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DYNAMIC CHARACTERISTICS OF A PARTIALLY FLUID-FILLED CYLINDRICAL SHELL

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A pressurizer in a small integral type pressurized water reactor is located inside the upper region of the reactor vessel, and uses a space between the upper head of the reactor vessel and the upper region of the upper guide structure which is partially filled with fluid depending on the operating power. This new design requires a comprehensive investigation of vibration characteristics. This study investigates the modal characteristics of a pressurizer which uses a simplified cylindrical shell model, focusing on how having fluid in the shell affects vibration and response characteristics. In addition, an analysis of sloshing is performed and the response characteristics are addressed.

KEYWORDS : Shell, Natural Frequency, Mode Shape, Response Spectrum, Sloshing, Equivalent Stress

1. INTRODUCTION

Various advanced types of small and medium reactors (SMRs) are currently under development worldwide [1], and some of them are ready for construction. KAERI is developing an advanced SMR called SMART (System-integrated Modular Advanced ReacTor), which is a small integral type pressurized water reactor with a thermal power of 330 MW. SMART offers substantially enhanced safety because of its integral layout, which integrates its major components (such as the reactor core, steam generator, coolant pump, and pressurizer) within a single pressure vessel [2].

Many innovative design features are employed in the reactor vessel internals, including a pressurizer which is located inside the upper region of the reactor vessel. A space between the upper head of the reactor vessel and the upper region of the upper guide structure is used as a pressurizer. Many structures, such as incore instruments, are located inside of the pressurizer. The pressurizer is also partially filled with fluid, the depth of which depends on the operating power. This new design requires a comprehensive investigation of the vibration characteristics, which is thus being performed analytically and experimentally by the designer in order to get a license.

This study investigates the modal characteristics of a pressurizer which uses a simplified cylindrical shell model, focusing on how having fluid in the shell affects vibration and response characteristics. In addition, because the pressurizer is partially filled with fluid, an analysis of sloshing is performed and the response characteristics are also addressed

2. ANALYSIS

2.1 Finite Element Model

Consider a shell which is partially filled with fluid, as shown in Fig. 1. The shell has a mean radius of 150 mm at mid-height, a length of 300 mm, and a wall thickness of 2 mm. The physical properties of the shell material are as follows: Young's modulus = 69.0 GPa, Poisson's ratio = 0.3, and mass density = 2700 kg/m^3. Water (density = 1000 kg/m^3) is used as the contained fluid. The speed of sound in water (1483 m/s) is equivalent to the bulk modulus of elasticity, 2.2 GPa.

A three-dimensional model is constructed for finite element analysis using ANSYS [3]. The fluid region is divided into a number of identical three-dimensional contained fluid elements (FLUID80) with eight nodes having three degrees of freedom at each node. The fluid element FLUID80 is particularly well suited for calculating hydrostatic pressures and fluid/solid interactions. The circular cylindrical shell is modeled as an elastic shell element (SHELL63) with four nodes. The model has

2048 shell elements and 11520 fluid elements when it is 75% filled with fluid, as shown in Fig. 2.

The fluid boundary conditions at the bottom are zero displacement and rotation. The nodes that are connected entirely by the fluid elements are free to move arbitrarily in three-dimensional space, with the exception of those that are restricted to motion in the bottom surface of the fluid. The radial velocities of the fluid nodes along the wet shell

surfaces coincide with the corresponding velocities of the shells. The bottom of the shell is considered a clamped boundary condition.

2.2 Modal Analysis

Finite element analysis using ANSYS Mechanical 12.0 [3] is performed to find the natural frequencies of the partially fluid-filled fluid shell with both a fixed and free boundary condition.

The Block Lanczos method is used to determine the eigenvalue and eigenvector extractions of the finite element model, which qualifies as a large symmetric eigenvalue problem [4]. Typically this technique is applicable to problems solved using the subspace eigenvalue method, but at a faster convergence rate, it can also be used to find all of the exact symmetric modes necessary to define the dynamic characteristics of the shell. In this case, the fluid exhibits several sloshing modes simultaneously, which means they should be excluded for the shell modes only.

2.3 Response Spectrum Analysis

Figure 3 shows the corrected accelerogram of the El Centro site of the Imperial Valley irrigation district on May 18, 1940 for east-west direction. The corresponding displacement time histories are also shown in Fig. 4. The response spectrum is generated from the time history for

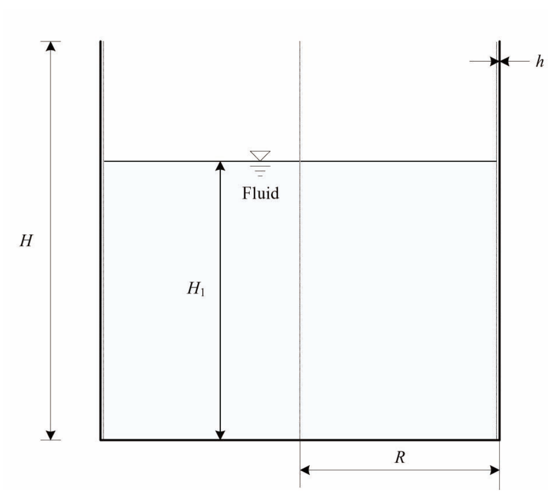

Fig. 1. Shell Partially Filled with Fluid

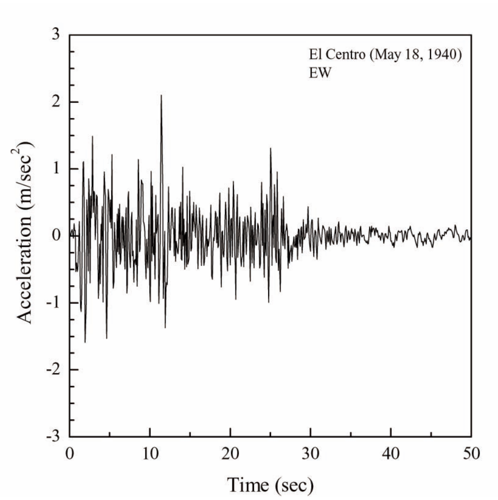

Fig. 3. Acceleration Time History

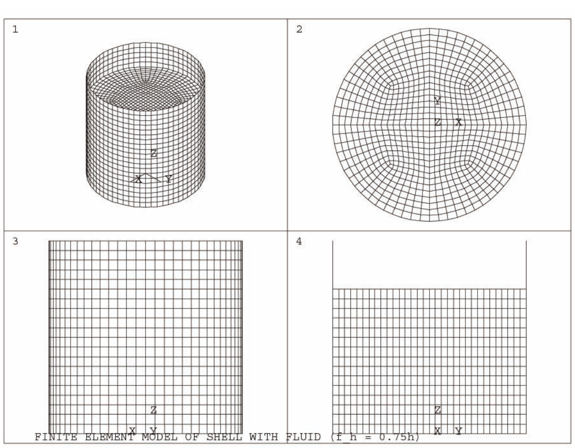

Fig. 2. Finite Element Model of Partially Fluid-filled Shell

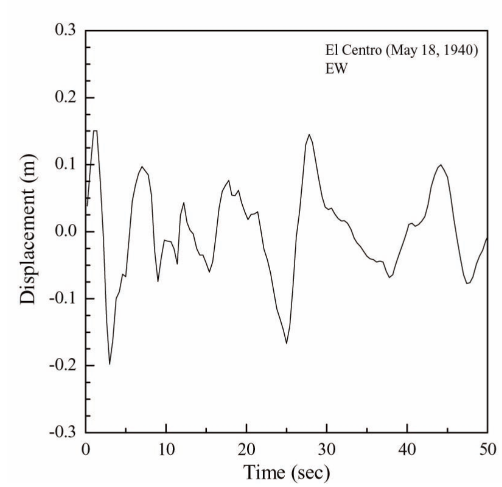

Fig. 4. Displacement Time History

a 2% damping ratio, as shown in Fig. 5 [5]. This spectrum is applied to the bottom of the structure which is fixed in all six degrees of freedom.

2.4 Sloshing Analysis

A three-dimensional model is constructed for two-way fluid structure interaction (FSI) analysis. The shell structure is modeled as a solid element with four nodes. The fluid region, composed of both water and air, is modeled as a hexahedron fluid cell. The model has 10660 solid elements and 84750 fluid cells, as shown in Fig. 6. Using the displacement time history of Fig. 4, sloshing analyses are performed for the partially fluid-filled shell using ANSYS CFX [6]. First, the displacement excitations are applied to the bottom of the shell. Then, the fluid motion is determined, and its effect is applied to the shell.

Sloshing analysis uses the computational fluid dynamics approach accompanying the multi-phase flow phenomena of gas and liquid. Therefore, a VOF (Volume of Fluid) model is used in the analysis because it is suitable for free surface analysis. Two-way FSI analysis consists of structural analysis using ANSYS Mechanical and fluid analysis using ANSYS CFX.

The displacement excitations are applied to the bottom of the shell and the information about deformation is transferred to the fluid analysis, which is used to calculate the fluid location generating the momentum of the fluid. The pressure generated by the momentum of the fluid flow is again applied to the structure as a load, and this procedure is repeated until the end of the transient.

3. RESULTS AND DISCUSSION

Natural frequencies of the partially fluid-filled shell are obtained for various fluid depths, as shown in Fig. 7. The symbol *m'* in the tables represents the number of the axial mode and the symbol *n* means the number of the circumferential mode. The natural frequencies of the shell do not ascend as the value of the modal index increases. The lowest frequency mode of a shell which is 75% filled with fluid is associated with the modal index *m'*=1 and *n*=4 (as shown in the mode shapes of Fig. 8) because the curvature of the shell causes coupling between the extensional and flexural deformations, which can vary from pure extensional to purely flexural [7]. In contrast, Fig. 7 shows the variations in strain energy of a cylindrical shell with an increasing number of circumferential waves.

Figure 9 shows the frequencies of a shell with respect to the fluid height, demonstrating that the frequencies

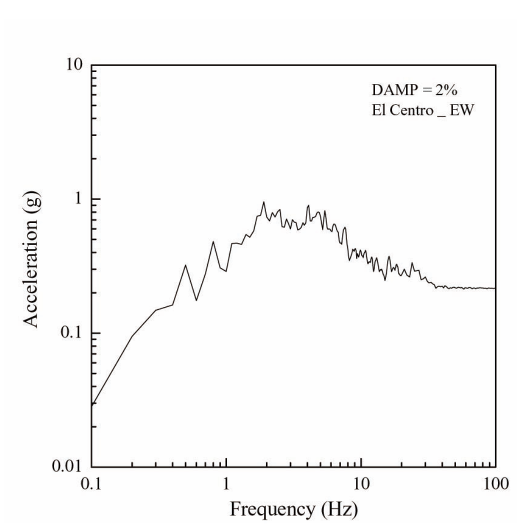

Fig. 5. Response Spectrum Generated for 2% Damping

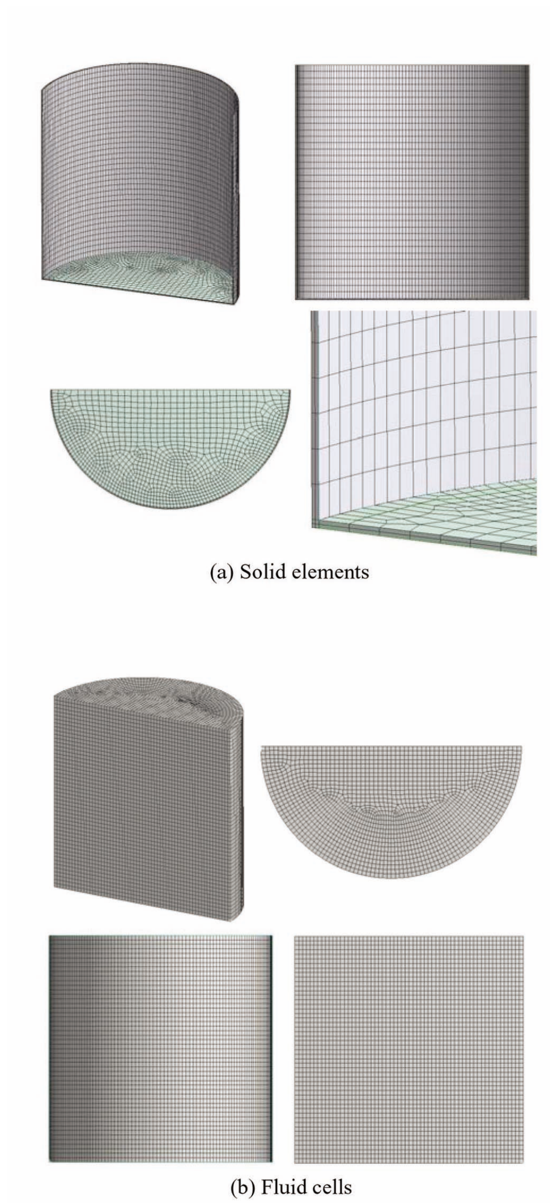

Fig. 6. Finite Element Model for Sloshing Analysis

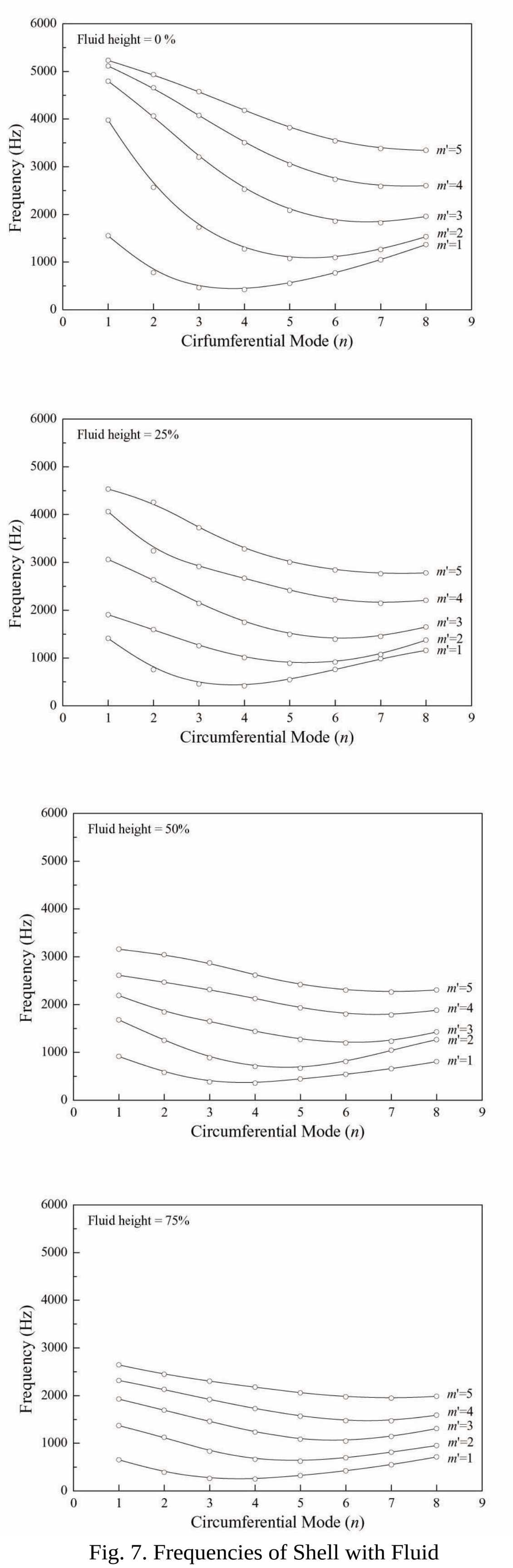

Fig. 7. Frequencies of Shell with Fluid

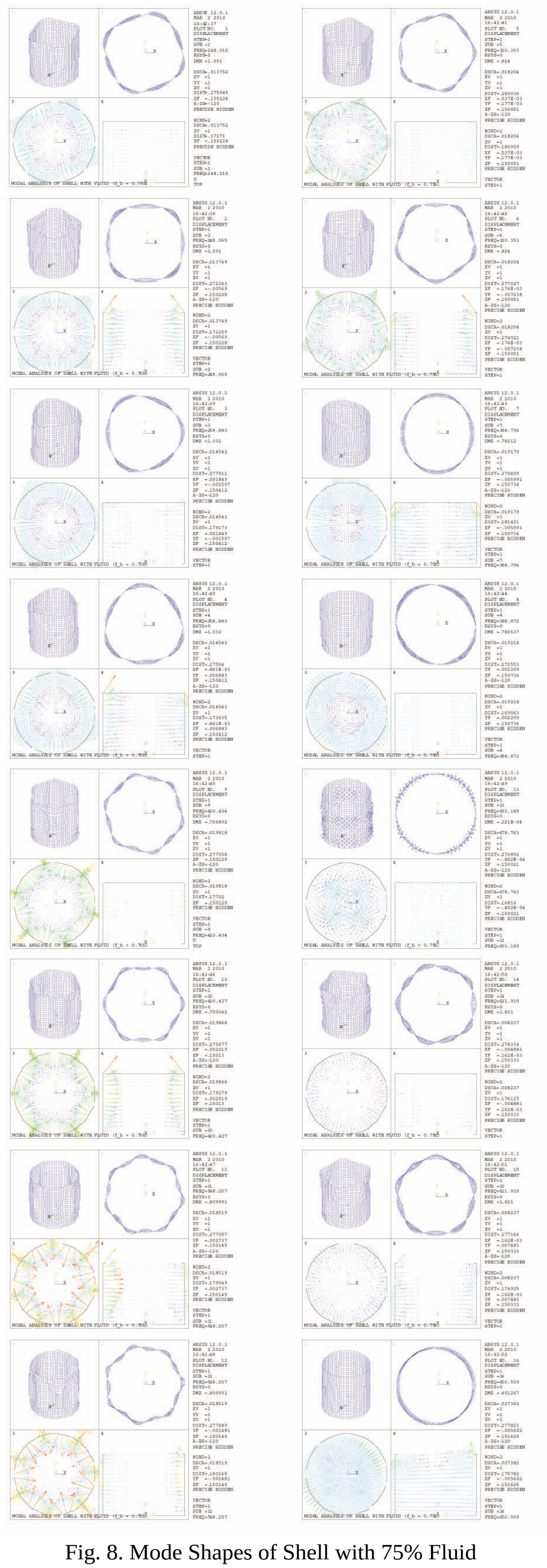

Fig. 8. Mode Shapes of Shell with 75% Fluid

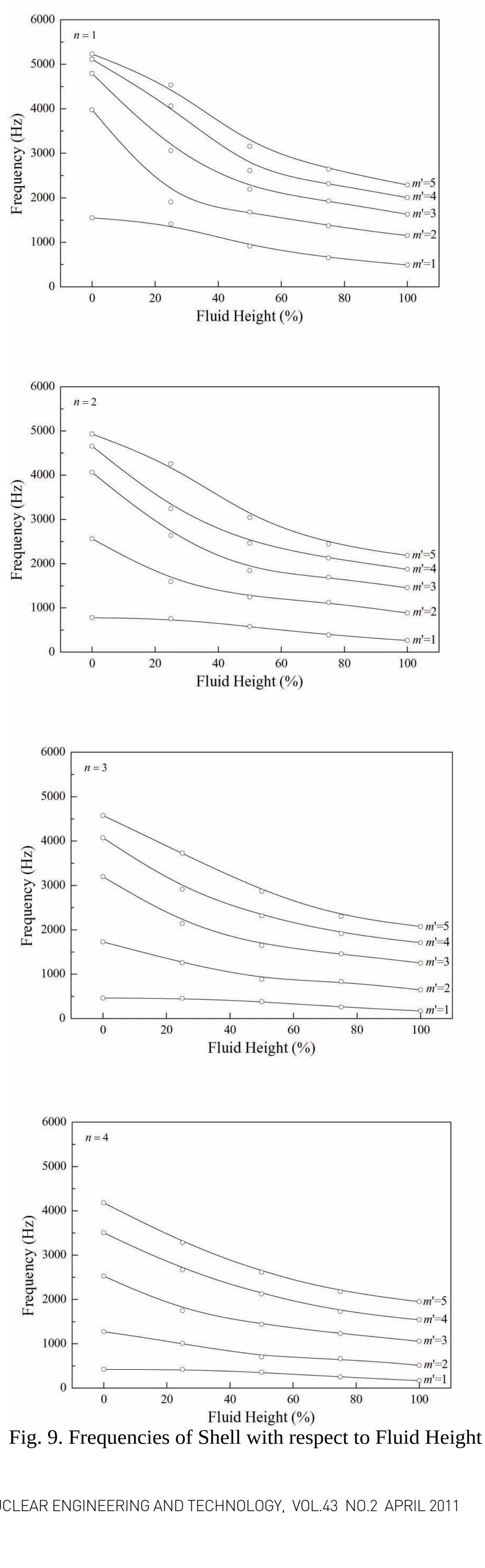

Fig. 9. Frequencies of Shell with respect to Fluid Height

decrease as the fluid height increases, due to the fluid effect. As the circumferential modes increase, the rate of diminishment of the frequency with respect to the fluid height becomes less significant. While the frequencies decrease significantly for the higher axial modes, the decline is negligible for the lower axial modes.

The effect of the presence of fluid on the frequencies can be assessed using the normalized frequency (defined as frequencies with fluid divided by frequencies without fluid), which ranges in value between one and zero due to the added mass effect of the fluid. Figure 10 shows the normalized natural frequencies of the shell with respect to the fluid height. As the fluid height increases, the frequencies are reduced more drastically due to the inclusion of the fluid. When the shell is only partially filled with fluid, the first axial mode is not significantly affected by the fluid inclusion. But when the shell is completely filled, the normalized frequencies greatly increase (as compared to shells without fluid) according to the increase of mode numbers. This result shows that lower circumferential and lower axial modes are more affected by the fluid. The normalized frequencies of each circumferential mode are shown in Fig. 11, with respect to the normalized fluid height. The rate of the frequencies decreases more significantly as the circumferential mode increases.

Figure 12 shows the maximum equivalent stress by response spectrum analyses. As the fluid height increases, the equivalent stress increases significantly, such that the fully filled fluid shell has ten times more equivalent stress than the shell without fluid. Comparing the frequencies of the shell and applying the response spectrum shows that all natural frequencies are higher than 100 Hz where the zero period acceleration of the spectrum is 0.2g. Therefore, the response spectrum analysis is not really necessary, and it may be conservative to perform the static analysis. To verify this procedure, static analysis with the applied force of 0.2g is performed and the same results are obtained.

Figure 13 depicts the free surface of the fluid, clearly showing the sloshing of the fluid inside of the shell. However, there is no indication of the fluid being scattered in all directions. The heaviest slopping of the fluid occurs when the shell is 50% full. The pressures which are acting on the inner surface of the shell, consisting of the hydrostatic pressure and momentum of the fluid, are shown in Fig. 14. The lack of an impact from the scattering of the fluid resulted in the appearance of hydrostatic pressure distributions. Figure 15 shows the equivalent stress distributions, which are larger in the lower part of the shell than in the upper part. As the fluid height increases, more stress is obtained, which duplicates the results of the response spectrum analysis.

Figure 16 shows the time history of the maximum equivalent stress, revealing that the trends of the maximum values are almost the same irrespective of the fluid height.

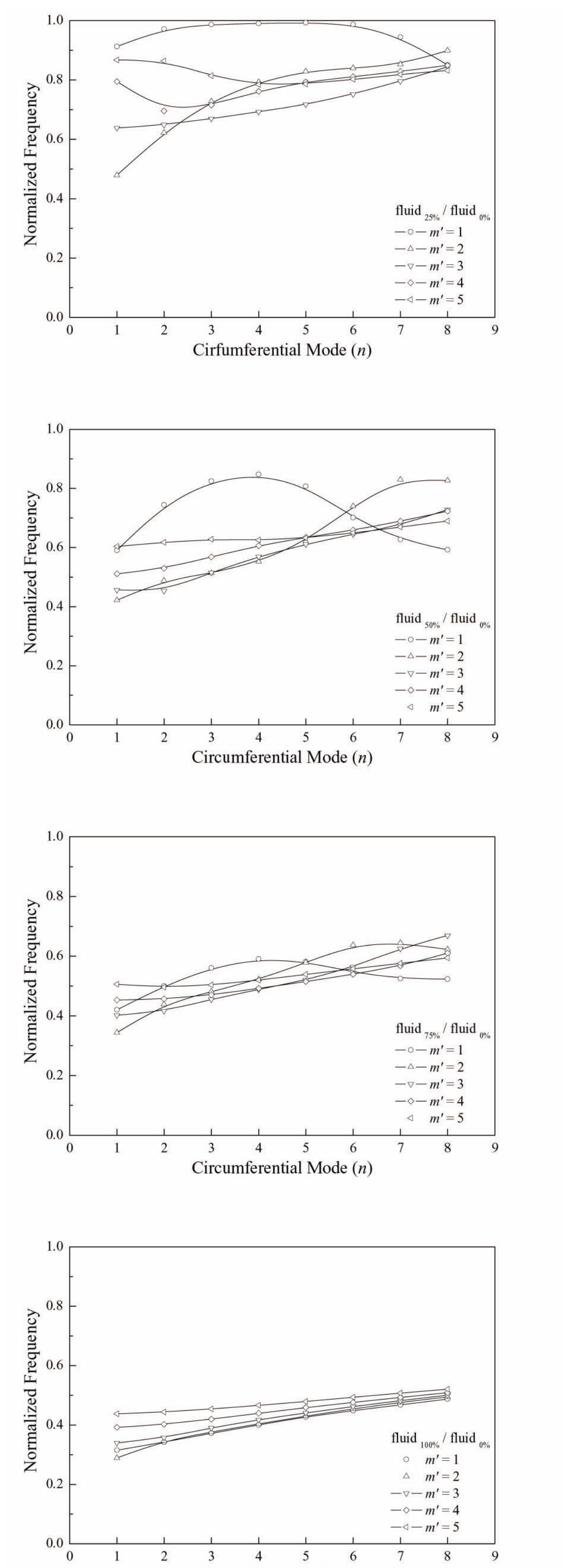

Fig. 10. Normalized Frequencies of Partially Fluid-filled Shell

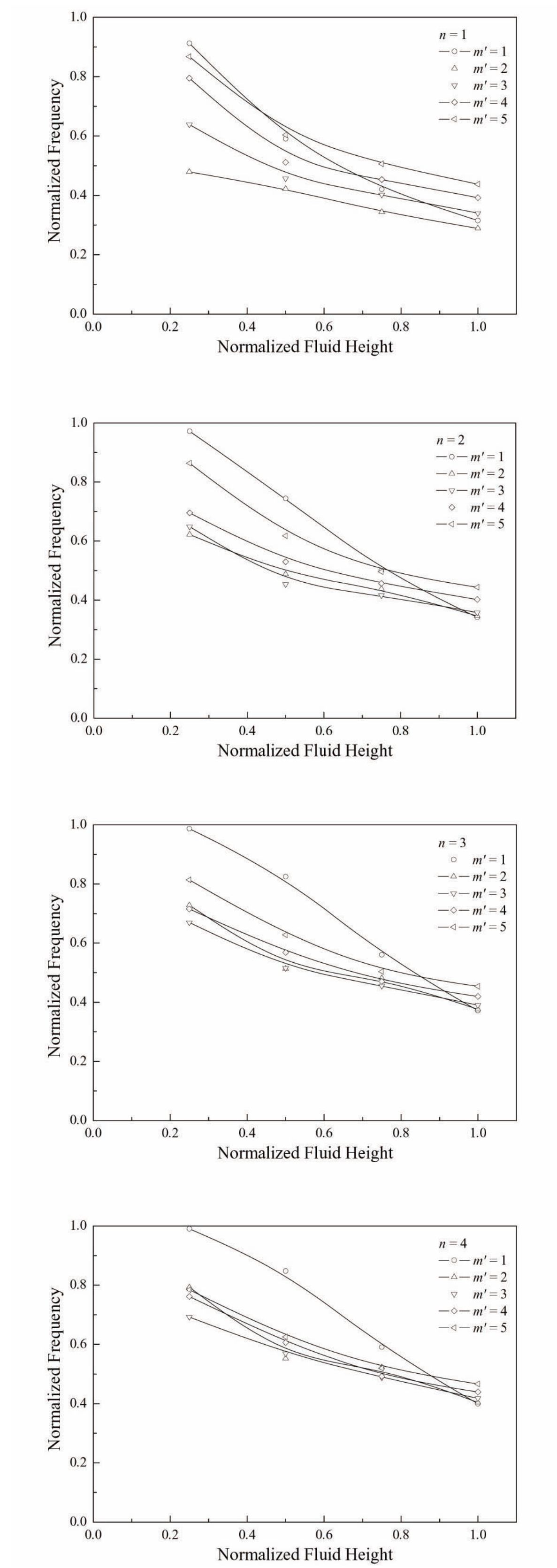

Fig. 11. Normalized Frequencies of Partially Fluid-filled Shell with respect to Fluid Height

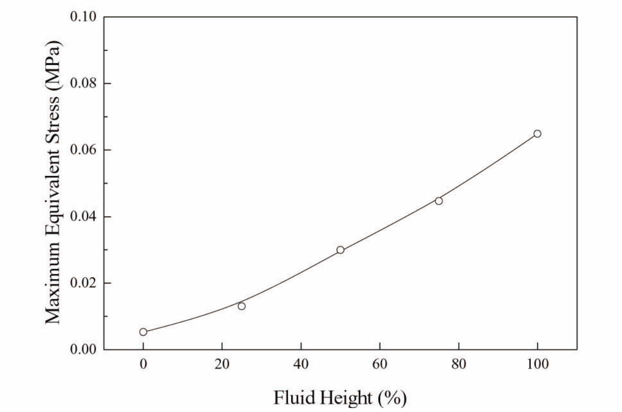

Fig. 12. Maximum Equivalent Stress Comparisons Among Fluid Heights

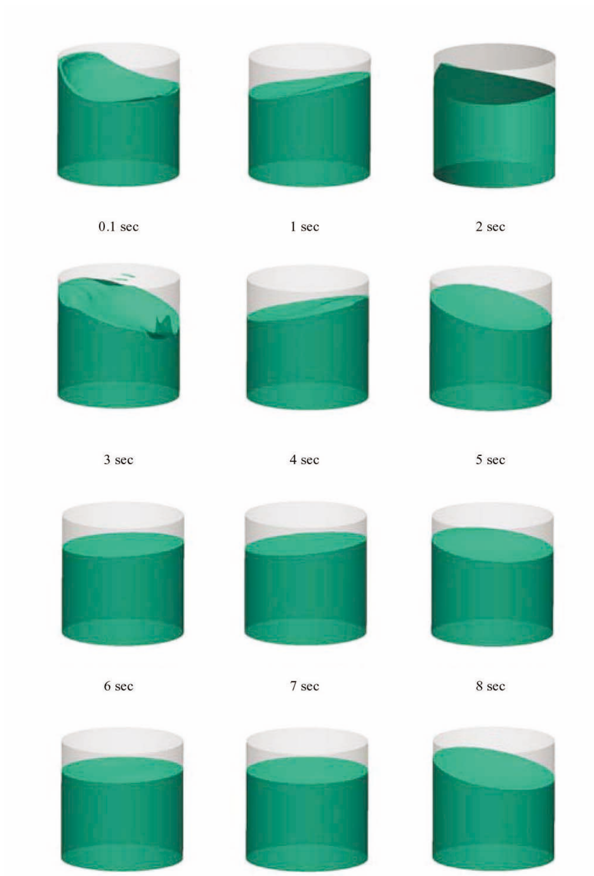

Fig. 13. Free Surface of Fluid with 75% Fluid-filled Shell

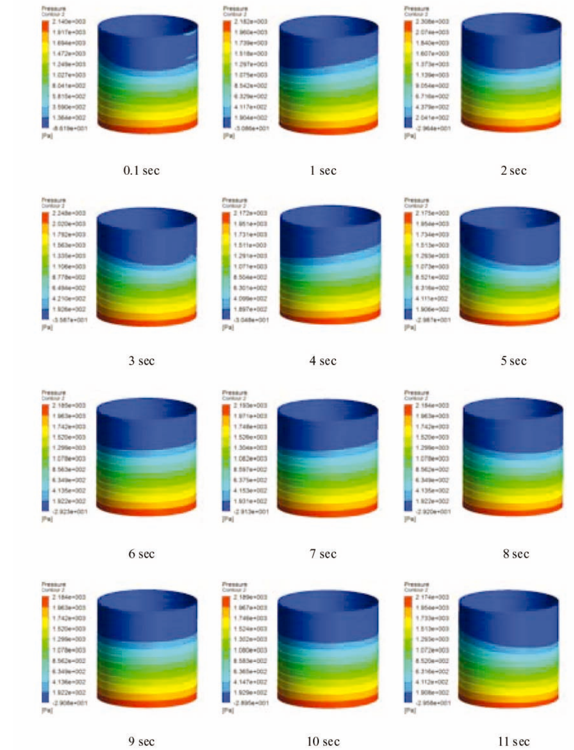

Fig. 14. Pressure On the Inner wall of 75% Fluid-filled Shell

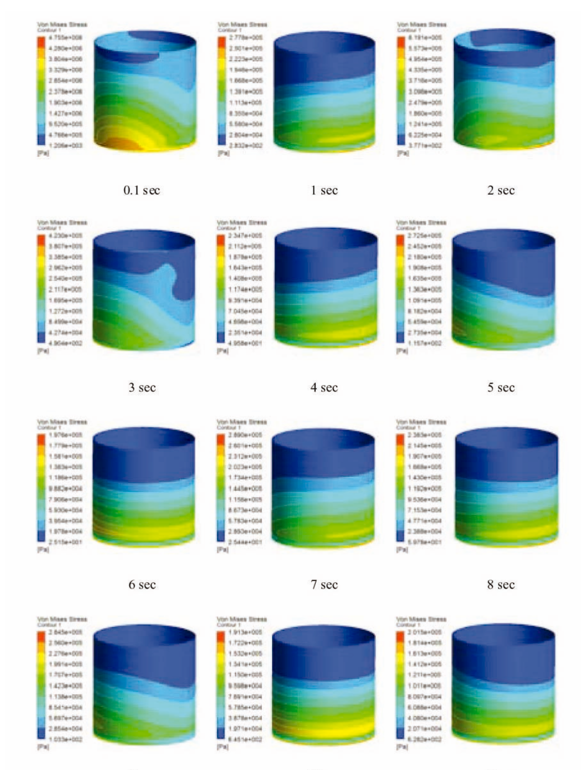

Fig. 15. Equivalent Stress of Shell with 75% Fluid-filled Shell

4. CONCLUSIONS

This study investigated how the presence of fluid in a cylindrical shell affects the vibration and response characteristics. As the fluid height increases the following observations are found:

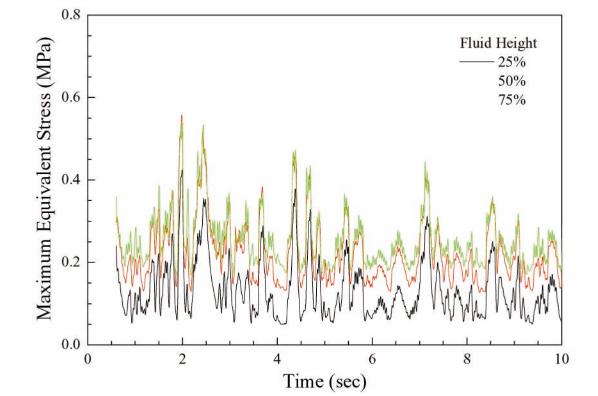

Fig. 16. Maximum Equivalence Stresses by Sloshing Analysis

- The frequency decreases as the axial mode number increases, and the rate of diminishment is more significant for the higher axial modes than the lower axial modes.
- The inclusion of fluid affects the lower circumferential modes more than the higher circumferential modes.
- As the fluid height increases, the equivalent stress increases significantly, such that the fully filled fluid shell has ten times more equivalent stress than the shell without fluid.
- The equivalent stress due to sloshing increases, even though the maximum fluid variation occurs in a shell that is 50% fluid-filled.

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