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NATURAL FREQUENCIES AND MODES OF PARAMETRIC VIBRATIONS OF RESERVOIR SHELL WITH SHAPE IMPERFECTIONS

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Abstract. Influence of real and modelled imperfections on natural frequencies and modes of reservoir shell parametric vibrations excited by axial load and on the shell stability loss was investigated. The finite element models of the shell was formed by software NASTRAN. The modelled shape imperfections as a lower buckling form of perfect shell under static pressure were presented. The real imperfections as the deviations of the shell wall from the vertical were obtained by theodolite surveying. The natural frequencies and modes of the imperfect shell taking into account the its previous stress state from action of the constant component of the parametric load were received by the Lanczos method.

Keywords: shell, shape imperfections, parametric load, finite-element method, modal analysis.

Introduction. Development of software led to intensive creation of the numeral methods for the decision of static and dynamic problems of the thin shells [1-7]. Software on the basis of the finite element method MSC.NASTRAN [8] is known in the world engineering design. The methods of building mechanics and mathematical physics, which are realized in this software, wide possibilities of computer simulation of different dynamic processes are opened. The finite element model of the shell has an infinite number of freedom degrees and natural frequencies, so solving the dynamics problem is difficult. If behavior of natural vibrations of the shell was researched, it is possible to talk about shell internal properties which take a great place at the forced vibrations including parametric one [9-14]. It is important to take into account influence of the constant component of parametric load on natural frequencies and modes of shell. Numeral approach to forming of reduced model of parametric vibrations of elastic shells with shape imperfections was presented in the articles [10-11]. This approach on the basis of finite element method with using of computational procedures of NASTRAN software and special program was applied to modeling of the imperfections of different forms and amplitudes. Nowadays forming of an effective model of parametric vibrations of the shell with shape imperfections and choice of the most dangerous imperfections model of the thin shell remain relevant [15]. The influence of real and modelled imperfections on natural frequencies and modes of reservoir shell parametric vibrations excited by axial load in this article was investigated.

1. Finite element models of reservoir shell. The reservoir was presented as thin-walled cylindrical shell with a height 5,96 m and a diameter 6,63 m. Reservoir wall was welded from rolled sheets with a thick $h = 0,005$ m. Steel had mechanical characteristics: $E = 2,06 \cdot 10^{11}$ Pa, $G = 0,792 \cdot 10^{11}$ Pa, $\rho = 7850$ kg/m³, $\mu = 0,3$. The finite element models of reservoir shell without and with imperfections using the software NASTRAN [8] were formed (Fig. 1).

The perfect shell (Fig. 1 (a)) and unperfected shells were modelled by the sets of flat rectangular shell finite elements with six degrees of freedom at the node in the cylindrical coordinate system. Every shell model contained 1400 elements and 1470 nodes. The reservoir shell with shape imperfections in the form the first bifurcation buckling mode of perfect shell under uniform pressure

(Fig. 1, b) was modelled. This model of the shape imperfections was adopted due to the fact that the reservoir was loaded with fuel for a long time. Real imperfections (Fig. 1 (c)) as the deviations from the vertical were obtained by theodolite surveying [16]. The restrictions of the radial and tangential displacements of the nodes of the shell upper edge were subjected, the nodes of the shell lower edge were fixed. Axial load in the form of concentrated forces on the shell upper edge nodes was applied.

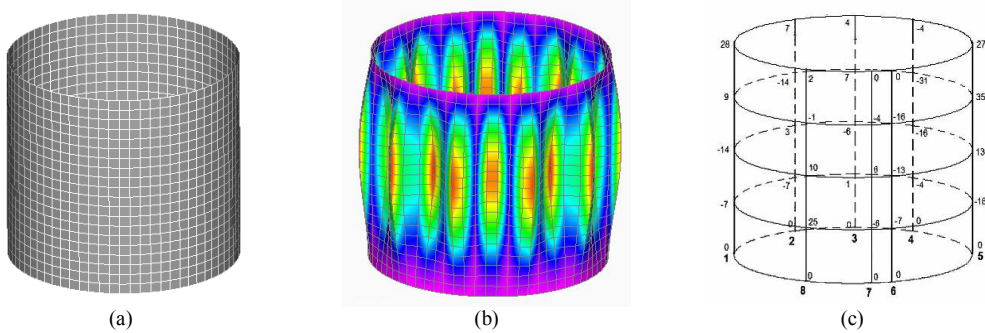


Fig. 1. The reservoir shell models without shape imperfections (a), with modelled (b) and real (c) ones

2. Modal analysis of reservoir shell. Modal analysis of the shell models were solved by the Lanczos method (*Normal Modes*) [8]. The first ten natural modes of all models were the same and were presented in Fig. 2.

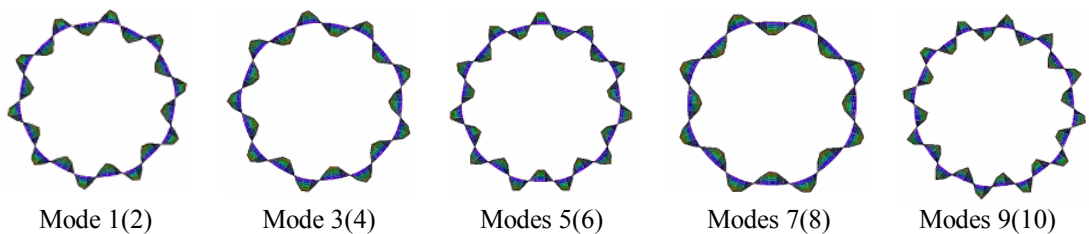


Fig. 2. The first ten natural modes of reservoir shell

The first ten natural frequencies and the number of half-waves in the circular and longitudinal directions of reservoir shell models were showed in Tab. 1.

Table 1

Reservoir shell models	Natural frequencies $\tilde{\nu}_i$, Hz / the number of half-waves in the circular and longitudinal directions				
	$\tilde{\nu}_{1(2)}$	$\tilde{\nu}_{3(4)}$	$\tilde{\nu}_{5(6)}$	$\tilde{\nu}_{7(8)}$	$\tilde{\nu}_{9(10)}$
without imperfections	<u>15,8295</u> (9,1)	<u>16,1276</u> (9,1)	<u>16,6184</u> (11,1)	<u>17,7830</u> (8,1)	<u>18,2285</u> (12,1)
with modelled imperfections $\delta = 0,2h$	<u>15,8267</u> (10,1)	<u>16,1245</u> (9,1)	<u>16,6130</u> (11,1)	<u>17,7793</u> (8,1)	<u>18,2255</u> (12,1)
with modelled imperfections $\delta = h$	<u>15,7593</u> (10,1)	<u>16,0481</u> (9,1)	<u>16,6190</u> (11,1)	<u>17,6788</u> (8,1)	<u>18,1576</u> (12,1)
with real imperfections	<u>15,8295</u> (10,1)	<u>16,1275</u> (9,1)	<u>16,6188</u> (11,1)	<u>17,7831</u> (8,1)	<u>18,2288</u> (12,1)

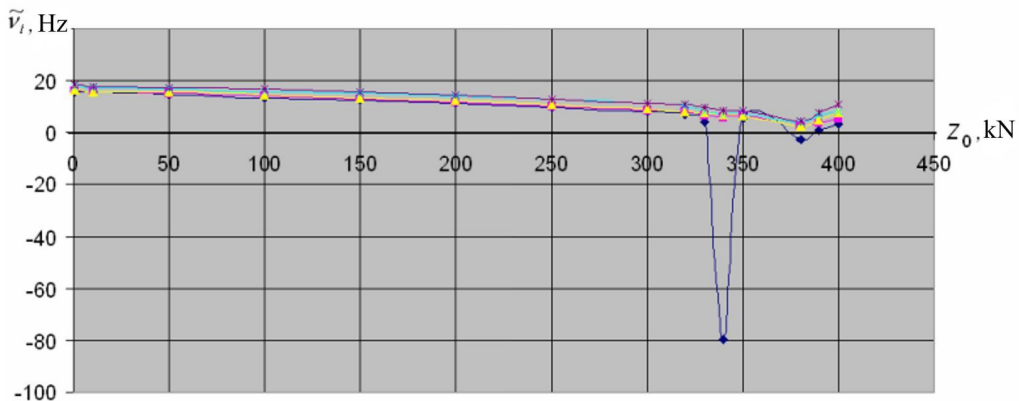
Values of the first ten natural frequencies of all shell models (Tab. 1) differed so slightly with exception of the natural frequencies of the shell with amplitude imperfections $\delta = h$. Natural modes of all shell models with exception of the first natural modes of the perfect shell model had the same number of half-waves in the circular direction and one half-wave in the longitudinal one.

3. Natural frequencies and modes of parametric vibrations of reservoir shell. On the fifth step of this investigation the static stress analysis of reservoir shell without and with shape imperfections under constant component of parametric load $z_0 = [1 - 400]$ kN was executed by the Newton-Raphson method (*Nonlinear Static*). Then the first ten natural frequencies and modes of shell taking into account the previous stress state were received by the Lanczos method (*Param Normal Modes*) [8]. The first ten natural frequencies $\tilde{\nu}_i$ of the perfect shell were showed in Tab. 2. The natural frequencies dependence of reservoir shell without imperfections on the constant component of the parametric load z_0 was showed in Fig. 3.

Table 2

z_0 , kN	Natural frequencies of parametric vibrations of reservoir shell without imperfections $\tilde{\nu}_i$, Hz				
	$\tilde{\nu}_{1(2)}$	$\tilde{\nu}_{3(4)}$	$\tilde{\nu}_{5(6)}$	$\tilde{\nu}_{7(8)}$	$\tilde{\nu}_{9(10)}$
1	15,8341	16,1342	16,6211	17,7910	18,2300
10	15,6677	15,9682	15,7660	17,6389	18,0924
50	14,9000	15,2049	15,7582	16,9441	17,4602
100	13,8680	14,1835	14,7931	16,0279	16,6153
150	12,7306	13,0691	13,7375	15,0487	15,6867
200	11,4501	11,8322	12,5463	13,9821	14,6269
250	9,9593	10,4249	11,1460	12,8376	13,3252
300	8,1205	8,7584	9,3726	11,4385	11,5540
320	7,2161	7,9772	8,4693	10,3085	10,9808
330	4,4476	6,7170	7,5000	7,9810	9,6188
342	-79,6614	6,1632	7,1101	7,3834	8,7955
350	5,5449	6,6273	6,7270	7,8147	8,6663
380	-2,4753	2,6547	2,876804	3,7684	4,2391
390	1,4987	3,9367	5,1827	6,8621	7,6355
400	3,1741	5,5087	7,5731	8,3449	10,9008

The natural frequencies dependence of reservoir shell without imperfections on the constant component of the parametric load z_0 was showed in Fig. 3.

Fig. 3. Natural frequencies dependence of the perfect shell on the constant component of the parametric load z_0

The deformation forms of the perfect shell when the constant component of the parametric load $z_0 = 300$ kN was applied and when the fifth natural frequency was zero $\tilde{\nu}_5 = 0$ were presented in Fig. 4.

The first ten natural frequencies $\tilde{\nu}_i$ of reservoir shell with modelled imperfections ($\delta = 0,2h$) were showed in Tab. 3.

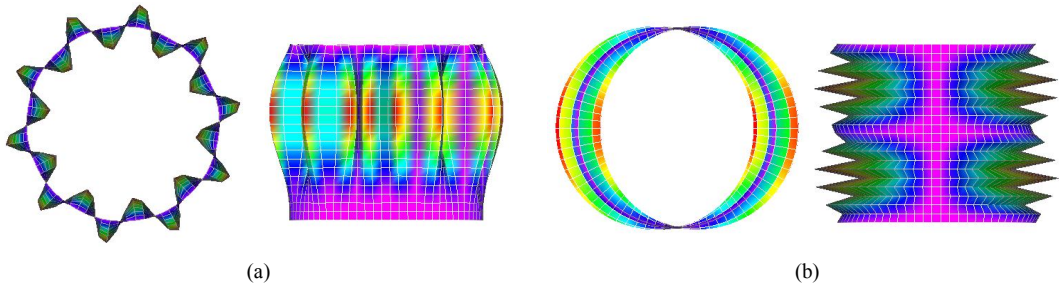


Fig. 4. Deformation forms of reservoir shell without imperfections when $z_0 = 300\text{kN}$ (a) and $\tilde{v}_1 = 0$ (b)

Table 3

z_0 , kN	Natural frequencies of parametric vibrations of reservoir shell with modelled imperfections ($\delta = 0,2h$) \tilde{v}_i , Hz				
	$\tilde{v}_{1(2)}$	$\tilde{v}_{3(4)}$	$\tilde{v}_{5(6)}$	$\tilde{v}_{7(8)}$	$\tilde{v}_{9(10)}$
1	15,8312	16,1310	16,6152	17,7874	18,2271
10	15,6647	15,9648	16,4605	17,6352	18,0894
50	14,8970	15,2010	15,7458	16,9400	17,4573
100	13,8636	14,1789	14,7853	16,0232	16,6116
200	11,4431	11,8254	12,5343	13,9856	14,6202
300	8,1077	8,7470	9,3506	11,4262	11,5447
320	7,2060	7,9684	8,4480	10,3002	10,9837
330	6,6882	7,5458	7,9298	9,5997	10,6911
340	6,1442	7,0945	7,3500	8,0237	8,7759
350	5,5232	6,6105	6,6885	7,6847	7,7926
360	4,8105	5,9120	6,08434	6,5804	7,3384
370	3,9551	4,9588	4,993	5,4468	6,5052
380	2,3759	2,5359	2,8328	3,6842	4,8500
384	-167,948	2,0367	2,7911	4,4852	5,5060
390	0,4561	1,3457	3,9327	4,0865	8,3145
396	-148,428	0,4896	3,6427	6,1804	9,1804
400	3,1344	5,4171	8,3293	8,6429	10,8808

The natural frequencies dependence of reservoir shell with modelled imperfections ($\delta = 0,2h$) on the constant component of the parametric load z_0 was showed in Fig. 5.

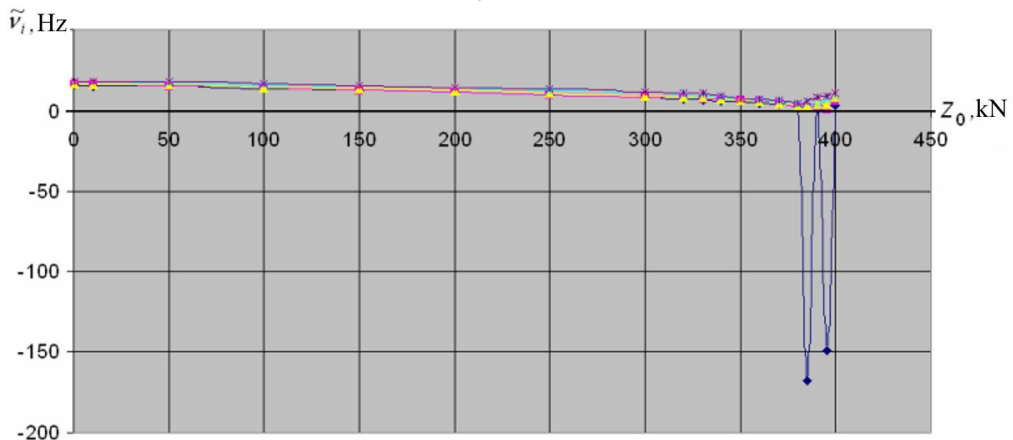


Fig. 5. Natural frequencies dependence of reservoir shell with modelled imperfections ($\delta = 0,2h$) on the constant component of the parametric load z_0

The first ten natural frequencies $\tilde{\nu}_i$ of reservoir shell with modelled imperfections ($\delta = h$) were showed in Tab. 4.

Table 4

z_0 , kN	Natural frequencies of parametric vibrations of reservoir shell with modelled imperfections ($\delta = h$) $\tilde{\nu}_i$, Hz				
	$\tilde{\nu}_{1(2)}$	$\tilde{\nu}_{3(4)}$	$\tilde{\nu}_{5(6)}$	$\tilde{\nu}_{7(8)}$	$\tilde{\nu}_{9(10)}$
1	15,7633	16,0541	16,4857	17,6865	18,1587
10	15,5939	15,8854	16,3257	17,5318	18,0184
50	14,8126	15,1090	15,5880	16,8250	17,3735
100	13,7583	14,0678	14,5824	15,8913	16,5088
200	11,2739	11,6582	12,2364	13,8080	14,4633
300	7,78211	8,4605	8,7889	11,1347	11,2900
320	6,8081	7,6361	7,7636	9,9421	10,7069
330	5,7554	6,2506	7,1597	7,1840	9,1941
340	5,6229	6,4648	6,6741	6,7028	8,3129
350	4,8934	5,6409	6,1628	7,2493	7,9355
360	3,9795	4,6123	5,5461	5,9386	6,3693
370	2,5235	3,1669	4,0134	4,2608	5,0201
380	1,7703	3,2746	6,4469	8,2635	10,8765
386	-112,306	2,6760	4,6174	8,0853	10,3936
390	0,4714	1,8976	7,8673	9,1900	10,3438
395	0,1368	7,6396	7,7875	9,5285	10,0643
400	-141,010	6,0198	7,3633	8,6408	9,7726

The natural frequencies dependence of reservoir shell with modelled imperfections ($\delta = h$) on the constant component of the parametric load z_0 was showed in Fig. 6.

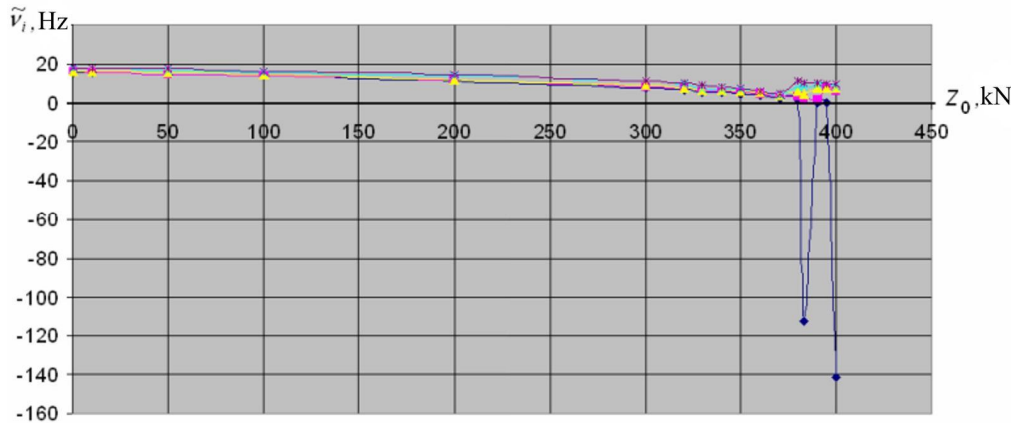


Fig. 6. Natural frequencies dependence of reservoir shell with modelled imperfections ($\delta = h$) on the constant component of the parametric load z_0

The deformation forms of the shell with modelled imperfections when the constant component of the parametric load $z_0 = 300$ kN was applied and when the first natural frequency was zero $\tilde{\nu}_1 = 0$ were presented in Fig. 7.

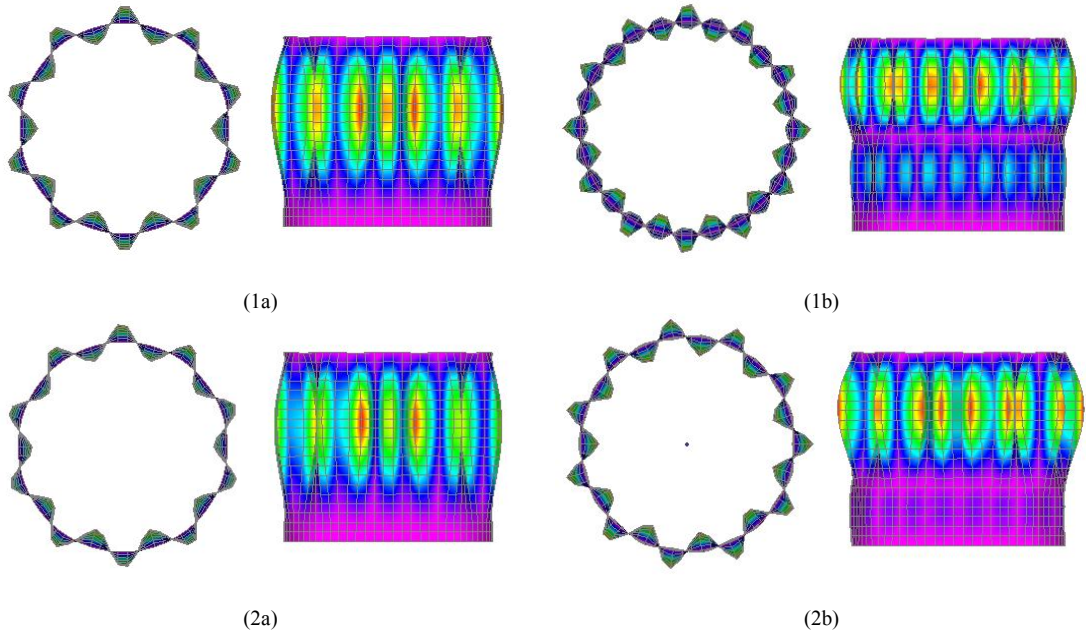


Fig. 7. Deformation forms of the shell with modelled imperfections with $\delta = 0,2h$ (1) and $\delta = h$ (2) when $z_0 = 300\text{ kN}$ (a) and $\tilde{v}_1 = 0$ (b)

The first ten natural frequencies \tilde{v}_1 of the shell with real imperfections were showed in Tab. 5.

Table 5

z_0 , kN	Natural frequencies of parametric vibrations of reservoir shell with real imperfections \tilde{v}_i , Hz				
	$\tilde{v}_{1(2)}$	$\tilde{v}_{3(4)}$	$\tilde{v}_{5(6)}$	$\tilde{v}_{7(8)}$	$\tilde{v}_{9(10)}$
1	15,8339	16,1340	16,6216	17,7911	18,2303
10	15,6675	15,9679	16,4665	17,6390	18,0928
100	13,8676	14,1831	14,7935	16,0280	16,6162
200	11,4494	11,8315	12,5464	13,9920	14,6267
300	8,1186	8,75703	9,3719	11,4361	11,5537
320	7,2187	7,9798	8,4735	10,3114	10,9933
330	4,8373	6,7138	7,5577	7,9580	9,6121
340	-47,8951	6,1597	7,1079	7,3819	8,7883
350	5,5406	6,6244	6,7259	7,8068	8,6466
360	4,8305	5,9557	6,0980	6,6004	7,2482
370	3,9790	4,5919	5,0109	5,0150	5,4601
380	2,4360	2,5511	2,8592	3,0923	3,7660
383	-108,875	2,0660	2,9063	4,5095	4,7371
390	0,5116	1,6038	2,6818	7,1133	8,3041
400	3,1696	5,4090	6,7378	8,3443	10,7002

The natural frequencies dependence of reservoir shell with real imperfections on the constant component of the parametric load z_0 was showed in Fig. 8.

The deformation forms of the shell with real imperfections when the constant component of the parametric load $z_0 = 300\text{ kN}$ was applied and when the first natural frequency was zero $\tilde{v}_1 = 0$ were presented in Fig. 9.

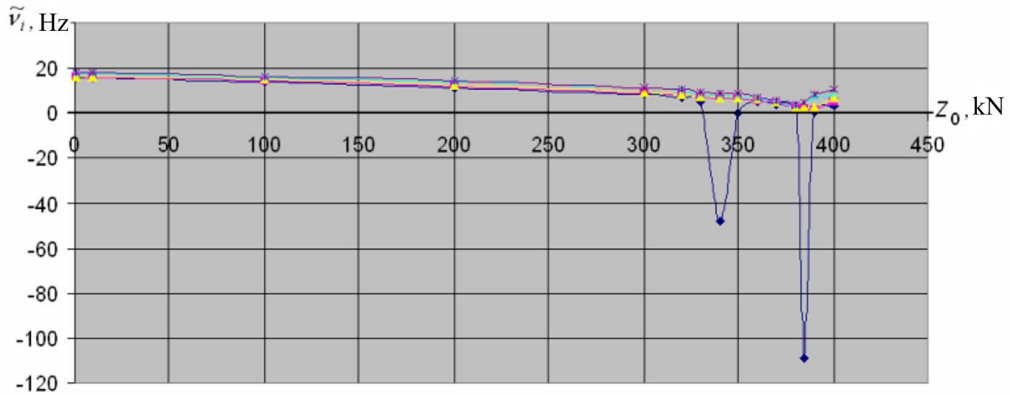


Fig. 8. Natural frequencies dependence of reservoir shell with real imperfections on the constant component of the parametric load z_0

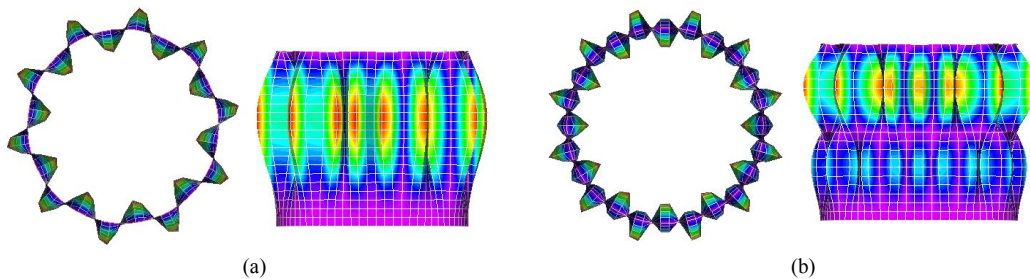


Fig. 9. Deformation forms of reservoir shell with real imperfections when $z_0 = 300\text{kN}$ (a) and $\tilde{\nu}_1 = 0$ (b)

Conclusion. Investigations showed that the real imperfections of shell a little influenced on natural frequencies and modes of parametric vibrations. These decreased the critical loads on the first natural frequency on 0,58 % and increased on the second natural frequency shells on 0,79 %, but qualitatively changed the form of stability loss on these frequencies. Modelled imperfections as the first bifurcation form of perfect shell under pressure had a greater but not considerable influence on natural frequencies and modes of the shell. But the modelled imperfections of the shell under constant component of parametric load considerably increased the critical load on the first and second natural frequency accordingly on 12,3 % and 5,26 % and changed the shell forms of stability loss. So the modelled imperfections of the shell in the form of the regular circular half-waves increased shell carrying capacity, but not decreased. This positive effect takes place at constructing of cylinder shells with vertical stiffness ribs and using the corrugated rolled sheets.

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ВЛАСНІ ЧАСТОТИ І ФОРМИ ПАРАМЕТРИЧНИХ КОЛИВАНЬ ОБОЛОНКИ РЕЗЕРВУАРУ З НЕДОСКОНАЛОСТЯМИ ФОРМИ

Розвиток програмного забезпечення на основі методу скінченних елементів веде до інтенсивного створення числових методів вирішення статичних і динамічних задач тонких оболонок. Скінченно-елементна модель тонкої оболонки має нескінченну кількість ступенів вільності і власних частот, тому розв'язання задач динаміки оболонки є важким. Якщо поведінка власних коливань оболонки досліджена, то можна говорити про внутрішні властивості оболонки, які мають значення при дослідженні вимушених коливань оболонки, зокрема параметричних. Важливо взяти до уваги вплив сталої складової параметричного навантаження на власні частоти і форми коливань оболонки. На теперішній час формування математичних моделей параметричних коливань оболонок з недосконалістю форми та вибір найнебезпечнішої моделі недосконалість оболонок залишаються актуальними. В статті досліджено вплив реальних і змодельованих недосконалостей форми на власні частоти і форми параметричних коливань оболонки резервуару, збуджених осьовим навантаженням, і втрату стійкості. Скінченноелементні моделі недосконалої оболонки сформовані у програмному комплексі NASTRAN. Недосконалість змодельована у вигляді нижчої форми втрати статичної стійкості оболонки з ідеальною поверхнею від поверхневого тиску. Реальні недосконалості представлено у вигляді відхилень стінки оболонки від вертикалі, які отримані за допомогою теодолітної зйомки. Власні частоти і форми оболонки з реальними і змодельованими недосконалістями отримані методом Ланцоша з урахуванням попереднього напруженого стану оболонки від дії сталої складової параметричного навантаження. В результаті дослідження виявлено, що реальні недосконалості мало вплинули на власні частоти і форми параметричних коливань оболонки, також незначно зменшили критичні значення навантаження на першій власній частоті і збільшили на другій власній частоті оболонки відповідно на 0,58% і 0,79%, але при цьому якісно змінили форму втрати стійкості на цих частотах. Змодельовані недосконалості зі зростанням амплітуди до одної товщини оболонки мали більший, але не значний вплив на власні частоти і форми параметричних коливань. Але змодельовані недосконалості при втраті стійкості оболонки при дії сталої складової осьового навантаження значно збільшили критичні значення навантаження на першій і другій власній частоті відповідно на 12,3% і 5,26% та якісно змінили форми втрати стійкості оболонки. Тобто змодельована недосконалість у вигляді регулярних колових півхвиль в радіальному напрямку при осьовому параметричному навантаженні збільшила несучу спроможність оболонки, а не зменшила. Цей позитивний ефект враховується при конструюванні циліндричних оболонок з гофрованих листів прокату.

Ключові слова: оболонка резервуару, недосконалості форми, параметричне навантаження, метод скінченних елементів, модальний аналіз.

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NATURAL FREQUENCIES AND MODES OF PARAMETRIC VIBRATIONS OF RESERVOIR SHELL WITH SHAPE IMPERFECTIONS

Development of software on the basis of the finite element method led to intensive creation of the numeral methods for the decision of static and dynamic problems of the thin shells. The finite element model of the thin shell has an infinite number of freedom degrees and natural frequencies, so solving the dynamics problem of the shell is difficult. If behavior of natural vibrations of the shell was researched, it is possible to talk about shell internal properties which take a great place at the forced vibrations including parametric one. It is important to take into account influence of the constant component of parametric load on natural frequencies and modes of the shell. Nowadays forming of an effective model of parametric vibrations of the shell with shape imperfections and choice of the most dangerous imperfections model remain relevant. Influence of real and modelled imperfections on natural frequencies and modes of reservoir shell parametric vibrations excited by axial load and on shell stability loss was investigated in this article. The finite element models of the shell was formed by software NASTRAN. The modelled shape imperfections as a lower buckling form of perfect shell under static pressure were presented. The real imperfections as the deviations of the shell wall from the vertical were obtained by theodolite surveying. The natural frequencies and modes of the imperfect shell taking into account the its previous stress state from action of the constant component of the parametric load were received by the Lanczos method. Investigations showed that the real imperfections of shell a little influenced on natural frequencies and modes of

parametric vibrations. These decreased the critical loads on the first natural frequency on 0,58 % and increased on the second natural frequency shells on 0,79 %, but qualitatively changed the form of stability loss on these frequencies. Modelled imperfections had a greater but not considerable influence on natural frequencies and modes of the shell. But the modelled imperfections of the shell under constant component of parametric load considerably increased the critical load on the first and second natural frequency accordingly on 12,3 % and 5,26 % and changed the shell forms of stability loss. So the modelled imperfections of the shell in the form of the regular circular half-waves increased shell carrying capacity, but not decreased. This positive effect takes place at constructing of cylinder shells from the corrugated rolled sheets.

Keywords: shell, shape imperfections, parametric load, finite element method, modal analysis.

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Досліджено вплив реальних і змодельованих недосконалостей форми на власні частоти і форми параметричних коливань оболонки резервуару, збуджених осьовим навантаженням, та втрату стійкості. Скінченноелементні моделі оболонки сформовані у програмному комплексі NASTRAN. Недосконалість змодельована у вигляді нижчої форми втрати статичної стійкості досконалої оболонки від поверхневого тиску. Реальні недосконалості представлено у вигляді відхилень стінки оболонки від вертикалі, які отримані за допомогою теодолітної зйомки. Власні частоти і форми оболонки з реальними і змодельованими недосконалістю форми отримані методом Ланцоша з урахуванням попереднього напруженого стану оболонки від дії сталого складової параметричного навантаження. Табл. 5. Іл. 9. Бібліогр. 16 назв.

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Influence of real and modelled imperfections on natural frequencies and modes of reservoir shell parametric vibrations excited by axial load and on the shell stability loss was investigated. The finite element models of the shell was formed by software NASTRAN. The modelled shape imperfections as a lower buckling form of perfect shell under static pressure were presented. The real imperfections as the deviations of the shell wall from the vertical were obtained by theodolite surveying. The natural frequencies and modes of the imperfect shell taking into account the its previous stress state from action of the constant component of the parametric load were received by the Lanczos method. Tab. 5. Fig. 9. References 16 items.

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