유체-구조물 상호작용을 고려한 실린더형 수중 구조물의 유한요소모델링 및 동적 응답 스펙트럼 해석

Finite Element Modelling of a Submerged Cylindrical Structure Considering Fluid-Structure Interaction Effect and Dynamic Response Spectrum Analysis

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요 지

유체-구조물 상호작용 효과를 고려하여, 실린더형 수중 구조물의 유한요소 모델을 상용 전산코드를 사용하여 작성하고 동적하중에 대한 응답해석을 수행하였다. 구조 유한요소에 부착되는 유체 유한요소로 인하여 발생하는 요소행렬의 비대칭성으로 인하여, 일반적으로 사용되는 유한요소 해석 전산코드로 유체-구조물 상호작용 모델에 대한 응답스펙트럼해석을 수행하는 것은 불가능하다. 이 문제의 해결을 위하여, 등가 비 유체-구조물 상호작용 모델을 구성하고, 등가 비 유체-구조물 상호작용 모델에 대한 응답스펙트럼 해석 및 조화가진 응답해석 결과를 이용하여 유체-구조물 상호작용 모델의 스펙트럼 가진에 대한 동적 응답을 계산할 수 있는 효율적인 방법을 제시하였다.

핵심용어 : 유체-구조물 상호작용, 수중구조물, 동적응답스펙트럼

Abstract

A finite element model of a submerged cylinderical shell structure is constructed considering fluid-structure interaction (FSI) effect using a commercially available finite element code. It is not possible to use the FSI model for response spectrum analysis due to the unsymmetric element matrix resulting from the attachment of fluid elements to structural elements. In this paper, an efficient procedure is proposed for the estimation of the response of the FSI model to response spectrum loadings using equivalent non-FSI models and harmonic response analysis results.

Keywords : *finite element model, fluid-structure interaction, modal analysis, natural frequency, mode shape, response spectrum analysis, harmonic analysis*

1. Introduction

Fig. 1 shows a submerged cylindrical structure which is to be modelled and analyzed in this paper. It has complicated internal substructures as shown in Fig. 1. The structure is located inside the PWR (pressurized water reactor) type reactor vessel. Its main function is to protect and guide the control rods of the nuclear reactor. This structure is subject to

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various static and dynamic loading conditions during normal operation and also during some possible accident conditions such as earthquakes. To maintain the safety of the reactor, the design of the structure should be verified to keep the structural integrity under expected loading conditions including dynamic loads such as seismic response spectrum and harmonic excitation loadings.

In this paper we want to construct a finite element model of the structure and perform response spectrum analysis especially for the horizontal direction. The entire structure is fully submerged in water. Therefore, the finite element model should properly represent not only the contained water inside, but the FSI (fluid-structure interaction) effect due to the water existing in the narrow gap between the outer barrel of the structure and another fixed cylindrical barrel outside. With the FSI modelling technique using acoustic fluid elements, the finite element model will automatically calculate the so-called annulus (or gap) effect[1] under the vibrational motion of the structure. If we neglect the annulus effect or do not account for it correctly, the calculated responses of the structure are usually fictitiously high and, therefore, result in very conservative and high cost design.

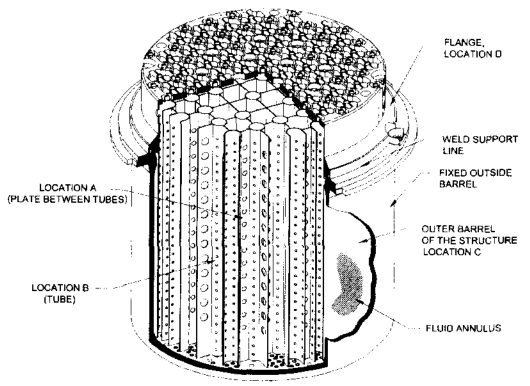


Fig. 1 Schematic of the structure to be analyzed

We use the commercially available ANSYS finite element code[2] to model and analyze the structure considering the annulus effect. However, due to the unsymmetric matrices caused by the fluid elements attached to the outer barrel, response spectrum analysis is not possible with the FSI model[2]. In order to overcome this problem, in this paper, we develop a methodology to estimate the responses to spectrum loadings utilizing the equivalent non-FSI model and harmonic response analysis results.

2. Finite Element Model and Modal Analysis

2.1 FSI(Fluid Structure Interaction) Model

Using the symmetry condition of the structure and applied loadings, just half of the structure is modelled in Fig. 2. The overall procedure for the structural modelling is so complicated and tedious because of the complex geometry of the structure, however, the modelling can be done by just a trivial practice. The appropriate boundary conditions should be assumed on the symmetry X-Z plane of the finite element model. We use mostly shell element (SHELL63

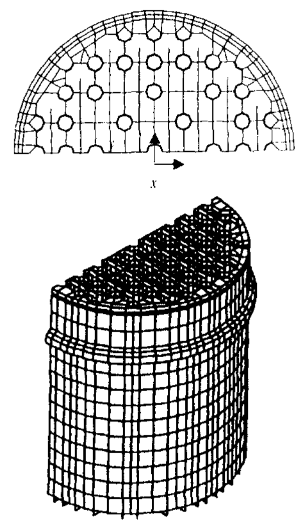


Fig. 2 Finite element model

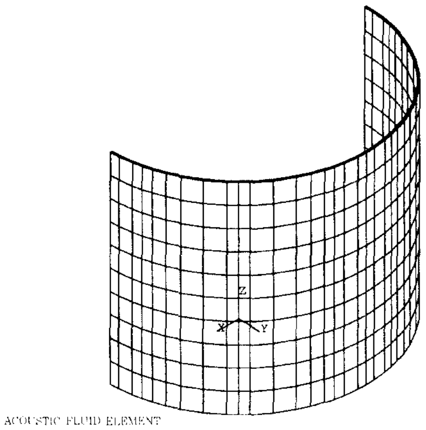


Fig. 3 Acoustic fluid elements

in ANSYS 5.5) except the flange, which is modelled as solid element (SOLID45). The structure is welded at the bottom surface of the flange to the support structure (ouside fixed barrel). Later for response analysis we excite the support structure by harmonic or spectrum loadings. The approximate radius and height of the structure are, respectively, 160cm and 400cm. The structure is made of stainless steel, which density is $5110 kg/m^3$. But, we need to use effective density of $9737 kg/m^3$ for SHELL63 elements accounting for the contained water (moving together with the structure) inside the structure.

The FSI model has three rows of acoustic fluid elements (FLUID30, See Fig. 3) attached to the outer barrel below the flange elevation. The outer row of the fluid elements is again in contact with the fixed outside barrel. The acoustic fluid elements have the following properties at the operating condition, 320℃ and 150 atm :

For the density ρ and bulk modulus ε of water,

Sonic velocity$=(\varepsilon/\rho)^{\frac{1}{2}}=1860$m/s.

The gap between the outer barrel and the fixed outside barrel is about 3cm, and filled with water.

2.2 Modal Analysis of the FSI model

The use of acoustic fluid elements that are in contact with shell elements results in unsymmetric element matrices. Therefore the modal analysis for the FSI model used the ANSYS unsymmetric method option[2]. The modal analysis is performed up to 33Hz modes because the seismic excitation spectrum value usually converges to the ZPA (zero period acceleration) above 33Hz[3),4)] : therefore, no amplification above 33Hz. The modal analysis result is summarized in Table 1. With the check of modal participation factors[5)], which are calculated as :

$$\gamma_i=\{\phi_i\}^T[M]\{D\} \tag{1}$$

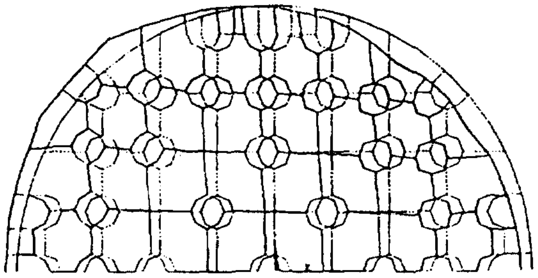
where

γ_i = i^{th} modal participation factor
$\{\phi_i\}$ = normalized eigenvector
$[M]$ = mass matrix
$\{D\}$ = unit vector describing excitation direction

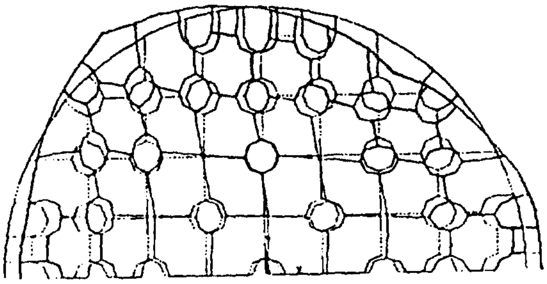
it is concluded that the Mode 1 and Mode 4 are governing. By looking at the corresponding mode shapes in Fig. 4 (more effectlvely using the animation function of the mode shapes in ANSYS) it is concluded that the Mode 1 and Mode 4 are respectively beam and shell modes.

Table 1 Modal analysis result (FSI model)

Mode	Freq(Hz)	X-direction Modal Part. Factor γ_i
1	15.32	-29.31
2	18.76	0.00
3	20.02	0.00
4	21.93	6.80
5	26.23	0.00
6	29.40	0.00
7	33.67	-1.22



a) Mode 1(15.3Hz) : beam mode



b) Mode 4(21.9Hz) : cos3θ shell mode

Fig. 4 Mode shapes of modes 1 and 4 of FSI model

Because of the unsymmetric element matrices the response spectrum analysis of the FSI model can not be performed[2]. Therefore, we need to develop an alternative methodology to estimate the responses of the FSI model to the response spectrum loadings such as seismic excitation.

First we develop equivalent finite element models which do not have unsymmetric matrices. Therefore, the equivalent model can not use the acoustic fluid elements. To keep the modal dynamic characteristics of the FSI model while the equivalent model do not use acoustic fluid elements, we add structural mass elements (MASS21 in ANSYS 5.5) to the outer barrel of the structure, instead of using acoustic fluid elements. Increasing the density of the shell elements representing the outer barrel may also be an another possibility, but mass elements have an advantage because we can specify the active directions (only horizontal) of masses. This is because the fluid annulus effect does not exist in the vertical motion of the structure. However, using the structural mass elements it is not feasible to construct the fully equivalent model so that it has completely identical dynamic characteristics to the original FSI model.

2.3 Non-FSI Model

2.3.1 Non-FSI Beam Model

By adjusting the magnitude of the added masses we can construct an equivalent model, which posseses the dynamic characteristics of the Mode 1 (Beam mode) of the FSI model, hereafter called as non-FSI Beam model. Modal analysis of the non-FSI Beam model was carried out and the result is summarized in Table 2. Mode 7 of the non-FSI Beam model is matching with the Mode 1 of the FSI model. This judgement is based on the comparison of the natural frequencies (Tables 1 and 2) and mode shapes.

2.3.2 Non-FSI Shell Model

Using similar procedure we can construct the non-FSI Shell model. This model has the dynamic characteristics of the Mode 4 (Shell mode) of the FSI model. Modal analysis of the non-FSI Shell model was performed and the

Table 2 Modal analysis result(non-FSI beam model)

Mode	Freq(Hz)	X-direction Modal Part. Factor γ_i
1	11.68	-0.74
2	12.53	0.0
3	12.92	0.0
4	12.93	-14.33
5	14.15	0.0
6	14.56	-13.17
7	15.34	35.98
8	16.61	0.0
9	16.71	-3.61
10	18.17	0.0

Table 3 Modal analysis result(non-FSI shell model)

Mode	Freq(Hz)	X-direction Modal Part. Factor γ_i
1	21.95	0.60
2	23.69	0.00
3	24.31	0.00
4	24.33	-8.22
5	26.21	0.00
6	26.81	0.00
7	27.57	7.99
8	28.57	19.45
9	31.69	0.00
10	31.78	-1.34

result is summarized in Table 3. Mode 1 of the non-FSI Shell model is matching with Mode 4 of the FSI model. This judgement is also ensured by comparing the natural frequencies (Tables 1 and 3) and the corresponding mode shapes.

3. Harmonic Response Analysis

The harmonic response analyses are performed at the exact beam and shell frequencies for both FSI and non-FSI models. A 1 g acceleration is applied parallel to the plane of symmetry. The SRSS (square root of the sum of squares) of real (in-phase) and imagination (out-of-phase) solutions in ANSYS produce the actual harmonic responses. The results are summarized in Tables 4 and 5 for the stress intensity values at the element nodal locations for membrane and bending for various sub-components : here called just as location *A*, *B*, *C* and *D* for a convenience *D* (Fig. 1).

In Tables 4 and 5 we can see that the use of FSI model 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 modes are well separated as can be seen in Table 1.

For the non-FSI Beam model, Modes 6 and 7 are close but the modal participation factor for Mode 7, the desired beam mode, is significantly larger than mode 6, a complex shell mode (Fig. 5).

By comparing the mode shapes, the non-FSI Shell model Mode 4 (Fig. 6) matches the Mode 7 of the FSI model, which has a frequency of 33.67Hz. The possible effect of the non-FSI Shell model Mode 4 on the calculated harmonic analysis results was investigated and corrected by the use of spectrum analysis in section 4.

Table 4 Harmonic response analysis for beam mode

Location	FSI Model Stress Intensity(psi)	Non-FSI Beam Model(masses on outer barrel) Stress Intensity(psi)	Ratio (Non-FSI/FSI)
A	12,192	484,810	39.76
B	14,861	463,080	31.16
C	8176	625,950	76.56
D	986	166,300	168.63

Table 5 Harmonic response analysis for shell mode

Location	FSI Model Stress Intensity(psi)	Non-FSI Shell Model(masses on outer barrel) Stress Intensity(psi)	Ratio (Non-FSI/FSI)
A	3,857	12,746	3.31
B	5,205	18,559	3.57
C	4,628	19,879	4.30
D	310	8796	28.38

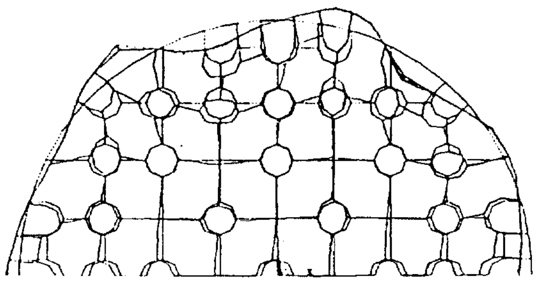


Fig. 5 Mode shape of mode 6(14.6Hz) of non-FSI beam model

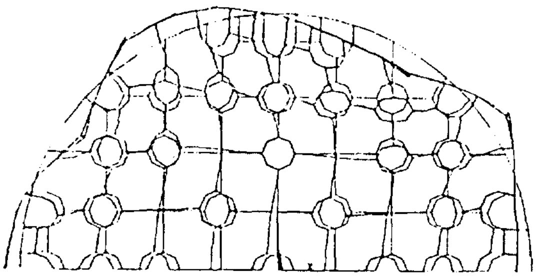


Fig. 6 Mode shapes of mode 4 (24.3Hz) of non-FSI shell model

4. Response Spectrum Analysis

The response spectrum analysis results for the non-FSI models are used to confirm that the harmonic analyses are valid. They are also used to provide an example of how the method is used for a design analysis and to give an estimate of the expected stresses of the real structures, whch has a narrow water annulus, to a real seismic spectrum loading.

Spectrum analyses were performed for the non-FSI Beam and Shell models using an example of a seismic floor response spectrum (Fig. 7). Two computer runs were made using 2% critical damping : Run 1) non-FSI Beam model using 2.4g spectrum value at 15.3Hz, Run 2) non-FSI Shell model using 0.73g spectrum value at 21.9Hz. The spectrum analysis method allows for the result for each mode to be individually calculated, thus avoiding the problem having more than one mode contributing to the result.

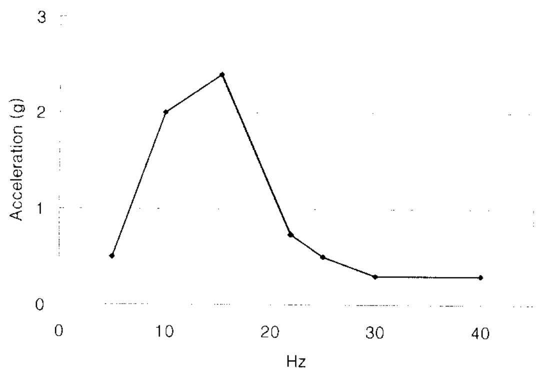


Fig. 7 A Sample response spectrum curve

Table 6 Response spectrum analysis of non-FSI model

Location	Stress Intensity(psi) For Beam Mode (2.4g at 15.3Hz)	Stress Intensity(psi) For Shell Mode (0.73g at 21.9Hz)
A	46,871	117
B	44,547	190
C	61,452	190
D	15,897	62

Table 6 provides the response spectrum results for the beam and shell modes.

Next, the harmonic results in section 3 were converted to match the response spectrum results :

1) 1g harmonic loading produces 25g response for 2% damping.
2) Beam mode response should be 2.4g, therefore, beam factor=2.4/25=0.096.
3) Shell mode response should be 0.73g, therefore, shell factor=0.73/25=0.0292.

Table 7 provides the results of multiplying the beam and shell harmonic analysis results in Tables 4 and 5 by the above factors and then dividing by the spectrum analysis results in Table 6.

The beam mode results in Table 7 show very good agreement with almost 1.0. The shell mode results in Table 7 indicate that the harmonic

Table 7 Ratios of factored harmonic/spectrum results for non-FSI models

Location	Beam Model	Shell Model
A	0.993	3.182
B	0.998	2.845
C	0.978	3.052
D	1.004	4.123

analysis results are consistently greater than the spectrum analysis results. This is most likely due to more than one vibration mode contributing to the harmonic analysis results as discussed in section 3. Since the FSI model does not have modes that are close together, it is concluded that the FSI model harmonic analyses can be used to predict the true response of the structure due to response spectrum loadings. This can be done by calculation of correction factors for the beam and shell modes in the following section.

5. Correction Factors

If the results in Table 7 were all 1.0, then the correction factors would be the reciprocal of the values in Tables 4 and 5. However, the results in Table 7 show that the harmonic analysis for the Shell mode, and to a lesser extent for the Beam mode, overpredict the result.

Therefore, the reciprocal ratio of harmonic results for FSI and non-FSI models have to be corrected. The correction factors are calculated as follows :

Beam correction factor=
Table 7 value/Ratio value in Table 4 (2a)

Shell correction factor=
Table 7 value/Ratio in Table 5 (2b)

However, for conservatism the larger of either 1.0 or the Table 7 value may be used in the calculation of the correction factor. Table 8 provides the correction factors calculated by Eq. (2) and Table 9 provides the corrected beam and shell mode results.

Table 8 Correction factors

Location	Beam Mode	Shell Mode
A	0.0251	0.9628
B	0.0321	0.7482
C	0.0131	0.7104
D	0.0060	0.1453

Table 9 Corrected response spectrum analysis results

Location	Beam Mode(psi)	Shell Mode(psi)
A	1179	113
B	1430	152
C	803	135

6. Missing Mass Analysis

In the previous sections we dealt with only two vibration modes through the entire frequency range. The remaining modal mass (missing mass) which is not related to the two modes are still existing in the structure, but not contributing to any dynamic amplification in the structural response to the given response spectrum loading. The missing mass undergoes only rigid body motion to the ZPA value of the response spectrum.

The missing mass is calculated by adding together the percent mass active in the beam and shell modes and subtracting from 1.0. The missing mass analysis was performed using a 1g unit acceleration in the direction parallel to the plane of symmetry. The calculated results are then scaled by the product of the percent missing mass and the ZPA value of the response spectrum. In the present case the percent missing mass is 0.434 (43.4%) as ANSYS calculates, and the ZPA is 0.4 g. Table 10 provides the missing mass results. As we will see in the next

Table 10 Missing mass results

Location	Stress Intensity(psi)
A	216
B	299
C	104
D	94

section, the missing mass contributes less than only 20% to the total response.

7. Total Response and Results/Discussion

The total response of the structure to the response spectrum loading can be formed by combining the three calculated results according to the SRSS equation[6] :

$$\text{Total response} = [(\text{Beam mode result})^2 + (\text{Shell mode result})^2 + (\text{Missing mass result})^2]^{1/2} \quad (3)$$

We can see that Mode 1 (beam mode) of the FSI model is the governing mode in the response. Table 11 provides the total result calculated by Eq.(3).

The correction factors developed in this paper are valid as long as the dynamic characteristics of the structure remain the same. In the case of different dynamic characteristics, new correction factors can easily be derived via the same procedure explained in this paper. The correction factors are independent of the spectrum loadings.

For other type of dynamic loading, e.g., random vibration excitation described as PSD (power spectral density)[7),8)], we can also develop the similar procedure. Either, the response of the structure to the PSD loading can be obtaind by converting the PSD to equivalent response spectrum loading, and then applying the correction factors presented in this paper.

Table 11 Total seismic response spectrum analysis results

Location	Stress Intensity(psi)
A	1204
B	1469
C	821
D	134

8. Conclusion

A finite element model of a submerged cylinderical shell structure is constructed considering fluid-structure interaction (FSI) effect via a commercially available ANSYS finite element code. The FSI model need to be used for the response spectrum as well as harmonic excitation analyses. However, due to the unsymmetry of acoustic fluid elements in the fluid-structure contact area, it is not possible to use the FSI model directly for response spectrum analysis. In this paper, an efficient procedure is proposed for the estimation of the response spectrum analysis result of the FSI model by using harmonic response analyses for the FSI and the equivalent non-FSI models combining with response spectrum analysis results for the equivalent non-FSI models.

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