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EXPERIMENTS ON THE VIBRATION OF FLUID-COUPLED COAXIAL CYLINDRICAL SHELLS

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SUMMARY

A precise experimental study is presented in this paper to compare with the theoretical results of the free vibration of free-clamped coaxial cylindrical shells, the annular gap of which is partially filled with water. The experimental results obtained for the natural frequency, circumferential wave number, shape of the axial mode, as well as their variations with liquid depth and annular gap-size were ascertained to be in good agreement with the theoretical ones.

INTRODUCTION

Knowledge of the free vibration characteristics of fluid-coupled coaxial cylindrical shells has been of primary importance for the design of fast breeder reactor systems subjected to the seismic loading. Hence, numerous theoretical and experimental researches have been conducted on this subject (Ref. 1-11). However, these good agreement between theoretical and experimental results has not been obtained yet. Therefore, recently one of the authors analyzed theoretically, taking the effects of the axisymmetric deformation due to the static liquid pressure and boundary condition on the free liquid surface into consideration (Ref. 12). It was found that the static liquid pressure and the liquid surface condition have a significant effect on the natural frequency, and that the interactive effect of the coaxial cylinders becomes small and the mode shape changes with an increase in the wave number and the annular gap.

With the object of providing data to examine the validity of the previous theoretical results (Ref. 12), detailed experimental studies were conducted using three polyester test coaxial cylinders with one end clamped and the other end free. Water was used as the contained liquid. As in the previous experimental study on a liquid-filled cylindrical shell (Ref. 13), two exciters were used for the sweeping excitation of the shell and resonant responses of the shell wall were observed with a noncontacting fiber-optic device, the Fotonic sensor. The results thus obtained for the natural frequency, wave number, mode shape and their dependence on the liquid level and the gap size were ascertained to be in good agreement with those theoretically predicted, clarifying the validity of the previous theoretical analyses.

TEST CYLINDERS AND TEST EQUIPMENT

Three test coaxial cylindrical shells with the same length L = 197.5 mm in the inner and outer shells were made of polyester film with nominal thickness h = 0.25 mm by lap-jointing along a longitudinal seam and bonding the duralumin end plate along one edge as shown in Fig. 1. Young's modulus E, Poisson's ratio ν and mass density ρ_s were found to be 5.56 GPa, 0.3 and 1.41×10^3 kg/m^3, respectively. The radius R_1 of the inner shell was chosen as 100 mm, which corresponds to Z = 1500, where $Z = \sqrt{1-\nu^2}L^2/Rh$ is the geometric parameter of the circular cylindrical shell. On the other hand, the radii R_2 of the outer shells were chosen as 107, 120 and 150 mm, which correspond to Z = 1400, 1250 and 1000, respectively. The mass density ρ_f of the contained water is 1.0×10^3 kg/m^3. The initial geometrical imperfection of the cylindrical surface was less than h/10.

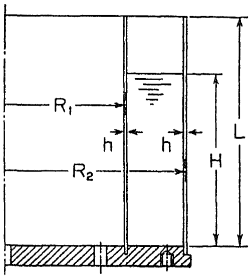

Fig. 1 Test Coaxial Cylinders with Liquid-Filled Annular Gap

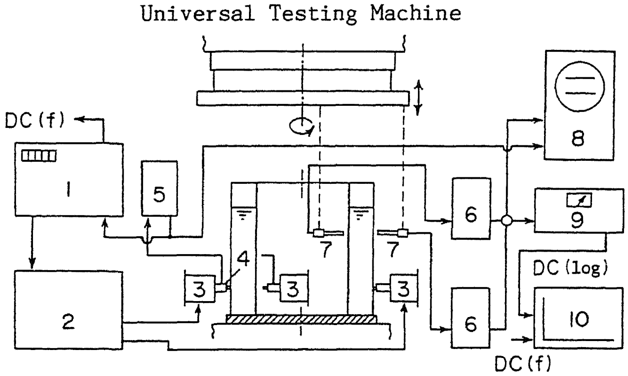

Fig. 2 Schematic Diagram of the Test Set-Up

A schematic diagram of the test set-up is given in Fig. 2. In this figure, 1 is a exciter control, 2 is a two-channel power amplifier providing two outputs with the same or the opposite phase angles, 3 is a pair of vibration exciters to excite the walls of the test coaxial cylinders at the diametrically opposite positions, 4 is an accelerometer, 5 is a conditioning amplifier, the output of which is fed back to the exciter control 1 to keep the excitation amplitude constant. The shell response was measured by two noncontacting fiber-optics devices, the Fotonic Sensor, and 6 and 7 are its main instruments and probes, respectively. Further, 8 is a dual-beam synchroscope which monitors the waveforms of both excitation and response, 9 is a measuring amplifier to obtain DC output logarithmically or linearly proportional to the rms value of the shell response and 10 is a X-Y recorder which records the frequency response curve. The sensor probes 7 are connected to a cross-head of the universal testing machine, so that it can be moved in both longitudinal and circumferential directions along the shell surface. The experimental lay-out and the instrumentation around the test cylinders are shown in Fig. 3.

TEST PROCEDURE

The free vibration characteristics of the shell were determined by measuring the resonant response of the shell when it was subjected to sweeping sine excitation of constant amplitude within the prescribed frequency range. In

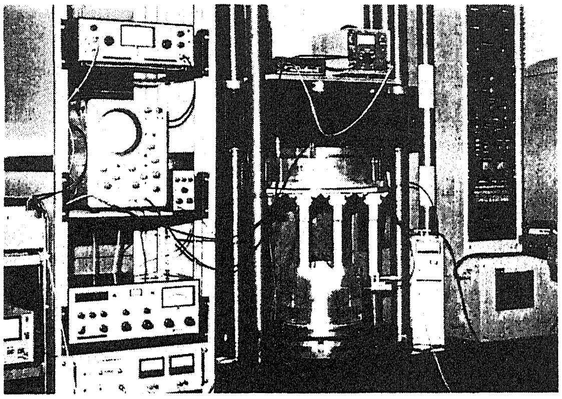

Fig. 3 Overall View of the Actual Test Set-Up

general, the two exciters were placed at the points of height L/4 and the cirumferential direction $\theta = 10°$ and $190°$, when the longitudinal seam of the cylinder was located along $\theta = 0°$. The excitation amplitude was kept at 5.0 μm, while the phase angles of both exciting forces were set to the same and the opposite, alternately, for the effective excitation of the natural vibrations having the even and odd circumferential wave numbers, respectively. For the determination of the axial mode m, tests were conducted when the probes were moved in the axial direction from 0.05 L to 0.95 L stepwise by 0.05 L increments, while to find the wave number N the probes were moved circumferentially from $\theta = 120°$ to $240°$ stepwise by $\theta = 3°$ increments along a suitably selected paralleled circle.

For example, frequency response curves of the inner and outer cylinders with R_2 = 107, 120 and 150 mm, measured at a point of height 0.35 L and $\theta = 100°$ are shown in Fig. 4. In this case, the filling rate of the contained water, $l_0 = H/L$ (H:liquid height) is chosen as 0.75. In this figure, $\Omega/2\pi$ (Hz) is the excitation frequency, $(W/h)_{rms}$ is the rms value of the shell wall amplitude W normalized with the thickness and each peak corresponds to one of the natural frequencies. It can be seen from this figure that the similar tendency of the frequency response curves of the inner and outer cylinders is lost when the gap size between two cylinders and the excitation frequency become large, that is, the coupling effect of two cylinders due to liquid becomes small.

TEST RESULTS

Effect of the Circumferential Wave Number on the Natural Frequency With the procedure stated above, the free vibration characteristics of test coaxial cylinders were measured precisely. The relations between the natural frequency $\Omega/2\pi$(Hz) and the circumferential wave number N, are shown in Fig. 5 for coaxial cylinders with R_2 = 120 mm and l_0 = 0.25, 0.75. The relations between $\Omega/2\pi$ and N are shown in Fig. 6 for cylinders with l_0 = 0.75 and R_2 = 107, 150 mm. In these figures, signs ● and ▲ indicate experimental results, while solid lines represent the theoretical results previously obtained (Ref. 12). Furthermore, ω_1, ω_2 and ω_3, ω_4 are the natural frequencies with axial modes m = 1 and 2, respectively. The natural frequencies ω_1, ω_3 and ω_2, ω_4 with the small circumferential wave number correspond to the out-of-phase and in-phase modes, respectively, and those with the large wave number are dominated by the deformation of either inner or outer cylinders, depending on the filling rate of liquid. It can be seen from these figures that the agreement between theory and experiment is quite good in the whole cases tested, and that the natural frequency decreases with an increase in the filling rate of liquid.

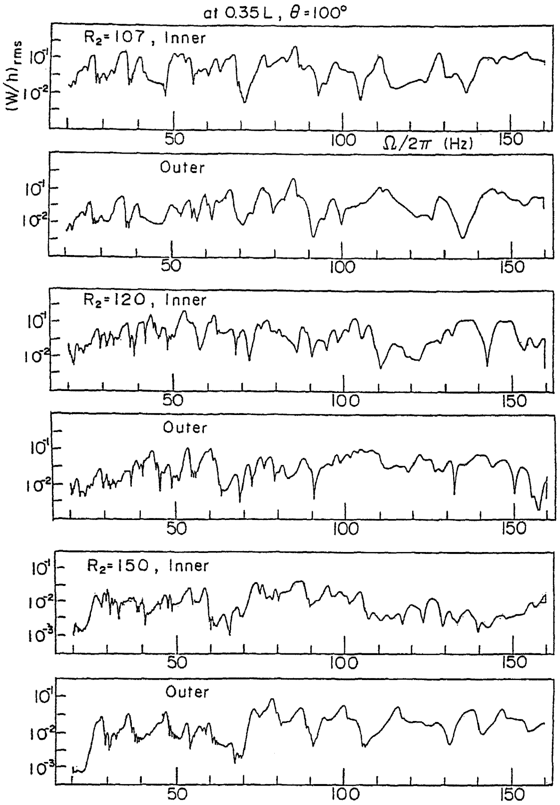

Fig. 4 Frequency Response Curves of the Test Cylinders with Filling Rate $l_0 = 0.75$

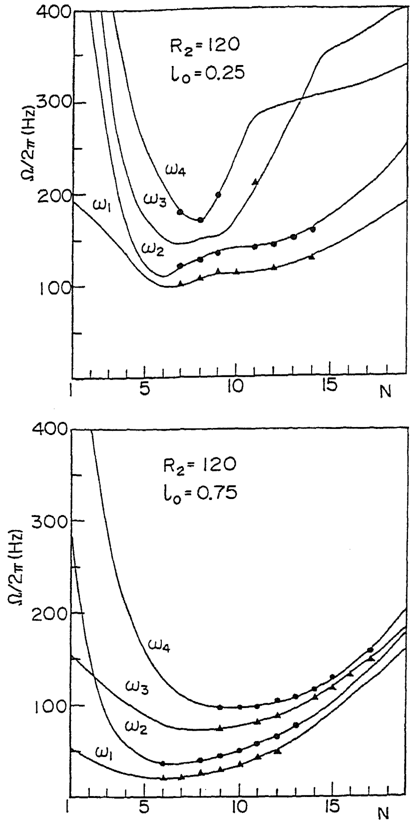

Fig. 5 Relations between $\Omega/2\pi$ and N of Coaxial Cylinders with $R_2 = 120$

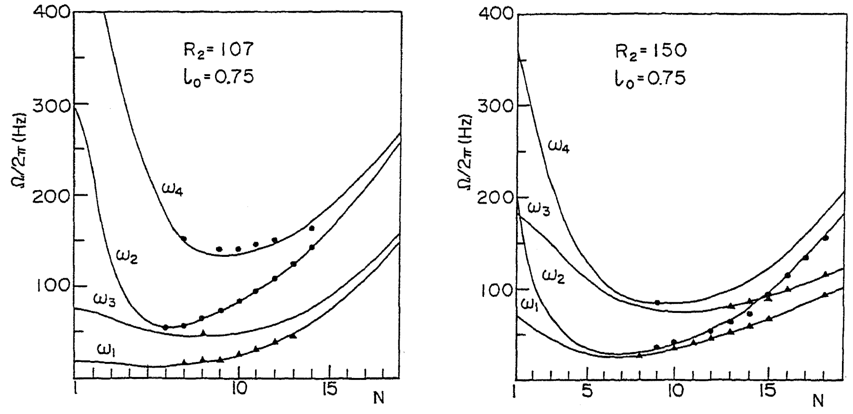

Fig. 6 Relations between $\Omega/2\pi$ and N of Coaxial Cylinders with $l_0 = 0.75$

Axial Mode Shapes for the Natural Vibration

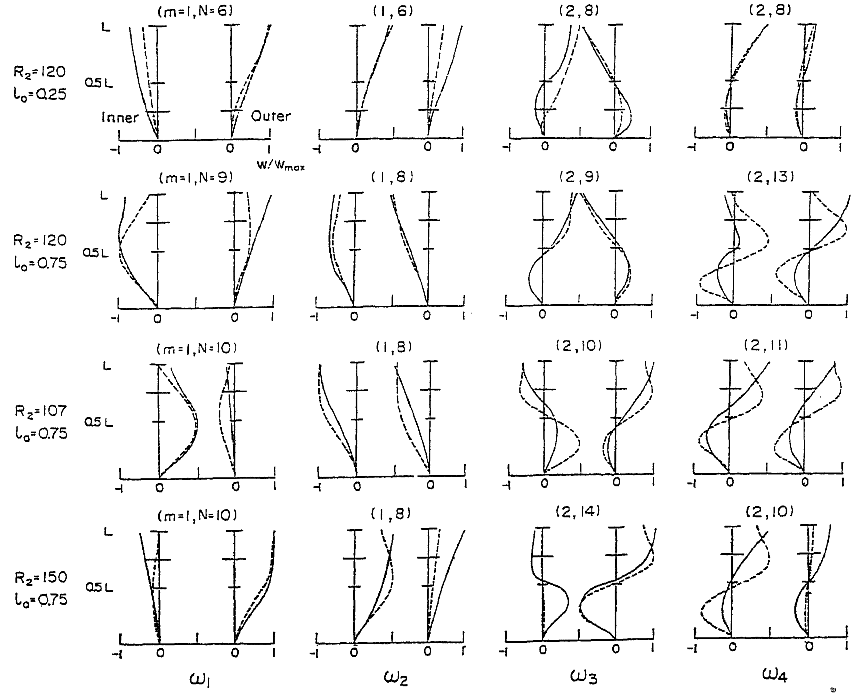

Fig. 7 Axial Distributions of the Vibration Amplitude W/Wmax

For the test coaxial cylinders with R_2 = 107, 120 and 150 mm, the axial modes of vibration were measured with respect to the natural frequencies ω_1, ω_2, ω_3 and ω_4. The phase of the vibration mode was distinguished with the dual-beam synchroscope in which both the responses of inner and outer cylinders were fed at the same time. The results are illustrated in Fig. 7. In this figure, solid and dotted lines correspond to the experimental and theoretical results, respectively. It can been seen from this figure that the agreement between theory and experiment is fairly well, except for ω_4.

Effect of the Gap Size on the Natural Frequency

The relation between the natural frequencies and the gap size is shown in Fig. 8, for the cases with the circumferential waves number N = 3, 10 and the axial mode m = 1. The gap parameter $G = (R_2 - R_1)/R_1$ is varied by fixing R_1 and changing R_2. In this figure, the kind of lines and signs is the same as Fig. 6. It can be seen from this figure that ω_1 increases and ω_2 decreases with an increase in G, and that there is the same tendency in both the theoretical and experimental results.

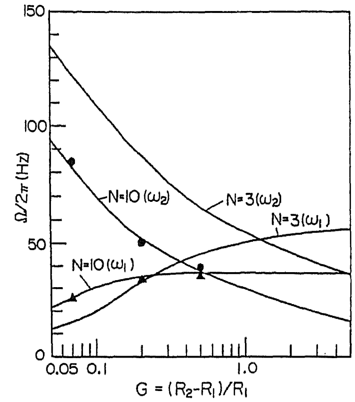

Fig. 8 Relations between the Natural Frequency and the Gap Size

CONCLUSIONS

Using the three polyester test coaxial cylinders, precise and detailed experiments were carried out on the free vibration characteristics of a clamped -free coaxial cylindrical shells, the annular gap of which is partially filled with water. Experimental results obtained here were ascertained to be in good agreement with those theoretically predicted in the previous paper (Ref. 12), which seem to indicate not only the validity of previous theoretical analyses but also the reliability of the present experimental data.

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