EXPERIMENTAL INVESTIGATION OF THE DYNAMICS OF SHELLS OF REVOLUTION (REVIEW)

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The results of experimental investigations carried out at the S. P. Timoshenko Institute of Mechanics of the National Academy of Sciences of Ukraine are analyzed in this review. The analysis suggests that experimental investigations of shell dynamics must be contained and developed if the method used to calculate the stressed-strained state and stability of dynamically loaded shells is to be developed further and made more precise.

The experiments were generally carried out in order to substantiate the reliability of computed results. The results of the experiments stimulated refinement of the computational procedures and led to broader experimental investigations. Reviews of experiments conducted up to 1990 are given in [2, 4–7, 21]. Below, using the example of research done at the S. P. Timoshenko Institute of Mechanics of the National Academy of Sciences of Ukraine, we demonstrate the role of experimental investigations in various methods of shell calculations. The methods used in the experiments discussed here are described in [46].

The natural oscillations of shells have been studied most fully, cylindrical shells being studied most often.

In [11], we calculated the natural oscillations of cylindrical shells, reinforced by an intersecting grid of ribs, on the basis of the theory of structurally orthotropic shells (the general case of deformation with one-term approximation of the components of the ribbed shell with due account for the discrete rib spacing [3] leads to the same computational formulas). The values so obtained are close to the experimental data when the annular ribs are arranged on the inner surface and the longitudinal ribs on the outer surface of the shell and differ substantially from the experimental data when the annular ribs are on the outer surface and the longitudinal ribs on the inner surface. During the experiment, we also found that when the excitation frequencies are close to the natural frequencies, the amplitudes of the oscillations of the annular ribs on the outer surface of the shell are substantially larger than their oscillations in the interval between them. The experimental data indicated that the discrete spacing of the edges must be taken into account more completely in calculations of the natural frequencies of oscillations. Two ways of making the calculated data more precise were proposed: determination of the natural frequencies, using multi-term approximation of the displacement components [7], and on the basis of a simple approximate formula, derived on the assumption that the natural frequencies of the ribbed shell are close to those of a system consisting of an annular rib and an "attached shell" [2]. The agreement between the experimental and calculated data was fairly good in both cases.

In almost all theoretical investigations a rib is assumed to be a one-dimensional elastic element. In [43], Telalov experimentally demonstrated that the assumption is meaningful only for ribs with relatively low rib shelves. Raising the height of the shelves may substantially increase the error in the calculated natural frequencies. That is seen from Fig. 1, where f is the natural frequency, k is the number of ribs, n is the number of circular modes, Δ are the measured natural frequencies for ribs with a low shelf and o are those for ribs with a high shelf; dashed and solid lines represent the respective results.

A natural mode with one longitudinal half-wave as a rule corresponds to the minimum natural frequencies of ribbed cylindrical shells. It can be changed significantly only if the shell is reinforced by one "stiff" annular rib in the median section [13]. It is interesting to note that if a shell is reinforced by "stiff" thin-walled U-section ribs (a rib is fastened to the shell by feet), when calculating the rib stiffness under torsion we must agree as to whether or not to consider the rib profile to be open

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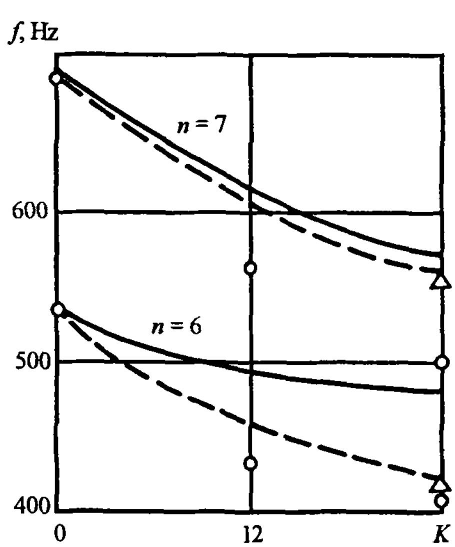

Fig. 1

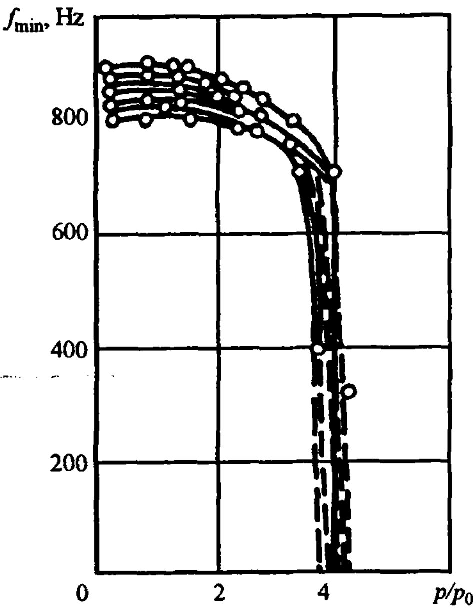

Fig. 2

or closed. Comparison of the calculated and experimental results showed that the normal frequencies calculated on the assumption that the rib profile was closed were closer to experiment.

We note that generally minimum and near minimum natural frequencies determined experimentally differ little from the calculated values. Such a difference does arise, however, because of the technological imperfections (initial cambers, thickness variations, inhomogeneity of the material, etc.) of the shells used in the experiment, as well as because of the disparity between the shell fastening conditions in the tests and those adopted in the computational model.

The initial cambers are the technological imperfections that most affect the characteristics of the stressed-strained state of the shells. Their effect on the natural frequencies was evidently first detected experimentally in the study [10] of the dependence of the natural frequencies of a ribbed cylindrical shell on the longitudinal compressive force. The study showed that for small values of that force, the natural frequencies rise as the force increases. The explanation given for this was that under such loads, the shape of the initial camber and the natural mode of the shells do not coincide and the camber increases the stiffness of the shell. The dependence of the minimum natural frequency (f_{min}) on the longitudinal compressive force (P) for the six ribbed cylindrical shells described in [10] ($P_0 = 9.8 \cdot 10^3$ N) is shown in Fig. 2.

A conclusion similar to that in [10] follows from the results of [16, 22]. In [16], the dependence of the natural frequencies on the shape of the shell meridian was studied experimentally, and, in [22], the initial cambers and natural frequencies were measured and the latter were calculated by a method that took the initial cambers into account. It was shown in [22], in particular, that the calculated and experimental natural frequencies become much closer when the cambers measured on the shells in the experiment are taken to be the initial cambers.

An integrated estimate of the stiffness of a shell having technological imperfections was given in [8]. It was proposed there to determine it by measuring the minimum natural frequency of a system consisting of the shell and a large attached concentrated mass. The stiffness of that system, considered as an oscillator, is then identified with the "equivalent stiffness" of the imperfect shell. Underlying this scheme is the experimental result obtained earlier, i.e., increasing the attached mass localizes the oscillation mode [7, 21, 42].

When shells are subjected to compressive forces, the effect of the discrete rib spacing on the natural frequencies increases with those forces. That conclusion follows from [10, 28], where the natural frequencies were determined experimentally for ribbed cylindrical shells [10] and ribbed cylindrical and slightly conical shells with cutouts [28]. Here, we use the terminology accepted in the scientific literature, although the resonance frequencies of a loaded shell are not its natural frequencies, strictly speaking.

The forced oscillations of shells cannot be studied fully enough by computations without knowing the energy dissipation characteristics. How the methods of rib fastening affect the oscillation decrement was studied in [38], where it

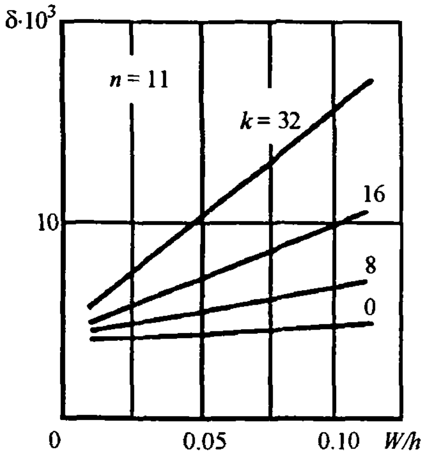

Fig. 3

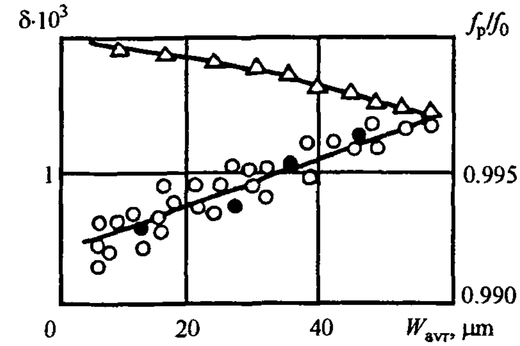

Fig. 4

was shown that a considerable change in the decrement could be obtained by varying the number of welding spots by which a rib is attached to the shell. Figure 3 (h is the shell thickness) shows the dependence of the logarithmic decrement (δ) of the camber w of a shell reinforced by longitudinal ribs.

Figure 4 shows the values of the logarithmic decrement as a function of the amplitude of the oscillations of a shell with 32 stringers for a mode with $n = 12$ ($f_0 = 596$ Hz, $k = 32$). White circles denote the decrements obtained by the oscillation damping method and the black circles denote the decrements found by the phase method. The figure also shows the values of the resonance frequency relative to the natural frequency of linear oscillations, depending on the amplitude of the shell camber.

It has been established that when the shell oscillations have an amplitude more than 1/10 of the shell thickness, stringer reinforcement increases the logarithmic decrement several-fold. The damping ability of the system decreases when stringers are attached more rigidly to the shell.

As was to be expected, the decrements of ribbed shell oscillations also increase substantially when the shell is in a liquid so that the ribs are in contact with it [39]. The liquid has a greater effect when the rib shelf is higher. That conclusion is illustrated by Fig. 5, where data are given for a shell with 24 outer longitudinal ribs: decrements of the oscillations of a shell in air (*1*), of a liquid-filled shell (*2*), and of a shell immersed in a liquid (in this case the ribs are in contact with the liquid) (*3*).

Experimental investigation of the parametric oscillations of cylindrical shells showed that technological imperfections cause the instability region to change substantially [46].

As shown in [34], because the glass-fiber-reinforced composite shells have initial cambers, the number of regions of dynamic instability doubles; the instability regions corresponding to the same wave number may partially overlap (Fig. 6).

A similar phenomenon was also detected in a study of the parametric oscillations of shells bearing concentrated masses. The "excitation threshold" is found to depend on whether we consider the main instability region or a new one that appears as a result of the "doubling." It thus follows that the initial cambers and the influence of the method of fastening the ribs must be taken into account in a theoretical study of the parametric oscillations.

The results of experimental investigation of the interaction of the parametric modes of incompletely fastened cylindrical glass-fiber-reinforced composite shells under kinematic excitation are reported in [12]. The cases of the interaction of coupled modes (corresponding to the same wave parameters) and uncoupled modes (with different wave parameters) are considered. The flexural modes of smooth glass-fiber-reinforced composite shells are shown in Fig. 7. The mode depicted in Fig. 7*a* corresponds to the axial excitation frequency $f = 72.4$ Hz and that in Fig. 7*b*, to the frequency $f = 75.6$ Hz.

The discussion above indicates that theoretical studies on the dynamics shells cannot be developed further without a corresponding development of experimental work in this field. This is particularly important at the present time, when the use of new structural materials raises problems that cannot be solved without a sufficiently complete idea of the dynamics of structures made of those materials; such information could be obtained only on the basis of a comprehensive theoretical and experimental study of the deformation of those structures.

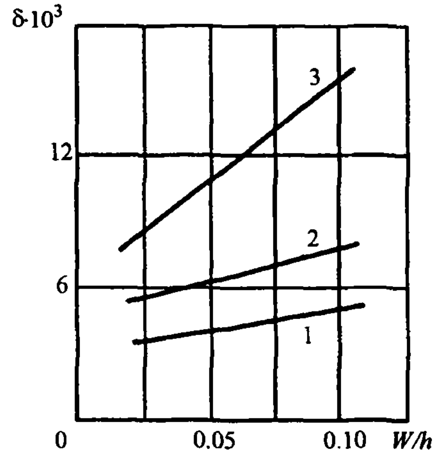

Fig. 5

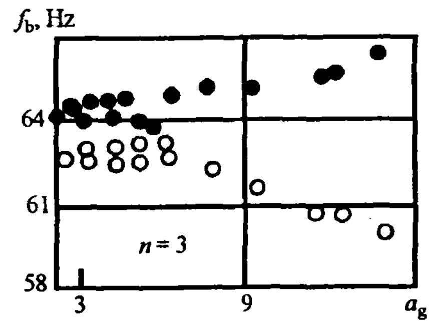

Fig. 6

Below we report experimental results that support the conclusions made above and indicate that experimental investigations reported in the cited papers and elsewhere must be continued.

The results of experiments to ascertain how ribs affect the natural frequencies and modes of cylindrical and conical frustum shells were reported in [13, 31]. The experimentally observed differences in the numbers of nodal lines of modes at the large and small bases of a conical frustum shell was explained by assuming that modes of the parts of the shell near its ends can be identified with the modes of cylindrical shells, with radii equal to the radii of the respective bases of the conical shell.

The natural frequencies and modes of a shell system, consisting of stiffened cylindrical and conical frustum shells connected by a rigid frame, were determined experimentally [20]. It was demonstrated experimentally that the lower part of the natural frequency spectrum of the indicated system can be determined with an accuracy sufficient for practical purposes by considering the oscillations of cylindrical and conical shells standing separately.

The results of experiments to determine how an axial compressive force affects the natural frequencies of cylindrical and conical frustum shells are given in [28], where the influence of annular ribs on the minimum natural frequencies and modes of shells was studied. The discrete rib spacing was found to have a considerable effect.

The results of experimental investigations of the influence of rigidly attached mass on the natural frequencies of cylindrical shells, depending on the coning angle of the structure and the number of stiffeners, are given in [23]. The attached mass causes the nodal lines of the natural mode to shift. A zone with an elliptical nodal line is formed around the point where the mass is attached.

The natural frequencies and modes were determined experimentally for spherical shells that were rigidly fastened along a reference parallel and carried concentrated masses. The results of determining the minimum natural frequencies and the corresponding mode of axisymmetric oscillations are described in [29, 42] (Fig. 8, where $\overline{M}$ is the ratio of the attached mass M to the mass of the shell, and W is the amplitude of the camber at the top of the spherical segment, where the mass is attached). It is easily seen that increasing $\overline{M}$ reduces the minimum natural frequency and localizes the mode. That experimental finding made is possible to propose a simple formula for calculating that frequency [42].

The natural frequencies of spherical shells rigidly attached along a reference parallel and reinforced by a regular annular stiffener were considered in [41]. The results of the measurements of the natural frequencies and modes of spherical shells reinforced by one, three, and seven annular ribs were reported. The experimental values of the natural frequencies and modes are compared with the calculated values.

A set-up for studying the natural frequencies and modes of spherical shells made of electrically conducting materials is described in [1]. The results of measurements for a shell, made of 12Kh18N10T steel and fastened along a reference parallel are reported.

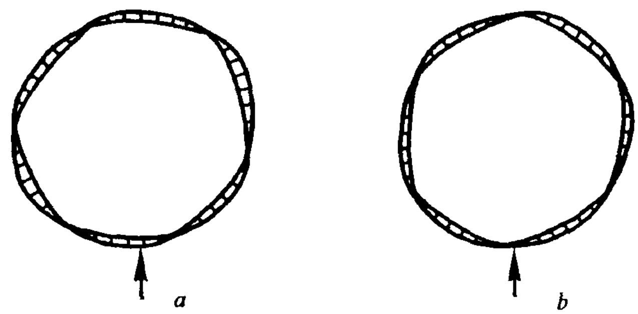

Fig. 7

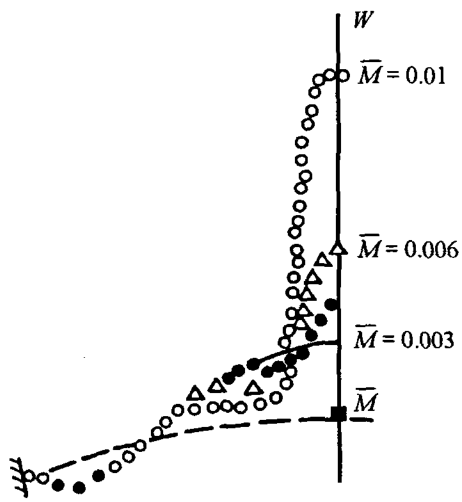

Fig. 8

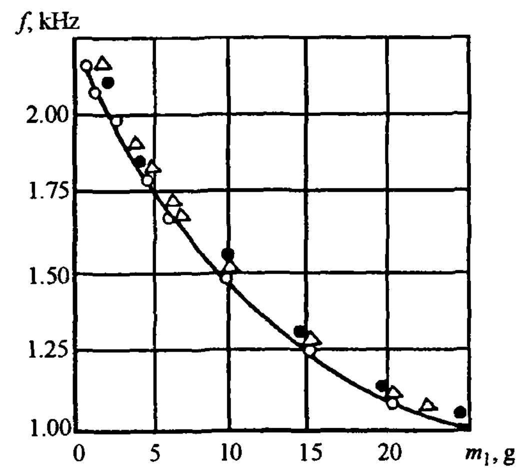

Fig. 9

Experimental investigation of the natural frequencies of ribbed spherical shells [7, 30] indicates that the influence of the discrete rib spacing is more important for shells with a positive Gaussian curvature than those with zero Gaussian curvature.

In [7], we reported the results of an experimental study of how the fastening parameters as well as the mass attached at the pole affect the minimum natural frequencies of spherical segments and also gave the data from experimental determination of the natural frequencies and modes of those systems. Some results of the studies are shown in Fig. 9 (the calculated curves for smooth and fastened segments coincided and are represented by a solid curve). The white circles in Fig. 9 represent results of measurements of the minimum frequency for a shell not fastened, the black circles, for a shell with one annular rib, and triangles, for a shell with three annular ribs. Comparison of the theoretical and experimental results indicates that they are in good agreement.

The results of experimental investigation of the oscillations of multilayer cylindrical shells are reported in [26, 27]. The annular flexural rigidity of such shells was determined from the results of measurements of their natural frequencies. The modes coincided with the natural modes of a ring. Each shell was tested in two states: after winding and after making annular weld seams along the edges. The seams were formed by densely spaced weld points. Annular weld seams were shown to quadruple the rigidity of pipes.

The results of determination of the strains of a fastened cylindrical shell with attached masses under longitudinal kinematic excitation are reported in [17]. The strains were measured by high-sensitivity strain gauges. An analysis of the experimental data indicates that the maximum stresses under resonance arise in the median section of the shell near where the point mass is attached.

The stressed-strained state of a liquid-filled ribbed cylindrical shell subjected to longitudinal and transverse pulsed loads was studied experimentally in [33]. Analysis of the experimental data suggests that the dependence of the vibrational stresses on the total pulse obtained for the kinds of pulsed load considered was nearly linear. The vibrational stresses are lower for the liquid-filled shell than for the "dry" shell, the membrane stresses being substantially higher than the flexural.

Experiments [44] demonstrated that the maximum pressure of the pulse that causes a camber during the bang equal to the camber of the shell prior to the discharge during quasistatic loading can be taken for the upper critical pressure of a spherical shell under pulse loading. The tests were done on a special set-up for static and pulsed loading of thin-walled spherical shells, fastened along a reference contour, by an external uniformly distributed pressure.

Reference [45] gives the results of experimental investigation of the stability of spherical shells reinforced by meridional ribs under dynamic loading. The values obtained for the critical pressures were analyzed, using data about the corresponding modes of wave formation under a static loss of stability.

The dependence of the logarithmic decrement of oscillations on the amplitude of the oscillations for liquid-filled glass-fiber-reinforced composite cylindrical shells was studied experimentally in [9, 34]. The dissipative characteristics of glass-fiber-reinforced composite shells were shown to increase significantly when the shell is filled with liquid. An inlet pipe substantially lowers the minimum natural frequency of the system "shell + inlet pipe," the amplitude of the oscillations of the free edge of the inlet pipe of a "dry" shell is roughly five times more than the amplitude of oscillations of the main shell. Those amplitudes of inlet-pipe oscillations increase 15 times for the liquid-filled shell.

Many current problems, concerning such matters as the oscillations of shells with distinctive structural features (ribs, attached mass, cutouts, etc.) at high levels of excitation, the propagation of waves in such shells, etc. have been studied little to date. This indicates that experimental investigation should be stepped up in the domain of the dynamics of shells, particularly, ribbed shells.

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