stiffeners (stringers), and compressed by a given axial load, which is carried out in the form of compressive stresses uniformly distributed along the shell edges (Fig. 1). Distance L_0 is the distance from the shell edges to the frames, at which the character of loading practically does not affect the shell edges. As noted above, the critical stresses are determined according to the linear theory in the elastic region of work of a material whose characteristics, the elastic modulus E, the proportionality limit σ_{pl}, and the Poisson ratio μ, are known. The stringers are thin-walled open-profile rods (in the form of a rectangular strip or an equal-leg angle profile) located centrally relative to the middle surface of the shell. It is required to find such values of the thickness of sheathing h, the thickness of ribs h_r (the rib height H is a dependent value and is determined by the standard value $\lambda = H / h_r$ that ensures the local stability of stringers), as well as the number of ribs k at which, at a given load, the shell has a minimum volume and its strength and sustainability conditions are simultaneously met.

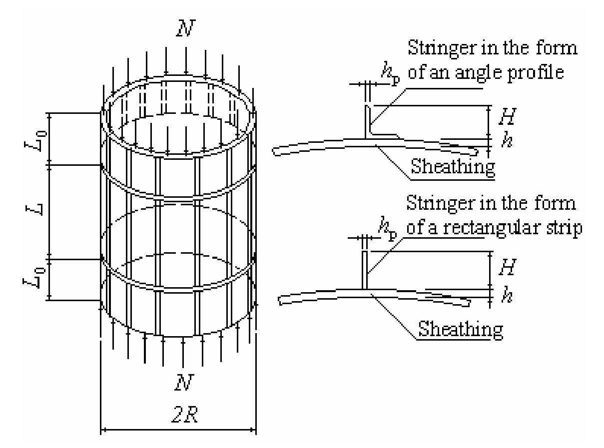

Fig. 1. Design diagram of a cylindrical shell, reinforced with longitudinal stiffeners

Thus, we need to find the minimum of the function

$$V = (2\pi Rh + Fk)L, \tag{1}$$

where F is the rib cross-sectional area under the following conditions:

$$(2\pi Rh + kF)\sigma_{pl} \geq N , \tag{2}$$

$$2\pi E\eta h\left(1+k\frac{F}{2\pi Rh}\right)\geq N\,. \tag{3}$$

Condition (2) is the strength condition, and condition (3) is the constraint on the critical load of buckling. In [5], the existence of several forms of buckling for a compressed shell with a discrete arrangement of edges is shown. Following work [1], we obtain expressions for the parameter η for such cases:

1) General case of buckling, when the stringers bend and twist

$$\eta_1=\frac{1}{1+k\dfrac{F}{2\pi Rh}}\left[\frac{1}{\sqrt{3\left(1-\mu^2\right)}}+\frac{\pi kJ}{2h^3Rz}+\frac{kGJ_{tw}}{2\pi REh^3}\left(\pi\sqrt{12\left(1-\mu^2\right)}\frac{1}{z}-\frac{\pi^2}{z}\right)\right], \tag{4}$$

where $z=\dfrac{L^2}{Rh}$; J and J_{tw} are the moments of inertia of stringers for bending and twisting, respectively;

2) Stringers only bend

$$\eta_2=\frac{2\sqrt{\dfrac{k^5J}{\pi hR^3}}}{\left(1+k\dfrac{F}{2\pi Rh}\right)\sqrt{12\left(1-\mu^2\right)}}\,. \tag{5}$$

3) Stringers only twist

$$\left.\begin{aligned}\eta_3&=\frac{1}{\sqrt{12\left(1-\mu^2\right)}}\left[2+\frac{3C^2kJ_{tw}G\left(1-\mu^2\right)}{\pi REh^3}\right], &&\text{if}\quad C\leq 1\\ \eta_3&=\frac{1}{\sqrt{12\left(1-\mu^2\right)}}\left[C^2+\frac{1}{C^2}+\frac{3C^2kJ_{tw}G\left(1-\mu^2\right)}{\pi REh^3}\right], &&\text{if}\quad C>1\end{aligned}\right\}, \tag{6}$$

where $C=\dfrac{2k}{\sqrt{\dfrac{R}{h}}\sqrt[4]{12\left(1-\mu^2\right)}}$.

Using the notations: $x_1=h$; $x_2=h_{\mathrm{p}}$; $x_3=k$; $A_1=2\pi RL$; $A_2=L(2\lambda-1)$; $A_3=L\lambda$; $B_1=\dfrac{2\pi R\sigma_{pl}}{N}$; $B_2=\dfrac{\sigma_{pl}}{N}(2\lambda-1)$; $B_3=\dfrac{\sigma_{pl}}{N}\lambda$; $D_1=\dfrac{2\pi E}{N}$; $D_2=\dfrac{2\lambda-1}{2\pi R}$; $D_3=\dfrac{\lambda}{2\pi R}$; $D_4=\dfrac{1}{\sqrt{3\left(1-\mu^2\right)}}$; $D_5=\dfrac{1.1\pi D_2}{3L\varphi(1+\mu)}$; $D_6=\dfrac{\pi}{L^2D_5}\left[\dfrac{\lambda^2(1-\lambda)}{10}-\dfrac{2\lambda-1}{12(1+\mu)}\right]$; $D_7=\dfrac{1\pi D_3}{3L\varphi(1+\mu)}$; $D_8=\dfrac{\pi\lambda^3E}{24L^2D_7}$; $D_9=\dfrac{2}{\sqrt{12\left(1-\mu^2\right)}}$; $D_{10}=\dfrac{\lambda^2(\lambda-1)}{5\pi R^3}$; $D_{11}=2D_2$; $D_{12}=\dfrac{1.1D_2\sqrt{12\left(1-\mu^2\right)}}{6R(1+\mu)}$; $D_{13}=\dfrac{R}{8}$; $D_{14}=2\varphi^4$; $D_{15}=\dfrac{3D_2}{R^2(1+\mu)}$; $D_{16}=\dfrac{\lambda^2D_3}{6R^2}$; $D_{17}=2D_3$; $D_{18}=\dfrac{D_3\sqrt{12\left(1-\mu^2\right)}}{6R(1+\mu)}$; $D_{19}=\dfrac{3D_3}{R^2(1+\mu)}$; $\varphi=\dfrac{2}{\sqrt{R}\sqrt[4]{12\left(1-\mu^2\right)}}$ and substituting them into expressions (1)–(6), we obtain two problems (respectively, for the reinforcement in the form of an angle profile and in the from of a strip) of partially integer nonlinear programming (x_3 can only take integer values).

A. Stringers in the form of equal-leg angle profiles. It is required to find the non-negative values x_1, x_2 and x_3, that minimize the function

$$V=A_1x_1+A_2x_2^2x_3 \tag{7}$$

and satisfy the constraints

$$B_1x_1+B_2x_2^2x_3\geq 1\,, \tag{8}$$

$$\eta D_1 x_1^2 \left(1 + D_2 \frac{x_2^2 x_3}{x_1}\right) \geq 1. \quad (9)$$

The value η is the smallest of the following ones:

1) $\eta_1 = \dfrac{1}{1 + D_2 \dfrac{x_2^2 x_3}{x_1}} \left[D_4 + D_5 \dfrac{x_2^4 x_3}{x_1^2} \left(D_6 + \dfrac{1}{\sqrt{x_1}} \right) \right];$

2) $\eta_2 = D_9 \dfrac{\sqrt{D_{10} \dfrac{x_2^4 x_3^5}{x_1} + 1}}{1 + D_{11} \dfrac{x_2^2 x_3}{x_1}};$

3) $\eta_3 = \begin{cases} D_9 \left(1 + D_{12} \dfrac{x_2^4 x_3^3}{x_1^2} \right), & \text{if} \quad C \leq 1 \\ \dfrac{D_{12}}{x_1 x_3^2} \left(2 + D_{14} x_1^2 x_3^4 + D_{15} \dfrac{x_2^4 x_3^5}{x_1} \right), & \text{if} \quad C > 1, \end{cases}$

where $C = \varphi x_3 \sqrt{x_1}$.

B. Stringers in the form of a rectangular strip. Find the non-negative values x_1, x_2 and x_3, that minimize the function

$$V = A_1 x_1 + A_3 x_2^2 x_3 \quad (10)$$

and satisfy the constraints

$$B_1 x_1 + B_3 x_2^2 x_3 \geq 1, \quad (11)$$

$$\eta D_1 x_1^2 \left(1 + D_3 \frac{x_2^2 x_3}{x_1}\right) \geq 1, \quad (12)$$

where η is also the smallest value of the following ones:

1) $\eta_1 = \dfrac{1}{1 + D_3 \dfrac{x_2^2 x_3}{x_1}} \left[D_4 + D_7 \dfrac{x_2^4 x_3}{x_1^2} \left(D_8 + \dfrac{1}{\sqrt{x_1}} \right) \right];$

2) $\eta_2 = D_9 \dfrac{\sqrt{D_{16} \dfrac{x_2^4 x_3^5}{x_1} + 1}}{1 + D_{17} \dfrac{x_2^2 x_3}{x_1}};$

3) $\eta_3 = \begin{cases} D_9 \left(1 + D_{18} \dfrac{x_2^4 x_3^3}{x_1^2} \right), & \text{if} \quad C \leq 1 \\ \dfrac{D_{13}}{x_1 x_3^2} \left(2 + D_{14} x_1^2 x_3^4 + D_{19} \dfrac{x_2^4 x_3^5}{x_1} \right), & \text{if} \quad C > 1. \end{cases}$

Problem (7)–(12) was solved using the stochastic method for finding the global extremum for a function with controlled boundaries of the interval of parameters being optimized [4].

For illustration, considered was the problem of finding the optimal parameters of a cylindrical stringer shell with the following data: R=0.5 m; L=0.387 m; E=6.87·10^4 MPa; σ_{pl}=148 MPa; N=264 kN; λ=16.4. The stringers were made: a) from an equal-leg angle profile, b) from a rectangular strip. The constraints on the variable parameters were chosen as follows: 0.0001 m≤h≤0.001 m; 0.001 m≤h_r≤0.005 m, 4≤k≤50 pcs. The integer character of the variable k (the number of edges) was taken into account.

The solution results are shown in table 1.

Table 1. Optimal design results for a stringer-reinforced shell

Method of solution	Type of reinforcement	Shell volume V, cm^3	Optimal parameters			Critical stress parameters		
			h, mm	h_r, mm	k, pc.	η_1	η_2	η_3
Random search	Strip stringer	691.0	0.28	1.26	34	4.99	3.805	3.860
Random search	Angle-profile stringer	917.0	0.35	1.24	26	2.35	2.360	2.518
According to work [1]	Angle-profile stringer	1006.0	0.39	1.27	27	2.97	3.820	2.774

In table 1 are compared the results obtained in this paper with those from [1], where an equal leg angle profile was used for reinforcement, and the greatest ratio N_r / N was chosen as an optimality criterion, where N_r, N are the critical forces, respectively, for a ribbed shell and a smooth one of the same cross-sectional area.

Comparison of the results obtained by the random search method and the results given in [1] makes it possible to conclude that the random search method allows one to more efficiently design reinforced cylindrical shells, with material savings reaching 10%. It is of interest to compare the parameters of critical stresses obtained in [1] and those obtained by the random search method. According to [1], the most dangerous is the special case of buckling, when the stringers are only twisted. The random search method gives a somewhat different picture, where the most dangerous is the general case of buckling. In this case, the critical stress parameters for all three cases of buckling, obtained by the random search method, have the lowest values in comparison with the lowest parameter value η in [1]. The latter circumstance is quite significant from the point of view of a more complete use of the material in a reinforced shell.

Of particular interest is the comparison of the effectiveness of the optimal reinforcement in the form of an angle profile and of a strip. For the reinforcement in the form of a strip, special cases of buckling are decisive. In this case, the shell wall thickness decreases, and the number of stringers increases in comparison with the cases of reinforcements in the form of an angle profile. The weight of a shell with the reinforcement in the form of an angle-profile is significantly higher than that of the shell reinforced with longitudinal ribs in the form of a strip.

In this regard, studies were carried out on the behavior of shell parameters with a change in the value of the axial compressive force N. So, taking the value N=264 kN for N_0=1, we will load the shell successively by forces having a dimensionless value N_0=0.5…4.0, for the two cases of reinforcement: a) in the form of an angle profile and b) in the form of a strip.

Tables 2 and 3 show values of optimal shell parameters, volumes, critical stress parameters, critical and normal stress values obtained for the above compressive force values.

Table 2. Optimization results for the parameters of a shell with the reinforcement in the form of an angle-profile for different compressive force values

N_0	V, cm^3	h, mm	h_r, mm	k, pcs.	η_1	η_2	η_3	σ_{tw}, MPa	σ_N, MPa
0.5	674.7	0.160	1.00	39	4.203	3.496	13.40	76.7	73.0
0.6	698.3	0.180	1.00	39	3.640	3.620	10.80	90.5	87.5
0.8	793.7	0.196	1.06	40	3.870	3.970	12.71	102.3	98.0
1.0	917.6	0.351	1.24	26	2.350	2.360	2.51	120.6	123.0
1.2	969.0	0.297	1.24	32	3.130	3.270	5.65	124.0	127.0
1.4	1043.0	0.312	1.30	32	3.700	3.640	8.27	157.0	137.0
2.0	1380.0	0.411	1.55	34	5.130	4.000	13.83	170.0	145.0
3.0	2071.0	0.401	2.22	26	8.330	3.140	15.48	173.0	147.0
4.0	2758.0	0.482	2.83	22	11.470	2.720	17.29	180.0	148.0

Table 3. Optimization results for the parameters of a shell with the reinforcement in the form of a strip for different compressive force values

N_0	V, cm^3	h, mm	h_r, mm	k, pcs.	η_1	η_2	η_3	σ_{tw}, MPa	σ_N, MPa
0.5	479.0	0.171	1.00	43	5.970	4.550	7.740	107.0	107.0
0.6	502.0	0.174	1.00	46	5.870	5.152	9.038	123.0	122.0
0.8	573.0	0.226	1.07	41	4.761	4.613	5.264	143.0	143.0
1.0	691.0	0.286	1.26	34	4.990	3.805	3.860	147.0	147.5
1.2	830.0	0.325	1.24	45	4.390	6.388	5.303	196.0	147.5
1.4	966.0	0.198	1.63	43	17.440	5.807	38.570	158.0	148.0
2.0	1382.0	0.509	2.46	20	10.930	2.456	3.550	172.0	147.5
3.0	2068.0	0.359	3.28	24	39.310	3.354	33.200	165.0	148.0
4.0	2763.0	0.416	4.34	19	60.810	2.594	37.320	143.0	148.0

Fig. 2, a shows graphs of shell volume dependence on the magnitude of the compressive load for the reinforcement in the form of an angle-profile and in the form of a strip. It is clearly seen that under a low load, the shell, reinforced with stringers in the form of a strip, is lighter than the one reinforced with stringers in the form of an angle-profile. Further, with increasing load, this difference in weight disappears.

Fig. 2, b shows graphs of changes in the thickness of stringers in the form of a strip and in the form of an angle profile, depending on the load N_0.

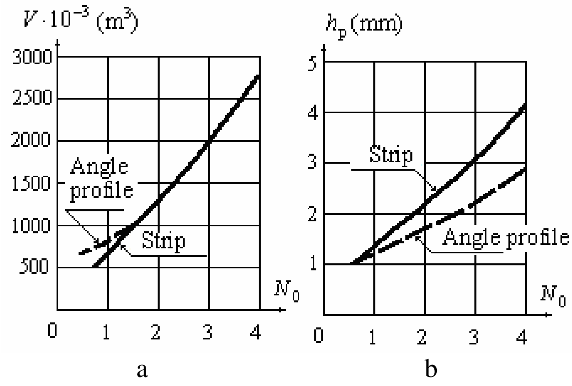

Fig. 2. Graphs of shell volume dependence on the magnitude of the compressive force (a) graphs of changes in the thickness of stringers in the form of a strip and in the form of an angle profile (b)

Conclusions

1. Application of the random search method to the optimal design of a ribbed shell made it possible to reduce its mass by 10%.

2. It was found that the critical stress parameters for all three cases of buckling, which were obtained by the random search method, have lower values in comparison with the smallest values of the parameter η in [1].

3. Comparison of the effectiveness of the optimal reinforcement in the form of an angle profile and in the form of a strip allows us to conclude that the reinforcement in the form of an angle profile is less effective than the reinforcement in the form of a strip, the weight of the shell with the reinforcement in the form of an angle profile is much higher than the weight of the shell reinforced with longitudinal ribs in the form of a strip.

4. Studies of the influence of the axial compressive force on the behavior of shell parameters makes it possible to conclude that with an increase in compressive force: the wall thickness of the optimal shell grows, the thickness of stringers increases with a slight decrease in their number, the shell volume grows, but with a small load (N_0=0.5…0.8) the volume of a shell reinforced by stringers in the form of an angle profile is greater than the volume obtained under the same load for a shell reinforced by stringers in the form of a strip. With increasing load, the volumes of shells for both cases of reinforcement become equal. It should be noted that the general case of buckling and the first partial case of buckling turned out to be decisive in choosing the optimal parameters of shells.

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Оптимальне проектування одношарових оребрених циліндричних оболонок

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У статті розглядається застосування методу випадкового пошуку для оптимального проектування одношарових підкріплених циліндричних оболонок, що працюють в нейтральному середовищі. Під час постановки задачі математичного програмування як цільова функція розглядається мінімальна вага оболонки. Критичні напруження визначаються за лінійною теорією у пружній зоні роботи матеріалу. Як обмеження, що накладаються на зону допустимих розв'язків, приймаються обмеження: з міцності, загальної і окремої втрати стійкості оболонки. Метою цієї роботи є дослідження вагової ефективності різних типів підкріплення оболонки і їхнього впливу на параметри стиснутої в осьовому напрямку оптимальної у ваговому відношенні оболонки. Проведено числовий експеримент. Досліджувалися залежності ваги оболонки, товщини її стінки, параметрів підкріплення від величини стискаючого навантаження для оболонки з різними типами підкріплення. Внаслідок проведеного числового експерименту встановлено, що зі збільшенням величини стискаючого навантаження намічається тенденція до збільшення товщини стінки оптимальної оболонки, зростає товщина поздовжніх ребер жорсткості (стрингерів), кількість ребер незначно зменшується. Крім того, слід зазначити, що визначальними під час вибору оптимальних параметрів оболонки виявилися загальний випадок втрати стійкості і перший окремий.

Ключові слова: *підкріплена циліндрична оболонка, оптимальне проектування, випадковий пошук.*

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