Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

A Method for Including Fluid Structure Interaction in an ANSYS Response Spectrum Seismic Analysis

Steve C. Austin[1] and Huinam Rhee[2]

1) ABB Combustion Engineering Nuclear Power, USA
2) Korea Power Engineering Company, Korea

ABSTRACT

The seismic response of structures located inside a fluid filled vessel subject to transient base excitation is a complex problem. For problems where the interaction between the fluid and the structure requires the use of a fluid structure element, the ANSYS structural analysis computer code has a fluid structure element available. However, this element can only be used to perform unsymmetric or damped modal, harmonic and nonlinear transient analysis. For complex structures performing a nonlinear transient analysis is not practical.

For finite element linear analysis methods the addition of contained plus displaced water mass produces the correct response frequency. It does not include the fluid structure interaction effects that reduce the response amplitude. Its use therefore produces conservative results. It is the objective of the paper to demonstrate a method for calculating more accurate and less conservative results.

This paper presents a method developed by ABB and KOPEC for including the fluid structure interaction effects, while performing the seismic analysis, using response spectrum methods. The method consists of constructing a fluid structure interaction model and multiple structural only models. Each structural only model duplicates one mode from the fluid structure model. Using the results from unit harmonic analyses, factors are calculated for each result quantity for each mode. These factors allow the results from spectrum analyses using the structural models to be modified to include the fluid structure interaction effects. The result is a significantly less conservative analysis than if fluid structure interaction had not been considered.

INTRODUCTION

Previous seismic spectrum analyses of reactor vessel internals components had used additional lumped mass to model the effects of contained plus displaced water. This mass only representation produces very conservative results. A less conservative and more accurate method is to include the water effects using a fluid structure interaction (FSI) analysis. All structural analyses for the Korean Next Generation Reactor (KNGR) were to be performed using the ANSYS code. The ANSYS code has FSI capability. However, the FSI capability can not be used to perform a response spectrum analysis. As part of the first of a kind engineering effort for KNGR, a method was developed for including the fluid structure interaction effect while performing the seismic analysis using response spectrum methods.

The component used for developing the method was the KNGR Control Element Assembly (CEA) Shroud Assembly (IBA). This is a large cylindrical shaped assembly which is supported from and mounted inside of the Upper Guide Structure (UGS) barrel. The water in the annulus between the IBA and the UGS produces the fluid structure interaction effect.

MODELS

The IBA is a cylindrical shaped assembly, approximately 160 inches tall and 147 inches in diameter. It is supported from a circular flange near its top. Inside of the cylinder the IBA is divided into vertical cells by plates. It is mounted to and inside of the UGS barrel. The gap between the UGS barrel and the IBA cylinder is 1.125 inches. The water in this 1.125 inch annulus provides strong fluid structure coupling between the IBA and the UGS. The water trapped in the cells inside the IBA acts as additional mass only. The UGS barrel is considered rigid compared to the IBA assembly and is included only as a fixed boundary for the FSI elements. The IBA structure is modeled using plate (stiff63), solid (stiff45) beam (beam4) and lumped mass (mass21) elements. The fluid structure interaction uses fluid30 elements. A half symmetry model is used with the appropriate boundary conditions. The X direction is parallel to the plane of symmetry, the Y direction is perpendicular to the plane of symmetry and the Z direction is vertical. The excitation and response direction is X, parallel to the plane of symmetry. The model consists of over 7000 elements. Three models were used. A complete model including FSI elements used for FSI modal and harmonic analyses. Two models were used that did not included FSI elements. These models included additional lumped mass elements on the IBA barrel. One model would be tuned to represent the beam mode as determined by the FSI modal analysis. The other would be tuned to the shell mode. These mass21 elements allowed the addition of the tuned mass to act in the horizontal directions only.

ANALYSES

Modal Analysis

The ANSYS fluid30 element uses unsymmetric matrices. Therefore, the modal analysis for the FSI model used the ANSYS unsymmetric method option. In order to minimize differences due to selection of master degrees of freedom the subspace method was used for all analyses. The FSI results are summarized in Table 1. Based on the FSI results, modes 1 and 4 are the modes which will produce dynamic amplification for a X direction excitation. If an input spectrum has very large peaks above 33 HZ, which would be typical of loss of coolant accident (LOCA) spectra, this method could be extended to include higher modes using the same procedures used for modes 1 and 4. However, since modes above 33 HZ will be higher shell modes it is unlikely that they would be excited by uniform motion in the X direction. Therefore, use of modes 1 and 4 plus static missing mass to account for the higher modes is justified. The mass21 elements added to the IBA shell were adjusted until the frequency and mode shapes match the FSI modal results. The beam model is adjusted to match FSI mode 1 and the shell model is adjusted to match FSI mode 4. The corresponding modes for the beam and shell models are highlighted in Table 1.

Harmonic Analysis

The harmonic analyses were performed at the exact beam and shell frequencies for the FSI and non-FSI models. A 1G acceleration is applied parallel to the plane of symmetry. The real and imaginary solutions are combined in Post1 by square root of the sum of the squares (SRSS) to produce the harmonic result. The results are summarized in Tables 2, and 3. The columns labeled TOP, MID and BOT provide the maximum stress intensity at the element centroid at the top surface, mid plane and bottom surface. The TOP and BOT results are membrane plus bending while the MID result is membrane only. For the higher stressed parts of the model, the webs and tubes, the difference between membrane plus bending and membrane only is not significant. The column labeled NODAL provides the maximum stress intensity at the element nodal locations for membrane plus bending. The use of FSI provides a very large reduction in the stresses due to the beam response mode. Although the input frequencies for the harmonic analyses are set to the exact frequency of the mode of interest, the other modes of the model are still active. For the FSI model the X direction modes are well separated. For the Beam model mode 6 and 7 are close but the participation factor for mode 7, the desired beam mode, is significantly larger than for mode 6, a complex shell mode. For the Shell model mode 1, the desired shell mode, and mode 4 are fairly close with mode 4 having the larger participation factor. The mode shape of Shell model mode 4 matches the mode shape of FSI mode 7, which has a frequency of 33.67HZ. The possible effect of Shell model mode 4 on the calculated harmonic results was investigated and corrected by use of spectrum analyses.

Response Spectrum Analysis

The response spectrum results are used to confirm that the harmonic analyses are valid. They are also used to provide an example of how the method would be used for a production analysis and to give an estimate of the expected stresses in the IBA. Spectrum analyses were performed for the beam and shell modes using the Yonggwang (YGN) 3&4 and YGN 5 & 6 Reactor Vessel (RV) flange Operational Basis Earthquake (OBE) 2% spectrum

The spectrum analysis method allows for the result for each mode to be individually calculated, thus avoiding the problem of having more than one mode contributing to the result. The harmonic results were converted to match the response spectra results using amplification formula for harmonic excitation;

Output = Input/(2*Damping):

1 G harmonic produces 25 G response for 2% damping.

Comparing the converted harmonic results to the spectrum results, the Beam mode results show very good agreement, with the Nodal results being essentially identical. The Shell mode results indicate that the harmonic results are consistently greater than the spectrum results. This is most likely due to more than 1 mode contributing to the harmonic results, as discussed above. Since the FSI model does not have modes that are close together it is concluded that the FSI harmonic analyses can be used to predict the true response of the IBA due to response spectrum input.

The results show that the harmonic analysis for the Shell mode, and to a lesser extent for the Beam mode, over predict the result. Therefore, the ratios of harmonic results for FSI model to

Shell and Beam models have to be corrected. The beam correction factors were calculated as follows:

Beam correction factor = (Converted Beam Harmonic / Beam Spectrum)

÷

(Beam Harmonic / FSI Harmonic for Beam Mode)

Tables 4and 5 provide the final correction factors for the beam and shell modes.

Missing Mass Analysis

The missing mass is calculated by adding together the percent mass active in the Beam and Shell modes and subtracting from 1.0. The mass values reported for the FSI modal analysis are not correct due to the unsymmetric matrices, therefore the percent masses are taken from the Beam and Shell models. Since these models have more low frequency modes then the FSI model the percent mass active in any one mode would be lower. Therefore, the calculation of missing mass is conservative. The missing mass analysis was performed using a 1G unit acceleration in the direction parallel to the plane of symmetry. The calculated results are than scaled by the product of the percent missing mass and the zero period acceleration (ZPA) of the response spectra.

Combination of Results

The total result is formed by combining the three calculated results according to the equation:

$$\text{Total} = [(\text{ Beam mode result })^2 + (\text{ Shell mode result })^2 + (\text{missing mass result})^2]^{1/2.}$$

RESULTS

Tables 4 and 5 provide the calculated IBA factors to adjust seismic response spectra analyses results to account for FSI effects. Table 4 indicates that including fluid structure interaction causes a significant reduction in the beam mode response of the IBA. The shell mode response, Table 5, is less significantly affected. A seismic response spectrum analysis of the IBA would be performed in the following steps:

- Perform response spectrum analysis of IBA using Beam model with input spectra only at beam mode frequency
- Perform response spectrum analysis of IBA using Shell model with input spectra only at shell mode frequency
- Perform static acceleration analysis using "missing mass" times ZPA of response spectra.
- Correct Beam and Shell mode results by use of factors in Table 1
- Combine results by SRSS of Beam and Shell Modes and with results from static acceleration analysis

Sample Result

Tables 6 and 7 provide the total results using seismic response spectra calculated for YGN 3 & 4 and YGN 5 & 6. The tables also provide, for comparison, the stress as calculated using added mass only for the Korean Standard Plant design. The KNGR design and methodology provide a 68% reduction in maximum stress for YGN 5 & 6 and a 82% reduction for YGN 3 & 4.

TABLE 1

Modal Results

FSI MODEL				
		PARTICIPATION FACTORS		
MODE	FREQ (HZ)	X DIRECTION	Y DIRECTION	Z DIRECTION
1	15.32	-29.31	0.00	0.00
2	18.76	0.00	-10.06	-0.01
3	20.02	0.00	-47.25	0.05
4	21.93	6.80	0.00	0.00
5	26.23	0.00	-1.05	1.51
6	29.40	0.00	-6.39	0.22
7	33.67	-1.22	0.00	0.00
BEAM MODEL				
		PARTICIPATION FACTORS		
MODE	FREQ (HZ)	X DIRECTION	Y DIRECTION	Z DIRECTION
1	11.68	-0.74	0.00	0.00
2	12.53	0.00	-11.81	-0.05
3	12.92	0.00	16.31	-0.03
4	12.93	-14.33	0.00	0.00
5	14.15	0.00	-0.24	0.00
6	14.56	-13.17	0.00	0.00
7	15.34	35.98	0.00	0.00
8	16.61	0.00	1.73	-0.04
9	16.71	-3.61	0.00	0.00
10	18.17	0.00	1.67	-0.02
SHELL MODEL				
		PARTICIPATION FACTORS		
MODE	FREQ (HZ)	X DIRECTION	Y DIRECTION	Z DIRECTION
1	21.95	0.60	0.00	0.00
2	23.69	0.00	7.32	0.05
3	24.31	0.00	8.38	-0.01
4	24.33	-8.22	0.00	0.00
5	26.21	0.00	0.06	1.47
6	26.81	0.00	-0.23	-0.01
7	27.57	7.99	0.00	0.00
8	28.57	19.45	0.00	0.00
9	31.69	0.00	-0.79	0.13
10	31.78	-1.34	0.00	0.00

Table 2

IBA HARMONIC RESPONSE ANALYSIS

For Beam Mode

as Calculated for 1G Input, 2% Damping, Harmonic Analysis

	FSI				Mass on Barrel			
Result	TOP	MID	BOT	NODAL	TOP	MID	BOT	NODAL
.25 inch web	9915	9929	9915	12192	364110	366750	363950	484810
.5 inch web	7451	6568	7450	15027	260010	227420	260050	632690
.375 inch tubes	2642	2712	2641	14861	108210	90551	108110	463080
.75 inch barrel	7858	7608	7858	8176	187270	187470	187100	625950
flange	452			986	39380			166300
top flange	295			943	12263			32148
top plate	750	185	772	1861	41108	10123	41137	93311
fingers	30	3	30	86	490	39.57	491	2557
max. disp inch	0.0650				2.74			
freq HZ	15.32				15.34			
cal peak accel G	1.56				65.79			

Results for components are maximum stress intensities in PSI

Table 3

IBA HARMONIC RESPONSE ANALYSIS

For Shell Mode

as Calculated for 1G Input, 2% Damping, Harmonic Analysis

	FSI				Mass on Barrel			
Result	TOP	MID	BOT	NODAL	TOP	MID	BOT	NODAL
.25 inch web	3197	3222	3199	3857	8248	7981.7	7761	12746
.5 inch web	2346	2217	2347	4869	10112	9754.2	10224	24196
.375 inch tubes	1714	1164	1714	5205	4173	3676	4311	18559
.75 inch barrel	1684	1843	1683	4628	9082	9319.8	9728	19879
flange	164			310	2127			8796
top flange	88			206	621			1813
top plate	325	62	316	649	1674	528.47	2546	5116
fingers	29	2	29	58	39	4	39	169
max. disp inch	0.0268				0.11			
freq HZ	21.95				21.95			
cal peak accel G	1.32				5.46			

Results for components are maximum stress intensities in PSI

Table 4

Beam Mode Correction Factors

Result	TOP	MID	BOT	NODAL
.25 inch web	0.0272	0.0271	0.0272	0.0251
.5 inch web	0.0380	0.0291	0.0288	0.0238
.375 inch tubes	0.0244	0.0299	0.0244	0.0321
.75 inch barrel	0.0420	0.0409	0.0425	0.0131
flange	0.0115			0.0060
top flange	0.0244			0.0296
top plate	0.0248	0.0183	0.0188	0.0199
fingers	0.0622	0.0700	0.0624	0.0344
max. disp	0.0237			

Table 5

Shell Mode Correction Factors

Result	TOP	MID	BOT	NODAL
.25 inch web	1.1130	1.1020	1.0614	0.9628
.5 inch web	0.8985	0.8779	0.8488	0.7482
.375 inch tubes	0.7992	0.8057	0.7366	0.7978
.75 inch barrel	0.8256	1.0046	0.8640	0.7104
flange	0.3463			0.1453
top flange	1.0791			0.6970
top plate	0.7433	0.9218	0.6463	0.6590
fingers	7.6728	1.3504	7.6468	3.5694
max. disp	0.9432			

Table 6

IBA SEISMIC RESPONSE ANALYSIS
YGN OBE 2% Damping

Result	TOP	MID	BOT	NODAL
.25 inch web	984	967	966	1184
.5 inch web	719	634	719	1450
.375 inch tubes	271	265	259	1438
.75 inch barrel	799	732	756	814
flange	44			96
top flange	29			91
top plate	73	18	77	182
fingers	4	1	4	9
max. disp inch	0.0277			

CEA SHROUD ASSEMBLY
YGN 3&4 OBE 2% Damping

Result	Stress
CEA Tubes	8203
CEA Webs	3572
Tie Tube Web	5420
Tie Rod Tube	5335
Tie Rod	503
Ring Plate	2123
Ring Beam	3408
Snubber	3354

Results for components are maximum stress intensities in PSI

Table 7

IBA SEISMIC RESPONSE ANALYSIS
YGN 5&6 OBE 2% Damping

Result	TOP	MID	BOT	NODAL
.25 inch web	1277	1257	1254	1548
.5 inch web	941	822	935	1914
.375 inch tubes	363	343	346	1895
.75 inch barrel	1026	943	973	1060
flange	65			174
top flange	46			128
top plate	106	28	125	271
fingers	8	1	8	18
max. disp inch	0.0082			

CEA SHROUD ASSEMBLY
YGN 5&6 OBE 2% Damping

Result	Stress
Reg Webs	2437
Tie Webs	5926
Inner Tubes	5831
Peri Tubes	3116
Per Tie Tubes	1418
Tie Rod Holder	177
Ring Plate	3431
Snubber	1492
Tie Rods	111
Web/Tube Weld	3873

Results for components are maximum stress intensities in PSI