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Dynamic Characteristics of the Integral Reactor SMART

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Abstract

In this study, a dynamic analysis of the integral reactor SMART (System-integrated Modular Advanced ReacTor) under postulated seismic events is performed to review the response characteristics of the major components. To enhance the feasibility of an analysis model, a detailed finite element model is synchronized with the products of concurrent design activities. *The artificial time history, which has been applied to the seismic analysis for the Korean* Standard Nuclear Power Plant (KSNP), is chosen to envelop broad site specifics in Korea. Responses in the horizontal direction are found slightly amplified, while those in the vertical direction are suppressed. Since amplified response is monitored at the control element drive mechanism (CEDM), minor design provision is considered to enhance the integrity of the subsystem.

Key Words : SMART, dynamic analysis, integral reactor, equivalent model, lumped mass system

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has been developing an integral reactor which is called SMART (System-integrated Modular Advanced ReacTor). SMART is a relatively small-sized advanced integral PWR that produces 330 MWt of thermal energy under full power operating conditions. The current design stage of SMART is laid on the beginning of the basic design by verifying fundamental concepts and provisions for typical safety issues. SMART is devised to be a typical co-generation plant providing electricity and energy for seawater desalination. Since the shortage of fresh water due to environmental contamination and anomalous weather is expected in many local regions including the Korean peninsular, the introduction of small to medium sized co-generation plants has been considered as a practical solution in many countries [1, 2, 3].

The prominent design feature of SMART is the adoption of an integral arrangement. All the primary components such as steam generators

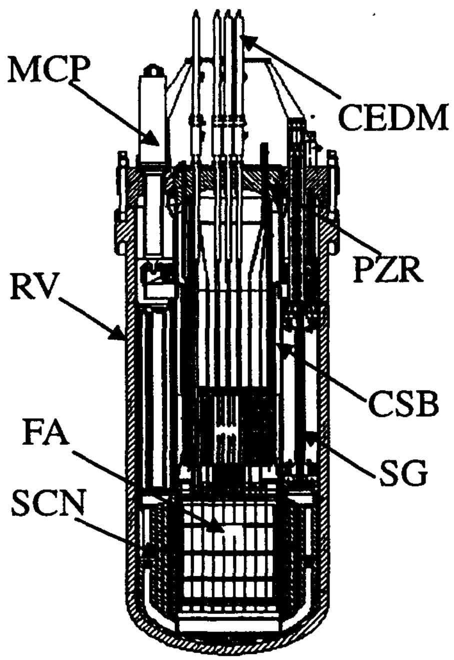

Fig. 1. Arrangement of SMART

(SGs), main coolant pumps (MCPs), and pressurizer (PZR) are assembled in a single reactor pressure vessel (RPV). Fig. 1 shows the typical configuration of SMART [4]. Twelve helically coiled, once-through type steam generator cassettes are located at the circumferential periphery between the core support barrel and RPV [5]. The reactor coolant, forced by four main coolant pumps (MCPs) installed vertically at the top of the RPV, flows upward through the core and enters into the shell side of the SG from the top of the SG. The secondary feedwater comes in the helically coiled tube side from the bottom of the SG, and flows upward to remove the heat from the shell side and then exits the SG in the superheated steam condition. The large volume in the top part of the RPV is used as a self-pressurizer. The primary system pressure is automatically controlled by steam and gas pressures that vary correspondently to the change of the core exit temperature. Surgelines connecting inside and outside of the pressurizer are also installed inside the vessel.

Since the general arrangement of SMART is totally different from that of a typical loop type plant, there exist many differences in the design concept and corresponding structural analyses. While overall arrangement of the reactor coolant system (RCS) could be quite simplified by elimination of the primary piping systems, the layout within the pressure vessel becomes very sophisticated. As the only single pressure boundary is devised to encompass all the primary components, the global behavior of the system shall be highly dependent upon the mutual interactions caused by each component. Design basis dynamic events such as seismic events and sudden failure of piping are considered during the design process of a reactor. In case of SMART, without the primary piping systems, seismic events are believed to govern the dynamic loads.

To investigate the dynamic characteristics of the reactor, a series of dynamic analyses shall be performed to get a better understanding at each design stage. Since the RCS is a very complicated structure having a huge number of dynamic degrees of freedom, the introduction of an effective modeling method to simulate the representative behavior of the system is essential for the structural analysis. A commonly referred method is to build an equivalent model matching the representative characteristics of the RCS using beam elements [6, 7, 8]. This method has been developed under the assumption that the representative behavior of the major components is close to a beam and believed to derive conservative results. While this method provides advantages to control the number of degrees of freedom and to reduce analysis effort, the probability of uncertainty caused by a lack of close simulation is still expected.

In this study, an effective modeling method to enhance the validity of the equivalent model for SMART is proposed. The equivalent beam model is constructed by referring to the results of detailed analyses of the major components. The mass system preserving the representative behavior of the major components is then developed to minimize the uncertainties in the model. The response characteristics of SMART under a seismic event are studied using the developed model. The artificial time history that was applied to the seismic analysis for the Korean Standard Nuclear Power Plant (KSNP) is chosen as an input motion. The responses of the major components are then evaluated and the resulting characteristics are discussed.

2. Method of Analysis

2.1. Assumptions

To construct an equivalent beam model for SMART dynamic analysis, the following assumptions are introduced.

1) Global beam mode vibration governs the dynamic behavior of the reactor vessel during external dynamic events, and a beam element could simulate the representative behavior of the major components.
2) The impact of small openings on components is neglected. Attachments or structures, which are irrelevant to the stiffness of the reactor, are considered as a lumped mass.
3) To afford conservatism in component loads, all the analyses are performed in the elastic range by neglecting potential non-linearities.

2.2. Development of the Equivalent Model

Since all the major components of SMART are located in the RPV, the pressure vessel shall govern the global dynamic characteristics. Though the pressure vessel is believed to control global motion, the weight of the pressure vessel is less than 50 % of the total weight as shown in Table 1. Therefore, the interaction between the pressure vessel and other components shall influence the motion of the pressure vessel in return.

A typical equivalent model can be simply defined by translating the section properties to beam

Table 1. Weight of the Major Components

Component	Weight (kg)
RPV	250,800
SG	89,400
CSB	47,700
Side Screen	82,300
FA	22,000
MCP	14,800
CEDM	24,600
Coolant	40,900
PZR	28,800
Total	601,300

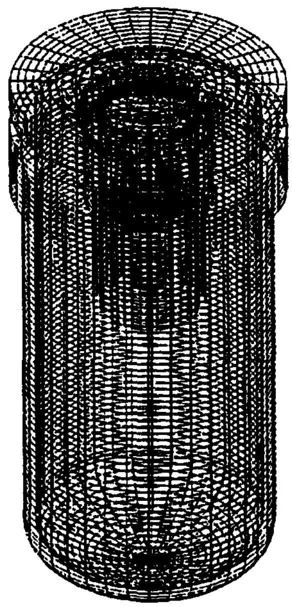

Fig. 2. Finite Element Model of RPV & PZR

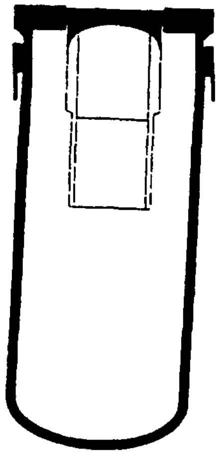

Fig. 3. First Mode Shape of RPV (Mode 1, 2 in Table 2)

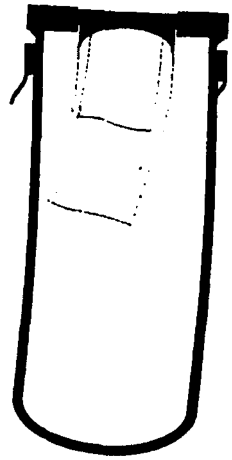

Fig. 5. Second Mode Shape of RPV (Mode 6, 7 in Table 2)

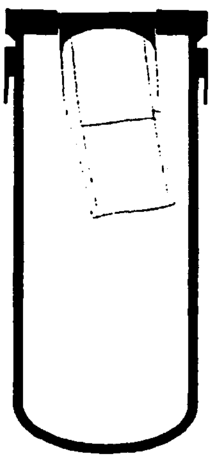

Fig. 4. First Mode Shape of PZR (Mode 3, 4 in Table 2)

Table 2. Results of Detailed Analysis for RPV & PZR

Mode	Frequency (Hz)	Participation Factor			Remark
		X	Y	Z	
1	29.160	0.219	0.000	0.262	RPV (X, Z)
2	29.160	0.262	0.000	0.219	RPV (X, Z)
3	52.737	0.027	0.000	0.004	PZR (X, Z)
4	52.737	0.004	0.000	0.027	PZR (X, Z)
5	68.039	0.000	0.002	0.000	
6	79.781	0.288	0.000	0.184	RPV (X, Z)
7	79.781	0.184	0.000	0.288	RPV (X, Z)
8	102.433	0.000	0.871	0.000	RPV (Y)
9	118.903	0.000	0.001	0.000	
10	138.596	0.001	0.000	0.001	
11	138.596	0.001	0.000	0.001	

elements with proper lengths. This method is convenient to build a model while it may not fully simulate the characteristics of the structures in certain cases. A more preferable method is to construct the equivalent model matching the principal characteristics of the reference structure, for example, the fundamental frequencies. In this study, a detailed finite element analysis on the RPV and PZR is preceded to provide the target frequencies in the equivalent model. Since a detailed analysis provides sufficient information to be kept in the equivalent model, it is possible to minimize the uncertainties in the subsequent modeling process.

The reactor pressure vessel is modeled with solid elements. The PZR consists of shell elements after considering its thickness. Fig. 2 depicts the finite element model of the pressure vessel and PZR.

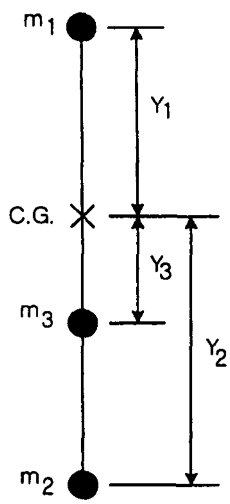

Fig. 6. Determination of Mass Points for RPV

Finite element modeling and analyses are performed using IDEAS MS 7.0 [9] on an HP workstation. Table 2 lists the resultant frequencies and corresponding modal participation factors. Figs. 3 through 5 display the major mode shapes, which support that the dominant modes in the horizontal direction resemble the typical beam modes. Two dominant frequencies (29 & 79 Hz) are maintained for the pressure vessel model after reviewing the results of the modal participation and mode shapes, and one mode is considered for the PZR (52 Hz).

If the same section properties are referred to build an equivalent model, the compatibility of the model might be dominated by the assumed mass model. The results of a detailed analysis suggest to keep the two modes for the reactor vessel and one for the PZR. Three mass points are considered on the pressure vessel since a three mass point system enhances the compatibility of the trial model in conserving the system properties. In the case of the PZR, two trial mass points are reserved to catch up the single frequency. Fig.6 and Eqs. (1) through (3) show the method to determine the

Table 3. Results of the Equivalent Model

Direction	RPV (Hz)	PZR (Hz)
X, Z	32.2(111.0% of 29.2)	52.7(100.0% of 52.7)
	86.6(110.9% of 79.8)	
Y	117.8(111.5% of 102.4)	-

location and magnitude of the three mass points based on the total mass and moment of inertia [8].

$$m_1 + m_2 + m_3 = M \quad (1)$$

$$m_1 Y_1 + m_2 Y_2 + m_3 Y_3 = 0, \; at \; C.G. \quad (2)$$

$$m_1 Y_1^2 + m_2 Y_2^2 + m_3 Y_3^2 = I_c \quad (3)$$

Where, M is the total mass of the system and I_c represents the mass moment of inertia of the system about the center of gravity. Thus, the total mass, global location of the center of gravity and the mass moment of inertia shall be maintained in the equivalent model. To define the exact location of the mass points using the previous equations, a series of iterative runs should be performed for each trial set.

At first, the pressure vessel is divided into several sections, and the mass information of the each section is gathered to define the mass properties of the upper part (m_1, Y_1), middle part (m_3, Y_3) and lower part (m_2, Y_2). Then the magnitude and location of the upper section (m_1, Y_1) and the location of the lower mass (Y_2) are set as the initial trial values. The remaining information of the initial mass system (m_2, m_3, Y_3) could be determined by Eqs. (1) through (3) . If the trial set fails to meet the target frequencies, the magnitude of m_2 is updated using the ratio of the current frequency to the target one. Thus a revised set is redefined until a reasonable set comes out. In case of PZR Eq. (3) is not applicable because only two mass points are reserved. Table 3 lists the results of the final run. The resulting frequencies of the reactor vessel are

Table 4. Target Frequencies of MCP & CEDM

Component	Target Frequency (Hz)
FA	2.25
MCP	49.14
CEDM	10.94

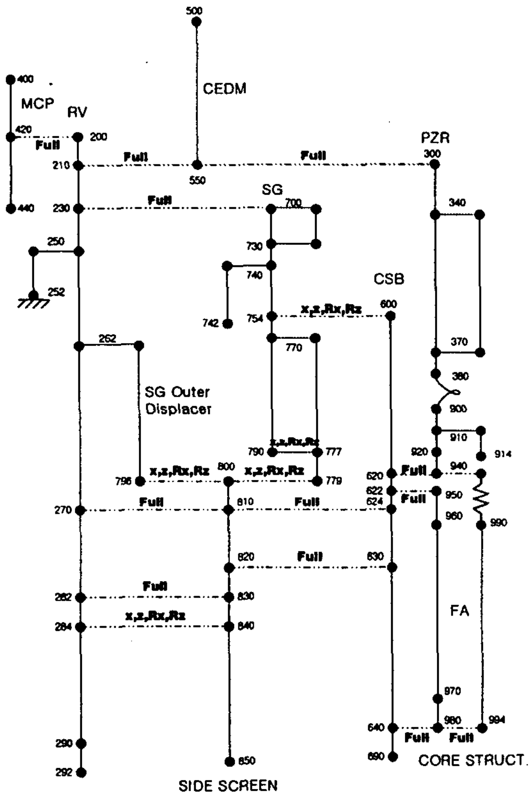

Fig. 7. Equivalent Model of SMART

maintained within a 10 % deviation in all directions in comparison with the target frequencies, and the exact frequency is obtained for the PZR. Iterative adjustment of the material properties of the vessel could minimize the deviation, though the current results are acceptable at this design stage.

The equivalent models representing other

Table 5. Modal Analysis Result of the Equivalent Model

Frequency (Hz)	Modal Participation (%)		Remark
	Horizontal	Vertical	
2.25	2.9	-	FA
10.92	4.2	-	CEDM
20.40	55.5	-	RPV
33.09	-	6.1	FA
46.80	11.9	-	MCP
51.85	3.3	-	Internals
58.87	2.2	-	PZR
61.31	-	26.7	SG
69.08	-	16.3	Internals
82.17	-	34.4	RPV
82.25	13.7	-	RPV

components are also built and coupled with the reactor vessel and PZR model. All the components except CEDM, MCP, and fuel assemblies (FAs) are directly converted to beams or pipe elements with a discrete mass system. MCP(4), CEDM(49) and FAs(57) consist of bundle of components distributed in a symmetrical pattern. In general, it is not simple to analogize a batch of components to a single structure without modification of the mass properties. A common method is to adjust the material property of the structure such as the elastic modulus. Detailed analysis using a discrete mass system of one single component is performed to define the target frequencies. Table 4 reports the target frequencies of each component. The equivalent models representing MCP and CEDM are developed and then coupled to the reactor vessel and PZR model with their target frequencies. The target frequency of the FA is tuned after assembling all the individual models because the motion of the FA is confined by the peripheral structures. Fig. 7 shows the equivalent model of the SMART reactor vessel assembly. All the modal analyses are done using ABAQUS Version 5.8 [10] on an HP workstation.

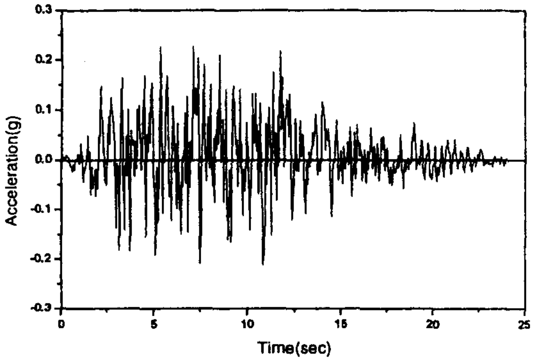

Fig. 8. Time History for NS (X) Direction

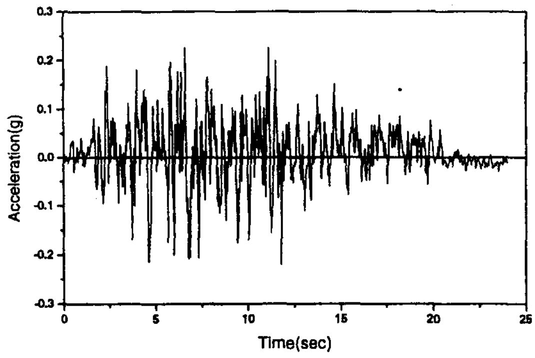

Fig. 10. Time History for EW (Z) Direction

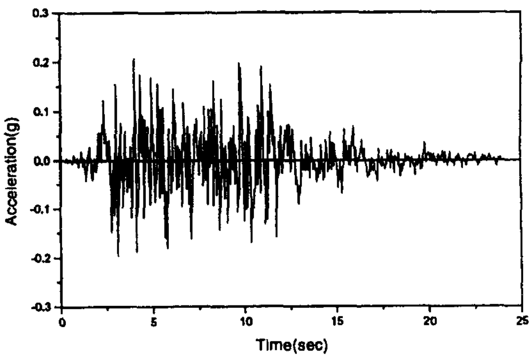

Fig. 9. Time History for Vertical (Y) Direction

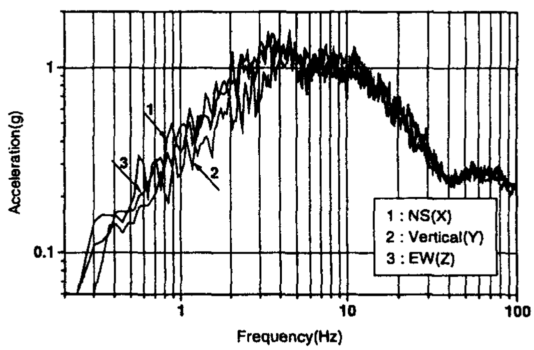

Fig. 11. Response Spectra of Input Time History (1 % damping)

2.3. Seismic Analysis

Seismic input to the RCS depends upon many factors including the geology of the construction site and the design of the containment building structure. Coupling of the containment building with the RCS is preferred to consider the interaction between the two structures. Since SMART is in the basic design stage, specific information on the construction site and containment building is not established yet. In general, the building structure derives responses in the lower frequency range. Table 5 indicates that the major frequencies appear at higher than 10 Hz. Normally, the transferred motion through the building has a minor influence upon the major RCS components with relatively higher frequencies. The impact of the building structure in the low frequency band could then be excluded from the global response for design purposes. In this regard, a seismic analysis without the building structure is acceptable to preview the response characteristics of the major components. The analysis model is shown in Fig. 7 and the dominant frequencies are listed in Table 5. The input motion is directly applied at the bottom of the support skirt, which is denoted as node 252 in Fig. 7.

The acceleration time history applied to the typical Korean Standard Nuclear Power Plant

Table 6. Response Acceleration of the Major Components

Location	X (g)	Y (g)	Z (g)
Top of RPV	0.23	0.22	0.26
Bottom of RPV	1.40	0.30	0.92
Top of MCP	0.78	0.23	0.57
Top of CEDM	3.41	0.23	4.35
Top of SG/CSB	0.55	0.29	0.38
Bottom of PZR	0.66	0.28	0.52
Top of side screen	0.92	0.28	0.62

Table 7. Amplification Factors

Location	X	Y	Z
Top of RPV	1.0	1.1	1.1
Bottom of RPV	6.2	1.4	4.1
Top of MCP	3.8	1.1	2.5
Top of CEDM	15.0	1.1	19.2
Top of SG/CSB	2.4	1.4	1.7
Bottom of PZR	2.9	1.3	2.3
Top of side screen	4.1	1.4	2.7

(KSNP), enveloping a wide range of site specifics in Korea, is adopted as the seismic input for SMART at this time. The time history is compatible with the requirements of the US NRC regulatory guide 1.60 [11] and SRP 3.7.1 [12]. The peak ground acceleration for the SSE, i.e., the zero period acceleration, is designed to be 0.2g in the horizontal direction. The time history of a 0.005 second sampling time and a 25 second duration is available. Figs. 8 through 10 show the input time histories, and Fig. 11 indicates the corresponding response spectra of the input motion in all directions.

The dynamic analyses are performed using the mode superposition method in the linear range. The integration time step (ITS) is defined as 0.0025 seconds and damping is not applied. The number of modes considered in the dynamic analysis is limited to 30 modes because more than a 90 % modal participation is gathered within 30 modes during the eigenvalue analysis. All the analyses are done by ABAQUS Version 5.8 on an HP workstation.

3. Results and Discussion

3.1. The Equivalent Model

Table 5 summarizes the natural frequencies and modal participation of SMART for the major components. The frequency of the FA is maintained as shown in Table 4 because it is tuned up through the coupled model. For the MCP and CEDM, only a minor variation is monitored in the coupled model (see Table 4). This result reveals that the stiffness of the mating elevation, which is the top of the reactor pressure vessel, is rigid enough to provide a fixed boundary condition.

The first mode of the reactor vessel in the horizontal direction moves to 20 Hz from 32 Hz due to the mass of non-structural parts, while minor deviation is monitored on the second mode. The frequency of the PZR slightly increases to 59 Hz from 53 Hz. The main reason for this shift comes from the increased stiffness due to the coupled components. In the vertical direction, the fundamental mode of the reactor vessel moves to 82 Hz from 118 Hz.

3.2. Seismic Analysis

Tables 6 and 7 compare the peak values in acceleration and the corresponding amplification factors upon the major components. In the horizontal direction, relatively high responses are monitored at the top of the CEDM and bottom of the reactor vessel, while only a small amplification is found in the vertical direction. This trend seems to be related to the natural frequencies of the major components. The dominant natural frequencies of the RPV and CEDM in the horizontal direction are found around 20 Hz and

Table 8. Relative Displacement of Components

Unit: mm

Location	Horiz.	Vert.
Top of RPV	0.003	0.001
Bottom of RPV	0.112	0.002
Top of MCP	0.018	0.001
Top of CEDM	1.289	0.002
Top of SG/CSB	0.017	0.001
Bottom of PZR	0.043	0.001
Top of side screen	0.070	0.001

11 Hz, respectively. Since the response spectra of the input has a plateau of acceleration between the frequencies of 2 Hz to 20 Hz as shown in Fig. 11, the modes within this range can be easily excited. Although MCP has higher participation than CEDM as shown in Table 5, relatively small amplification is monitored compared with the CEDM. Table 5 indicates that all the vertical modes appear above 33 Hz except FA. Therefore, the suppressed responses in the vertical direction are quite reasonable. The amplification factors of internal structures such as PZR, SG and core support barrel (CSB) are also believed to be reasonable compared to the response of the RV. Thus, any significant anomalies forcing the design modification of internal structures from the viewpoint of response characteristics is not expected. Table 8 lists the maximum relative displacement occurring on each component location. Though the maximum displacement occurring at the top of the CEDM is less than 2 mm in the horizontal direction, the high ratio compared to the displacement at the bottom of the RV suggests the possibility of an excessive response.

Figs. 12 and 13 show the response spectra obtained at the major components. In the horizontal direction, the response of the CEDM shows a peak around its fundamental frequency, and a relatively high level of acceleration is maintained above 30 Hz. The response of the MCP shows a reasonable level of acceleration up to 100 Hz except the typical peaks caused by resonant frequencies. Because various kinds of equipment and subsystems are attached on the CEDM, appropriate design modification is planned to moderate the response of the CEDM and guarantee the integrity of the structure. A separate support structure restraining the motion of the CEDM is under consideration.

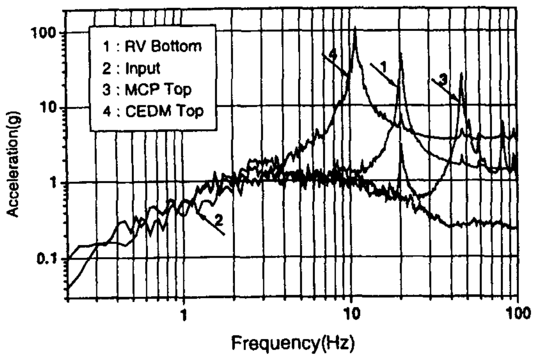

Fig. 12. Response Spectra for NS (X) Direction (1 % damping)

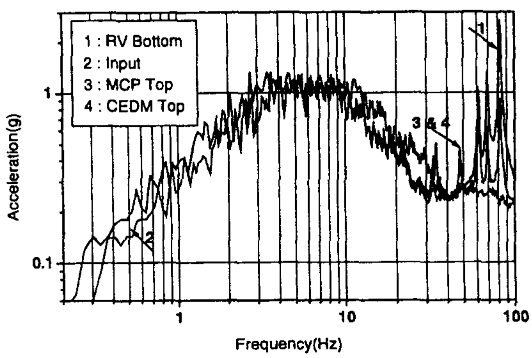

Fig. 13. Response Spectra for Vertical Direction (1 % damping)

4. Conclusions

The equivalent beam model for a dynamic

analysis of SMART is developed through iterative runs, and a dynamic analysis under seismic events is carried out. The mass system, which consists of three lumped masses, is applied to simulate the dominant modes of the pressure vessel, and less than 10% deviation from the reference frequencies validates the adequacy of the current modeling method. The equivalent model shows that the fundamental frequency of the SMART resides around 20 Hz in the horizontal direction. In case of the MCP and CEDM model, minor deviations are monitored between the individual model and coupled model.

Although amplified responses are locally monitored in the horizontal direction, the response acceleration and amplification factors support that the global response characteristics of the major components are reasonable. The proper design modification to enhance the integrity of the subsystems on the CEDM is raised because a high level of acceleration is monitored at the CEDM. In the vertical direction, the suppressed responses are delivered due to higher system frequencies.

Acknowledgment

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