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Coupled sloshing studies in 500 MWe pressurized heavy water reactor calandria

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Abstract: In this paper coupled sloshing analysis of PHWR calandria in horizontal configuration is presented with shell and fluid elements. The coupled shell fluid model results in time domain are compared with frequency domain results. A method to simplify sloshing problem in complex tank geometry is evolved.

1. INTRODUCTION

In the event of design basis earthquake the structural integrity of safety related equipments and systems has to be proven to demonstrate the safe shutdown capability of a nuclear plant. Any simplified design and analysis method in common use must be supplemented with detail analysis to justify the assumptions made in modelling of these equipments which are subjected to hydrodynamic loads on account of sloshing and impulsive motion of liquid contained in it. In the present paper a novel modelling concept is evolved for hydrodynamic and seismic analysis of first generation of 500 MWe Pressurised Heavy Water Reactor(PHWR) calandria. The calandria shell in its horizontal core configuration is enclosed by two heavy end-shields which provide support for reactor fuel and coolant accessories along with necessary shielding outside the calandria vaul (Fig.1). The heavy water moderator inside the calandria induces hydrodynamic load on the calandria shell and two independent shutdown devices which are designed to shutdown the reactor immediately following a seismic event above a particular acceleration level.

The sloshing analysis of calandria is complicated due to its horizontal configuration, flexible diaphragm supports,non-flat bottom and multiple compartment geometry with shell and subshells of different sizes and cross-sectional curvatures. This necessitates evaluation of antisymmetric sloshing load along two principal shell axes in transverse and longitudinal directions. Due to small length to diameter ratio of calandria some fundamental shell multilobe modes may be important and classical formulae for evaluation of slosh mass, associated spring stiffness and impulsive mass is prohibitive as these are applicable for upright fixed base tanks in flexural mode.It is also desirable to study the effect of vertical moderator slug motion in symmetric modes and quantify the peak sloshing and impulsive pressures for the design of two independent shutdown devices in addition to the investigations related to moderator shell coupling and shell flexibility.

In the first part of the present work a three dimensional shell-fluid interaction coupled problem is studied on calandria-endshield shell and moderator fluid models with finite element code FLUSHELL developed by Singh(1990,1991a,1991b). It uses nine node degenerate shell elements and trilinear eight node fluid elements. The sloshing and impulsive moderator frequencies and calandria shell frequencies are obtained for transverse, longitudinal and vertical motion modes. The response of calandria shell, subshell, annulus plate and diaphragm supports are obtained in this analysis in time domain. This study is further used to evolve a simple mechanical model for calandria endshield assembly where the moderator fluid impulsive and sloshing masses and its stiffnesses are derived from the fluid model. This second model is further used to obtain the response in frequency domain. This two level modelling approach allows complex structural details to be included appropriately. The paper brings out some important conclusions about hydrodynamic and seismic modelling of safety related nuclear equipments.

2. MATHEMATICAL MODEL AND ANALYSIS

A simple mathematical model with shell elements of calandria(Fig.2) with 3-D moderator fluid model(90% level) is used for the analysis.It may be assumed that both the endshields always move together for all the three direction seismic motions. So all the channel masses with its contents are lumped on endshield tube sheets.The channels account for only 12% volume of moderator hence an equivalent homogeneous moderator density is used in the present model. The effects of heterogeneity due to the tubes on fluid response and calandria tube stiffness are planned to be studied separately. The calandria is deeply submerged in vault water so a portion of vault water mass is suitably added to calandria shell. The vault water sloshing is unlikely to influence the impulsive pressure on calandria on account of high submergence as shown by Singh(1987). The coupled equations of motion with implicit-implicit partitioning of shell and fluid meshes are solved in staggered fashion in time domain with code FLUSHEL. The Rayleigh damping parameters are α=0.2331E-01 and β=0.2888E-03 which give 1 to 2% damping in frequency range of interest. The acoustic speed in moderator is taken as 1433 m/sec. Analyses are carried out for transverse, longitudinal and vertical seismic motions for safe shutdown earthquake motions and peak responses are obtained.

3. RESULTS AND DISCUSSIONS

3.1 Time Domain Coupled Analysis

Table.1 summarises the results for all the three direction seismic motions obtained by flexible and rigid shell analyses with sloshing. It is noted that peak sloshing pressure(figs.3-4) for lateral motions builds almost near the end of the earthquake(36.52 sec for transverse and 32.04 sec for longitudinal motion) while peak impulsive pressure at the bottom portion of calandria is observed within the strong motion period of earthquake.In case of vertical motion the peak sloshing pressure occurs at 12.9 sec indicating that the sloshing motion effect is uniform and in higher symmetric modes very little mass is excited[Fig.5]. Comparison between flexible and rigid calandria shell results demonstrates that the effect of shell flexibility affects impulsive pressure for longitudinal direction only as calandria is very flexible in this direction due to diaphragm and annulus plate. As expected free surface sloshing motion is independent of shell flexibility on account of its low frequency components.Figs.6-7 show slosh pressure contours at free surface of calandria for two direction seismic motions at times which are close to their respective peak values. It is noted that in transverse direction first mode is significant while in longitudinal direction the peak pressure is at a location midway between main shell centre and annulus plate. This is due to interaction between mainshell and subshell compartments and reflection of free surface waves from annulus plates. In case of vertical motion the pressure distribution at free surface is found to be more uniform due to slug motion and higher symmetric modes contribution to slosh pressure is very small.

It is obvious that low frequency lateral sloshing phenomena takes time to build up and peaks are observed in the decaying portion of earthquake motion while the impulsive pressure peak (high frequency phenomena) is observed in the strong motion period of the earthquake. The vertical slosh pressure is smaller than lateral sloshing pressure and its frequency is very small due to the major contribution from slug motion(a rigid body phenomena).

It is seen from Table.1 that stresses are very small for transverse and vertical seismic motions of calandria. For longitudinal motion the annulus plate and diaphragm are very flexible so peak endshield tubesheet deflection of 8mm is noted at its centre. The bending stresses are also significant in annulus plate and diaphragm plate for this case.

TABLE.1 . SUMMARY OF COUPLED ANALYSIS RESULTS

	Transverse	Longitudinal	Vertical
Frequency(Hz)			
Sloshing	0.4619[0.438]	0.4401[0.475]	0.0
Impulsive	115.68[113.2]	137.39[113.2]	52.87[50.8]
Dry Calandria--1	39.41	6.245	37.5
1+Vault Water--2	14.70	6.222	14.75
2+Moderator----3	9.57	5.440	9.103[10.6]
Pressure (MPa)-Flexible			
Maximum Slosh	0.01349(36.3)	0.01489(32)	0.4023E-2(13)
Maximum Impulsive	0.01406(20.7)	0.01369(16.6)	0.01677(15)
Max. Deflection(mm)	0.2395	7.986	0.221
Pressure (MPa)-Rigid			
Maximum Slosh	0.01348(36.5)	0.01463(32)	0.3973E-2(13)
Maximum Impulsive	0.01481(20.7)	0.00697(16.6)	0.01549(15)
Max. Deflection(mm)	0.2386	11.78	0.1549
Max. Memb./Bend. Stress	(in MPa) - Flexible		
Main Shell	2.92/3.05	14.58/67.2	2.78/1.97
Sub Shell	2.65/5.01	16.05/67.52	1.76/2.23
Annulus Plate	3.71/5.46	7.59/148.99	2.26/2.96
Diaphragm	2.47/5.56	0.39/194.48	0.11/0.46
Max. Memb./Bend. Stress	(in MPa) -Rigid		
Main Shell	2.91/3.04	20.24/95.24	2.64/1.433
Sub Shell	2.58/4.98	22.40/98.96	1.70/2.13
Annulus Plate	3.62/5.43	10.6/216.71	2.17/2.63
Diaphragm	2.44/5.54	0.61/275.70	0.11/0.44

Note:Values within bracket are time in secs and values within square brackets are classical values or experimental values for a case close to calandria dimensions.

4.2 Frequency Domain Analysis

The calandria shell frequencies with dry calandria, empty calandria with vault water and calandria with vault water and moderator(90% level) are affected in transverse and vertical directions significantly due to added mass of fluid. In longitudinal direction small amount of vault water and moderator gets added to annulus plate and rest of the moderator mass is added to heavy endshield tube sheet thus the effective change in frequency is very small. The first frequency in these three cases are found to be with higher shell multilobe modes(7 to 8 lobes across the cross section) as shown in figs.8-10. Frequencies from both the analyses have been found to be in good agreement.

In order to study the effect of complex structural details such as effect of reactor channels it is necessary to simplify fluid model. In the first attempt as a validation step the moderator fluid was lumped on the shell model by calculating centre of pressure of sloshing moderator, slosh mass and stiffness numerically derived from earlier analysis for transverse motion. The shell frequency and maximum deflection obtained by this method is 9.7 Hz and 0.295mm respectively which are in good agreement with coupled analysis results reported in table.1. This approach is being studied in detail for all other direction seismic motions to perform the analysis and compare the results with coupled analysis results.

4. CONCLUSIONS

In this work two approaches are followed to evolve models for sloshing analysis in multicompartment horizontal configuration of calandria. The coupled time domain analysis by code FLUSHEL enables modelling of sloshing for all the three directions seismic motions. For complex geometry like calandria this study helps to get peak sloshing loads useful for design of shutdown devices and calandria shell. The uncertainties in the modelling of sloshing mass and coupling effects are also investigated. In transverse direction the first mode of calandria shows shell modes with 7 lobes however due to very small modal mass in this mode the simplified mechanical model in frequency domain gives results similar to time domain analysis results. In the frequency domain analysis more structural details can be suitably modelled for all the other directions. The two approaches of analysis are complementary to each other to get confidence in final results. Slosh pressures within first two critical seconds of reactor shutdown are very small hence functional and structural integrity of both shutdown devices is ensured for 500Mwe PHWR design.

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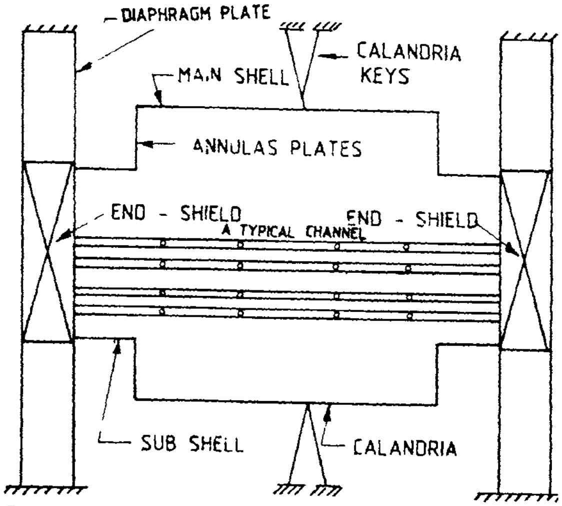


FIG. 1 SCHEMATIC DIAGRAM OF CALANDRIA-END SHELD ASSEMBLY

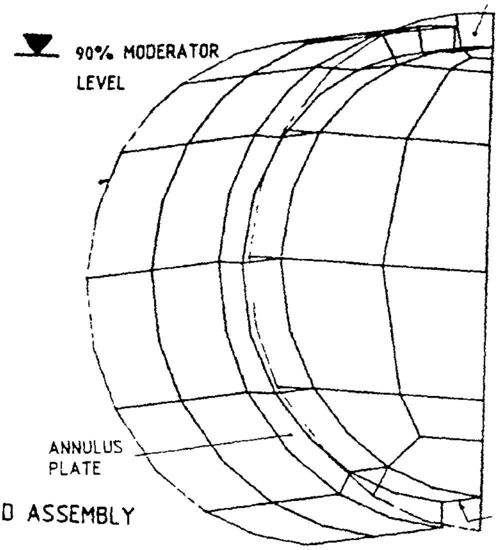


FIG. 2 500 MWe PHWR CALANDRIA SHELL MODEL FOR SLOSHING ANALYSIS

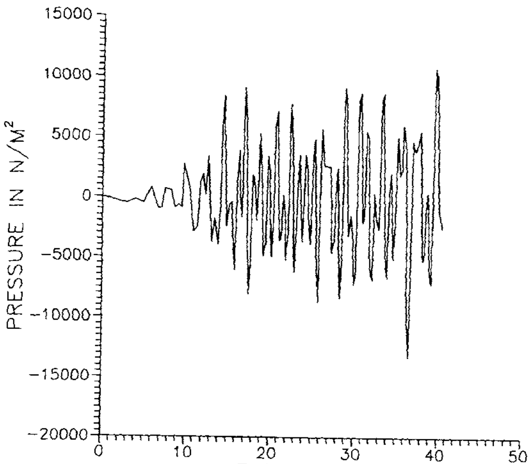


FIG.3 SLOSH PRESSURE IN TRANSVERSE MOTION

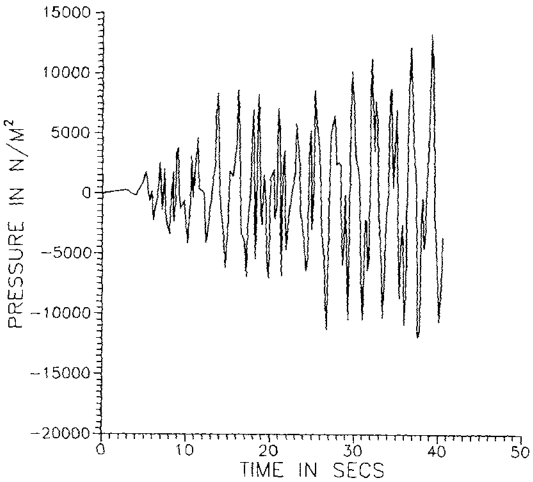


FIG.4 SLOSH PRESSURE IN LONGITUDINAL MOTIO

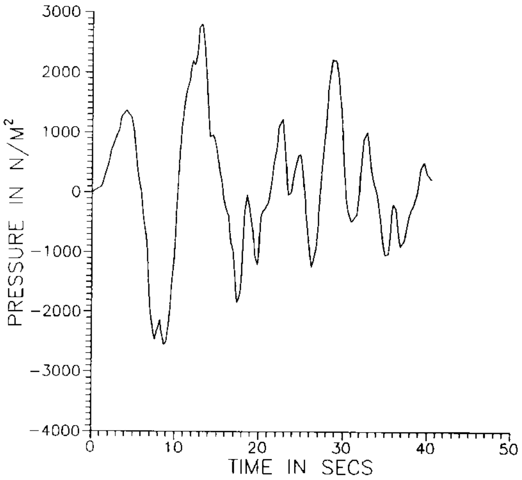
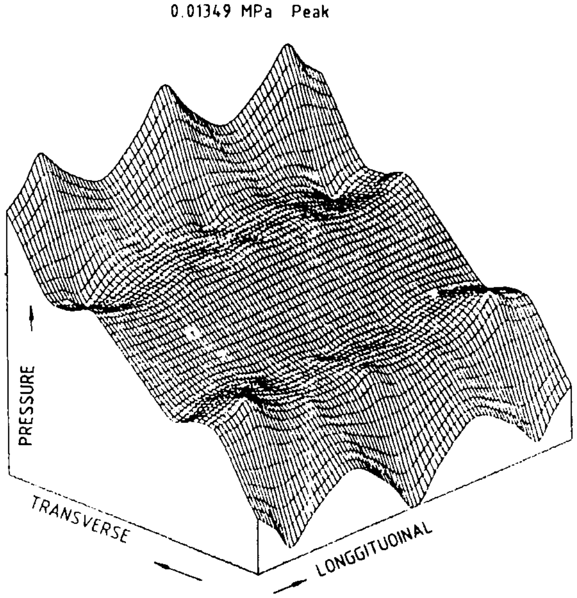


FIG.5 SLOSH PRESSURE IN VERTICAL MOTION



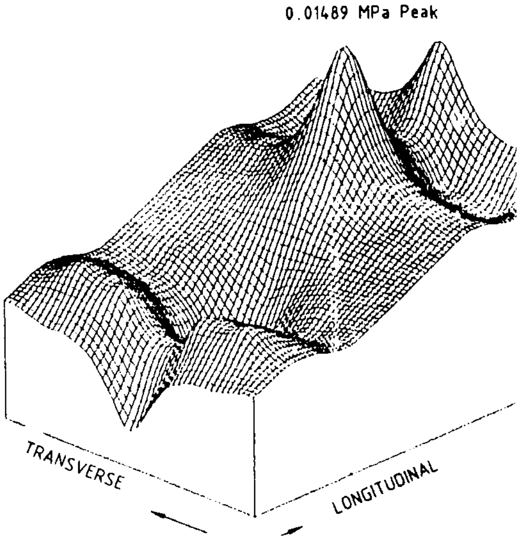
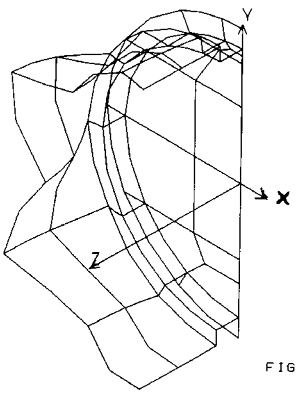
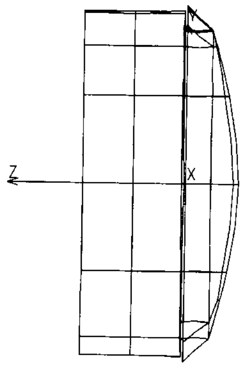


FIG. 7. SLOSH PRESSURE FOR LONGITUDINAL SEISMIC MOTION

FIG. 6. SLOSH PRESSURE FOR TRANSVERSE SEISMIC MOTION





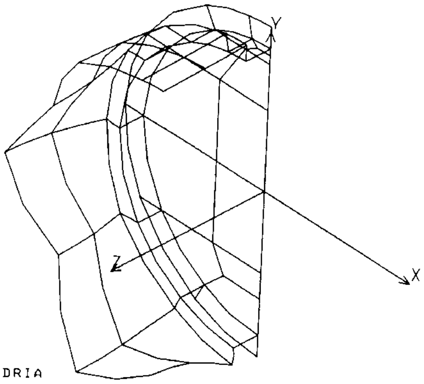


FIG.9 FIRST NATURAL MODE OF CALANDRIA IN LONGITUDINAL DIRECTION

FIG.8 FIRST NATURAL MODE OF CALANDRIA IN TRANSVERSE DIRECTION

FIG.10 FIRST NATURAL MODE OF CALANDRIA IN VERTICAL DIRECTION