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Characteristics of Dynamic Behavior for Integral Reactor SMART

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Abstract

Dynamic characteristics of an advanced integral reactor, the SMART (System-integrated Modular Advanced ReacTor), were investigated using an equivalent beam model. An effective lumped mass model to preserve the dynamic behavior of the reactor vessel is presented. The equivalent beam model for the dynamic analysis was developed through iterative runs. The results show that the fundamental frequency of the SMART is around 20Hz in the horizontal direction.

1. Introduction

Korea Atomic Energy Research Institute (KAERI) is currently developing an advanced integral reactor, the SMART (System-integrated Modular Advanced ReacTor)[1][2][3]. The power of the SMART is designed as 330MWt for supplying the energy for seawater desalination as well as for electricity generation. The important design concept of the SMART is to integrate whole major components into a single pressure vessel, as shown in Fig.1. Since the steam generators (SG) and pressurizer (PZR) are designed as in-vessel type components, the piping systems connecting SG and PZR could be removed. In this regard, the general arrangement of the nuclear steam supply system (NSSS) could be simplified in comparison with loop type. Fig.1 shows the typical arrangement of the SMART.

Total 12 cassettes of once-through type steam generators using helically coiled tubes are installed around core support structure, i.e., inside the vessel [4]. The PZR resides in the top space of the pressure vessel building a common pressure boundary, and surge lines are also installed in the vessel. Four main circulation pumps (MCP) circulate the coolant to support the heat exchange through each SG. Since the primary piping system is removed, the postulated dynamic events due to the break of the primary piping systems can be eliminated. In general, the configuration of the reactor vessel support system should be devised upon the consideration of thermal expansion and a dynamic event caused by the external source during normal operation. In loop type plants, the reactor vessel support structure is designed to release the thermal expansion and dynamic load simultaneously. Since only small bore lines except steam and feed water lines are applied to the SMART, the design concept of the reactor support system mainly aims to keep the integrity of the reactor under external dynamic loads. The SMART is designed to be supported by a skirt structure.

Many cases of scheduled dynamic events such as seismic events or sudden failure of piping systems are considered during the design process of a reactor. Therefore, the control of dynamic characteristics, such as natural frequencies or sizing of major components, is crucial to keep the validity of the design under dynamic loads. To investigate the dynamic characteristics of a reactor, a series of dynamic analyses are required to get better understandings at each design stage. Since the NSSS is a very complicated structure having a huge number of dynamic degree of freedoms to analyze, the common method is to use an equivalent model matching the representative characteristics[5][6]. One of the popular methods is to build a beam model having equivalent section properties with minimum mass points. This method has been developed under the assumption that the representative behavior of major components is close to a beam and believed to introduce conservative results for dynamic responses. Since a beam element may not fully simulate the general characteristics of a structure, uncertainties caused by the lack of close simulation are expected. Therefore, it is important to develop a modeling method to minimize uncertainties during the construction of an equivalent model.

In this study, an effective modeling method to enhance the validity of an equivalent beam model for the SMART is proposed. To constitute an accurate equivalent model, a detailed finite element model is prepared to define the dynamic characteristics of pressure vessel and PZR. A proper lumped mass system representing the behavior of the pressure vessel and PZR is determined after reviewing the results of the detailed analysis. The equivalent models representing the control element drive mechanism (CEDM), MCP, and fuel assemblies (FA) are developed individually using a detailed model and coupled with the reactor vessel and PZR model. Other components are directly converted to beams or pipe elements with a discrete mass system.

2. Method of Analysis

2.1 Basic Assumptions

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

1) Since global beam mode vibration may govern the dynamic behavior of a reactor vessel during external dynamic events, a beam element could simulate the representative behavior of all major components.

2) The impact of small openings on the stiffness of a component is neglected. Attachments or

structures, which are irrelevant to the stiffness of the reactor, are considered as lumped masses.
3) Although the reactor coolant may shift down the natural frequencies of internal structures due to the fluid-structure interaction effect, the coupling effect on the reactor vessel is expected to be negligible. Thus, only the structural masses of the coolant are considered.

2.2 Detailed Model for the Pressure Vessel and PZR

Because the major components of the SMART are installed in the pressure vessel, the pressure vessel shall be the dominant component over the global dynamic characteristics. Table 1 shows brief summaries of the component weight. Although the pressure vessel is believed to control the behavior of the SMART, the weight of the pressure vessel is only 40% of the total weight. In this regard, the impact of other components on the motion of the SMART is quite expectable. Thus the direct modeling method based on the direct translation of section properties is convenient to build an equivalent model, but it is difficult to examine local behavior of components in detail. Since a typical beam element may not fully represent the characteristics of some components, the direct method translating section properties might increase uncertainties. The most preferable method is to reduce a detailed model into an equivalent model through iterative tuning runs.

In case of the SMART, the detailed finite element analysis on the pressure vessel and PZR is preceded to review the behavior of the pressure vessel and PZR. Since the detailed analysis provides enough information to be kept in the equivalent model, it is possible to minimize uncertainties in modeling process. The pressure vessel is directly modeled with solid elements, while shell elements are applied after reviewing the thickness of the PZR shell. Fig. 2 indicates the finite element model of the pressure vessel and PZR. The finite element modeling and analyses are performed using the IDEAS MS 6.0 on the HP workstation [7], and Table 2 briefly shows frequencies and corresponding modal participation. Fig. 3 through 5 shows typical mode shapes of the pressure vessel and PZR. Fig. 3 through 5 also supports that dominant modes in horizontal direction resemble typical beam modes. Two lumped mass points are enough for the pressure vessel model after reviewing the results of modal participation and mode shapes, whereas only one mass point is determined for the PZR. In case of vertical modes, only one mode is considered for simplicity.

2.3 Equivalent Beam Model for the Pressure Vessel and PZR

Though the detailed analysis proposes two mass points for the pressure vessel, total 3 mass points are considered for the pressure vessel model to accommodate the interaction between other components. But one mass point is still reserved for the PZR model. Since the same section properties are used to build an equivalent model, the validity of the model shall depend upon the mass properties. The best way is to develop a mass model without modification of section properties. Fig. 6 shows a typical method to define the location and magnitude of three mass points only based on section properties. The Eq. (1) through (3) in the Fig. 6 preserve the mass system of the equivalent model to be identical with the original system. For the initial run, the pressure vessel is divided into three parts, and each mass point defined at the center of gravity of each part. In case of the PZR, two trial mass points are defined. To determine the magnitude and location of each mass point, iterative dynamic analyses are required to match the target frequencies. The equivalent model for the vessel and PZR consists of typical beams and pipe elements, and all the section properties are directly converted without any modification. Table 3 reports the results of trial runs using the equivalent model. The resulting frequencies for the reactor vessel are maintained within 10% of deviation in all direction, while the exact frequency is obtained for the PZR. Although the iterative adjustment of the material properties of the vessel could decrease the deviation, the current results are still acceptable under consideration of numerous uncertainties. All analyses are performed using the ABAQUS Ver. 5.8 on the HP workstation [8].

2.4 Development of the Reactor Vessel Assembly Model

The equivalent models representing other components are built and coupled with the reactor vessel and PZR model. All components except the CEDM, MCP, and FA are directly converted to beams or pipe elements with discrete mass system. In case of the MCP, CEDM and FA, the same type of structure is installed repeatedly with a symmetric pattern about the center of reactor vessel. Therefore, it is convenient to convert each batch of structures into a single member. To review the dynamic characteristics of a single component, detailed dynamic analyses with a distributed mass system are carried out. Table 4 reports the target frequencies of each component. Since the MCP and CEDM are installed at the top of the pressure vessel using fasteners, a fixed boundary condition is assumed at the corresponding location. Generally, it is difficult to analogize a batch of structures to a single structure without modification of section properties. One of the popular methods is to adjust the material property of a structure to meet the target frequencies. The equivalent models representing the MCP and CEDM are developed based on the Table 4 and coupled to the reactor vessel and PZR model with other components. Because the motion of the FA is confined by peripheral structures, the target frequency of the FA is tuned after assembling all the individual models. Finally the equivalent model for the SMART is constructed. Fig. 7 shows the equivalent model for the SMART.

3. Results and Discussions

Table 5 reports natural frequencies and modal participation of the SMART with governing components. The frequency of the FA is maintained because it is tuned through the coupled model as described in section above. In case of the MCP and CEDM, only minor variation of frequencies is found in the coupled model (see Table 4). This trend reveals that the equivalent model for the MCP and CEDM could be developed exclusively. And it also confirms that the boundary condition applied for the detailed analysis on the MCP and CEDM is reasonable. Table 5 indicates that the first mode of the reactor vessel in the horizontal direction moves to 20Hz from 32Hz, while minor deviation is monitored on the second mode. The frequency of the PZR is slightly increased to 59Hz form 53Hz. The main reason of this trend comes from the increase of stiffness due to the coupling with other structures. In case of the vertical direction, the fundamental mode of the reactor vessel moves to 82Hz from 118Hz due to coupled structures. Since the difference between the first and second mode of internal structures is less than 10%, it is more preferable to reduce the number of vertical mass point.

4. Conclusion

The equivalent beam model for the dynamic analysis of the SMART is developed through iterative runs, and the dynamic characteristics are reviewed. The results show that the fundamental frequency of the SMART remains around 20Hz in the horizontal direction. In case of the MCP and CEDM model, minor deviations are monitored between individual model and coupled one. Therefore, it is quite possible to build equivalent models for the MCP and CEDM excluding the impact of the peripheral components. Since two modes having large amount of modal participation are closely spaced in the vertical direction, the reduction of vertical mass point might be necessary.

Acknowledgement

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5. References

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Table 1 List of primary component weight

Comp.	Weight(kg)
RV	250800
SG	89400
Core Strut.	47700
Side Screen	82300
FA	22000
MCP	14800
CEDM	24600
Coolant	40900
PZR	28800
Total	601300

Table 2 Results of detail analysis for RV & PZR

Mode	Freq. (Hz)	Participation Factor		
		X	Y	Z
1	29.160	0.219	0.000	0.262
2	29.160	0.262	0.000	0.219
3	52.737	0.027	0.000	0.004
4	52.737	0.004	0.000	0.027
5	68.039	0.000	0.002	0.000
6	79.781	0.288	0.000	0.184
7	79.781	0.184	0.000	0.288
8	102.433	0.000	0.871	0.000
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

Table 3. Results of equivalent model

Dir.	RV(Hz)	PZR(Hz)
X,Z	32.177(11.0%) 86.627(10.9%)	52.688(0.0%)
Y	117.83(11.5%)	-

Table 4 Target frequencies of MCP & CEDM

Comp.	Target Freq.(Hz)
CEDM	49.14
MCP	10.94

Table 5 Results of the equivalent model

Freq. (Hz)	Modal Partc.(%)		Note
	Horz.	Vert.	
2.25	2.9	-	FA
10.92	4.2	-	CEDM
20.40	55.5	-	RV
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	RV
82.25	13.7	-	RV

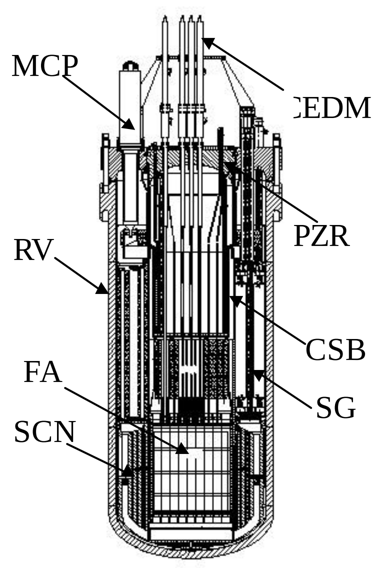


Fig. 1 General arrangement of the SMART

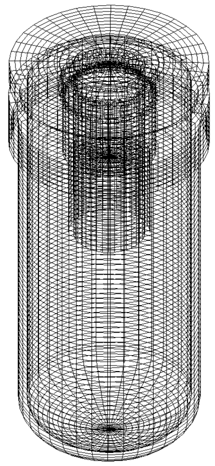


Fig. 2 F. E. model for RV & PZR

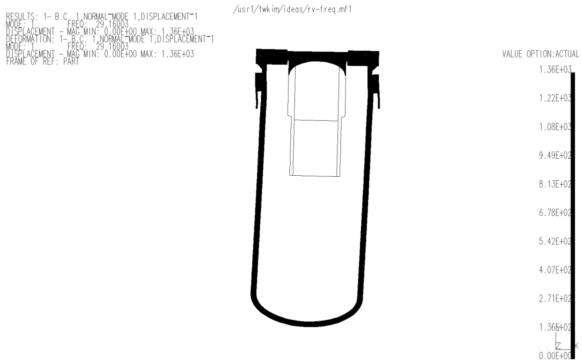


Fig. 3 1st mode shape of RV

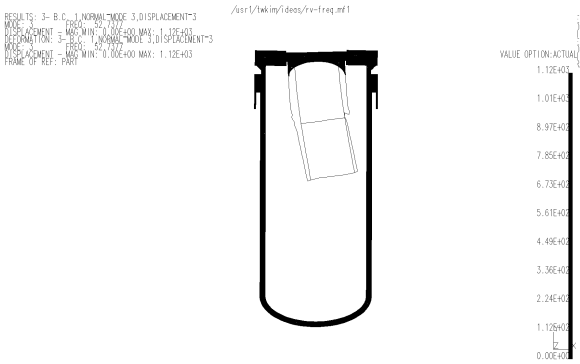


Fig. 4 1st mode shape of PZR

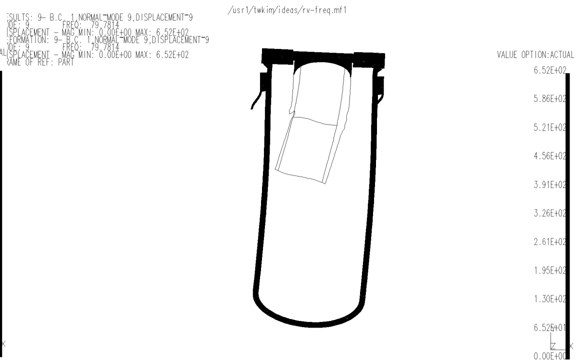
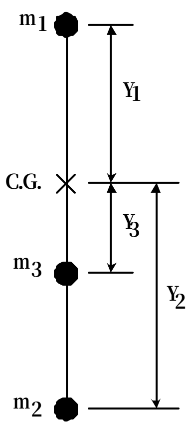


Fig. 5 2nd mode shape of RV



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

$$m_1Y_1 - m_2Y_2 - m_3Y_3 = 0 \qquad (2)$$

$$m_1Y_1^2 + m_2Y_2^2 + m_3Y_3^2 = Ic \qquad (3)$$

Where, *M* denotes the total mass of RV, and *Ic* represents the mass moment of inertia of RV about center of the gravity.

Fig. 6 Determination of mass point location for RV

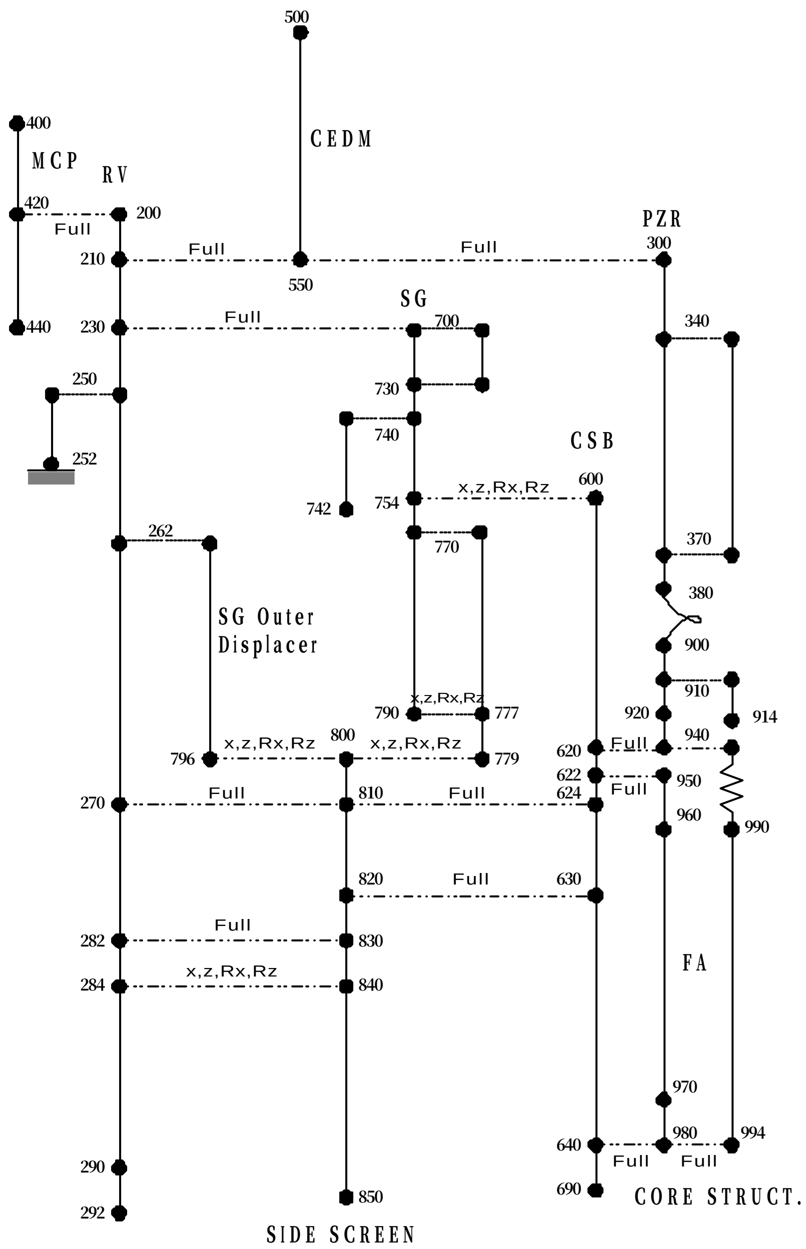


Fig. 7 Beam model for the SMART RVA