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〈 Original Paper 〉

Dynamic Interactions between the Reactor Vessel and the CEDM of the Pressurized Water Reactor

가압경수로 원자로용기와 제어봉 구동장치의 동적 상호작용

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ABSTRACT

The dynamic interactions between the reactor vessel and the control element drive mechanisms (CEDMs) of a pressurized water reactor are studied with the simplified mathematical model. The CEDMs are modeled as multiple substructures having different masses and the reactor vessel as a single degree of freedom system. The explicit equation for the frequency responses of the multiple substructure system are presented for the case of harmonic base excitations. The optimum dynamic characteristics of the CEDMs are presented to reduce the dynamic responses of the reactor vessel. The mathematical model and its response equations are verified by finite element analysis for the detailed model of the reactor vessel and the CEDMs for the harmonic base excitations. It is finally shown that the optimal dynamic characteristics of the CEDM presented can be applicable for the aseismic design.

요 약

본 연구에서는 가압경수로의 핵심부품인 원자로용기와 제어봉구동장치사이의 동적 상호작용의 영향을 평가하였다. 원자로용기와 제어봉구동장치를 단순 수학모델화하여 단순조화 기저가진에 대한 정상상태 주파수응답을 구하고, 응답을 최소화 할 수 있는 설계변수를 제시하였다. 단순 수학모델의 적합성을 입증하기 위하여 원자로용기와 제어봉구동장치의 유한요소 모델에 대하여 ANSYS 코드를 사용하여 해석한 후 정상상태응답을 수학모델로 구한 응답과 비교하였다. 또한 기존설계와 최적화설계에 대하여 지진사고 시간이력해석을 각각 수행함으로써, 본 연구에서 제시한 최적설계변수가 내진설계에 대하여도 적용할 수 있음을 확인하였다.

1. Instroduction

The control element drive mechanisms (CEDMs) of a pressurized water reactor are electro- mechanical devices for moving the control element assemblies in the reactor vessel. The pressure housings for these mechanisms are threaded onto the nozzles on the reactor vessel closure head and seal welded. The reactor vessel is, in turn, supported by four vertical columns located under the vessel inlet nozzles.

Fig.1 shows a descriptive view of the CEDMs

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and the reactor vessel. Since the CEDM is a slender structure, the supports may be required if the loads on the CEDMs are increased. Various support concepts can be investigated to produce optimum dynamic parameters of the CEDMs[1]. Since the dynamic behavior of the CEDM, however, is coupled with the reactor vessel movement, the change of the CEDM design will affect the dynamic motion of the reactor vessel. It is known that the second mode frequencies of the CEDMs are very close to the first mode frequency of the reactor vessel. Therefore, it is desired to know a dynamic interaction effect between the CEDMs and the reactor vessel to develop design requirements for an optimum support configuration. Jin and et.al.[2] investigated the dynamic interactions between the reactor vessel and the CEDMs with a simplified two degree of freedom model which lumped all the CEDMs as a single mass. It is possible to change the dynamic characteristics of the CEDMs to tune the natural frequencies of the CEDMs to the natural frequency of the reactor vessel[3]. Since the CEDMs have different dynamic characteristics because of the different lengths as can be expected from Fig.1, dynamic interactions can be more precisely investigated by considering the CEDMs as multiple substructures. In this paper the multiple substructures system model is developed to represent the CEDMs with the reactor vessel modeled as a single mass as shown in Fig.2.

Recently, there have been studies on the dynamic characteristics of these multiple substructures system especially in the field of civil engineering to find the optimal design of the multiple tuned mass damper (MTMD). Igusa and Xu[4,5] proposed a design concept for the MTMD to suppress vibration of the primary structure. The basic configuration of the MTMD is a large number of small oscillators whose natural frequencies are distributed around the natural frequency of a primary structure. Abe and Fujino[6] derived modal properties of the MTMD system using purturbation technique and presented effectiveness of the multiplicity for the harmonic force excitations and self-excited force excitations. However, because the studies so far have focused on the effectiveness of the TMD to reduce the responses of the primary structure, the substructures were assumed to be same masses. And no explicit form of the solution for the responses was presented for the case of base excitation.

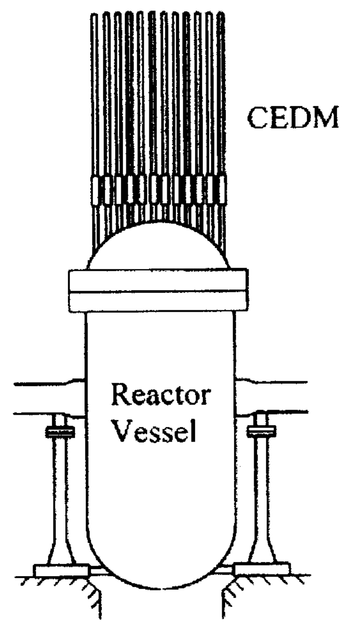

Fig.1 Descriptive view of the reactor vessel and the CEDMs of a pressurized water reactor

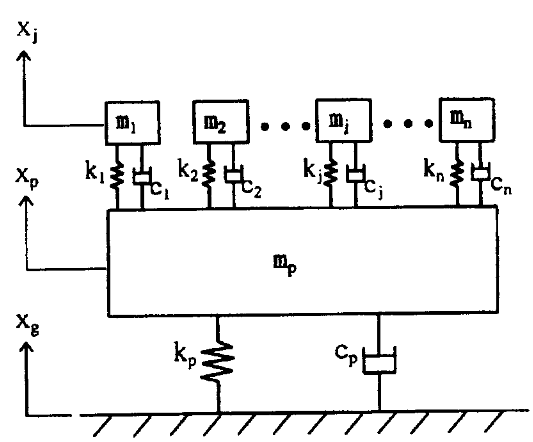

Fig. 2 Simplified mathematical model representing the reactor vessel and the CEDMs

In this paper the frequency response equations of the primary and the multiple substructures which have different masses are developed to apply to the system of the reactor vessel and the CEDMs. The optimal parameters are presented to reduce the responses of the primary system while not increasing the responses of the substructures. The mathematical model representing the reactor vessel and the CEDM is verified by harmonic analyses for the detailed FEM model using ANSYS code[7]. To show that the optimal design parameters presented in this paper are applicable to the seismic disturbances, the time history analyses with typical seismic input are performed for the present design and the optimal design and the response spectra are compared.

2. Equation of Motion and Steady State Responses

The equation of motion of the system shown in Fig.2 for the case of base excitation is

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -M_g \ddot{x}_g(t) \qquad (1)$$

where $x(t)$ is a displacement vector,

$$x(t) = \left\{ x_p(t) \;\; x_1(t) \;\; x_2(t) \;\; \cdots \;\; x_j(t) \;\; \cdots \;\; x_n(t) \right\}^T \qquad (2)$$

x_p is a relative displacement of the primary mass to the ground and x_j $(j=1,2,..,n)$ is a relative displacement of the j-th substructure to the primary mass. M, C, and K are mass, damping, and stiffness matrices of the system, respectively, as presented in the appendix of this paper. $x_g(t)$ is a ground displacement and M_g is as follow:

$$M_g = \begin{Bmatrix} m_p + \sum_{j=1}^{n} m_j \\ m_1 \\ m_2 \\ \vdots \\ m_n \end{Bmatrix} \qquad (3)$$

If the base excitation is harmonic with its displacement amplitude fixed and independent of exciting frequencies, i.e.,

$$x_g(t) = X_g e^{i\omega t} \qquad (4)$$

then the steady state response of the system will be of the following form

$$x(t) = X(w) e^{iwt} \qquad (5)$$

where X is the amplitude vector of the system,

$$X = \{X_p \;\; X_l \;\; X_2 \;\; \cdots \;\; X_n\}^T \qquad (6)$$

Substituting the equation (5) into the equation (1) gives

$$AXe^{i\omega t} = \omega^2 M_g X_g e^{i\omega t} \qquad (7)$$

where

$$A = \left[-\omega^2 M + i\omega C + K \right] \qquad (8)$$

$$= \begin{bmatrix} G & L_1 & L_2 & \cdots & L_n \\ & g_1 & & & \\ & & g_2 & & \\ & (sym) & & \ddots & \\ & & & & g_n \end{bmatrix} \qquad (9)$$

$$G = -\left(m_p + \sum_{j=1}^{n} m_j \right)\omega^2 + 2i m_p \varsigma_p \omega_p \omega + m_p \omega_p^2$$

$$L_j = -m_j \omega^2$$

$$g_j = -m_j \omega^2 + 2i m_j \varsigma_j \omega_j \omega + m_j \omega_j^2$$

(10), (11),(12)

where ω_p and ω_j are the uncoupled natural frequencies of the primary and the subtructures and ζ_p and ζ_j are the damping factors of the primary and the j-th substructures, respectively.

The displacement transmissibility, $D(\omega)$, of the system is expressed as

$$D(\omega) = \begin{Bmatrix} D_p(\omega) \\ D_j(\omega) \end{Bmatrix} = \frac{1}{X_g} \begin{Bmatrix} X_p \\ X_j \end{Bmatrix} = A^{-1} \omega^2 M_g \qquad (13)$$

where $j = 1,2,\ldots,n$.

The inverse of the A matrix can be obtained as presented in the appendix of this paper. We introduce the following notations

$$\mu_j = \frac{m_j}{m_p}$$

$$\mu_{tot} = \frac{\sum_{j=1}^{n} m_j}{m_p} \qquad (14), (15)$$

$$r = \frac{\omega}{\omega_p}$$

$$f_j = \frac{\omega_j}{\omega_p} \qquad (16), (17)$$

where μ_j is the ratio of the j-th substructure mass to the primary mass, μ_{tot} is the ratio of the total mass of the substructures to the mass of the primary system, r is the ratio of the excitation frequency to the natural frequency of the primary system, and f_j is the natural frequency ratio of the j-th substructure to the primary system. Then the $D(\omega)$ is written as

$$D(\omega) = \frac{r^2}{G' - r^4 \sum_{k=1}^{n} \frac{\mu_k}{g_k'}} \begin{Bmatrix} E_p \\ E_j \end{Bmatrix} \qquad (18)$$

where

$$E_p = (1 + \mu_{tot}) + r^2 \sum_{k=1}^{n} \frac{\mu_k}{g_k'} \qquad (19)$$

$$E_j = \frac{1}{g_j'} \left\{ G' + r^2(1 + \mu_{tot}) + r^2 \left(\mu_j \sum_{k \neq j} \frac{1}{g_k'} - \sum_{k \neq j} \frac{\mu_k}{g_k'} \right) \right\}$$

$$(20)$$

$$G' = 1 - r^2(1 + \mu_{tot}) + 2i\varsigma_p r \qquad (21)$$

$$g_k' = f_k^2 - r^2 + 2i\varsigma_k r f_k \qquad (22)$$

where j, $k = 1, 2, \ldots, n$.

The equation (18) is rewritten to show more explicitly,

$$D_p = \frac{(1 + \mu_{tot}) r^2 + r^4 \sum_{k=1}^{n} \left(\frac{\mu_k}{f_k^2 - r^2 + 2i\varsigma_k r f_k} \right)}{1 - (1 + \mu_{tot}) r^2 + 2i\varsigma_p r - r^4 \sum_{k=1}^{n} \left(\frac{1}{f_k^2 - r^2 + 2i\varsigma_k r f_k} \right)} \qquad (18a, b)$$

$$D_j = \frac{r^2 \left[1 + 2i\varsigma_p r + r^4 \left\{ \mu_j \sum_{k=1}^{n} \frac{1}{g_k'} - \sum_{k=1}^{n} \frac{\mu_k}{g_k'} \right\} \right]}{\left[1 - (1 + \mu_{tot}) r^2 + 2i\varsigma_p r - r^4 \sum_{k=1}^{n} \left(\frac{\mu_k}{f_k^2 - r^2 + 2i\varsigma_k r f_k} \right) \right] \left[f_j^2 - r^2 + 2i\varsigma_j r f_j \right]}$$

where $j = 1, 2, \ldots, n$.

Fig.3 and Fig.4 show the responses obtained from equation (18) for the current design of the reactor vessel and the CEDMs whose design

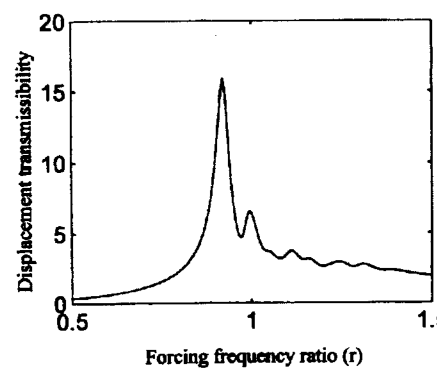

Fig. 3 Displacement transmissibility of the reactor vessel for $\mu_{tot} = 0.0425, \varsigma_p = \varsigma_s = 0.02$.

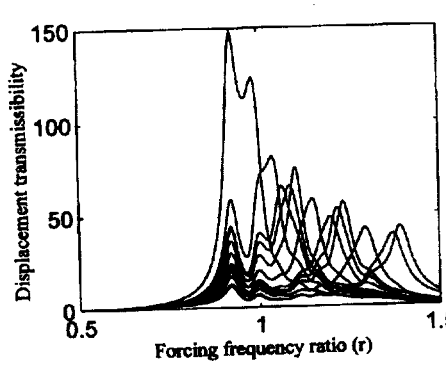

Fig. 4 Displacement transmissibility of the CEDMs for $\mu_{tot} = 0.0425$, $\varsigma_p = \varsigma_s = 0.02$.

Table 1 Typical dynamic characteristics of the reactor vessel and the CEDMs of a pressurized water reactor.

CEDM group No.	Mass ratio (μ_j) (x10^{-3})	Frequency ratio (f_j)
1	0.582	1.392
2	2.328	1.370
3	4.656	1.289
4	2.328	1.232
5	2.328	1.214
6	4.656	1.197
7	4.656	1.146
8	2.328	1.098
9	4.656	1.083
10	2.328	1.068
11	4.656	1.039
12	6.984	0.971

parameter values are presented in Table 1. It can be seen from Fig.3 and Fig.4 that the only a few CEDMs are interacting with the reactor vessel which means that the responses can be reduced by optimizing the design parameters.

For the parametric study of the response characteristics of the system for various design parameters, the followings are assumed:

(a) all the substructures have same masses and same damping factors

(b) the natural frequencies of the substructures are equally spaced and the central frequency is tuned to the frequency of the primary system.

Then the equation (18) become simplified as follows

$$D_p = \frac{(1+\mu_{tot})r^2 + \mu r^4 \sum_{k=1}^{n}\left(\frac{1}{f_k^2 - r^2 + 2i\varsigma_s r f_k}\right)}{1-(1+\mu_{tot})r^2 + 2i\varsigma_p r - \mu r^4 \sum_{k=1}^{n}\left(\frac{1}{f_k^2 - r^2 + 2i\varsigma_s r f_k}\right)}$$

$$D_j = \frac{r^2(1+2i\varsigma_p r)}{\left[1-(1+\mu_{tot})r^2 + 2i\varsigma_p r - \mu r^4 \sum_{k=1}^{n}\left(\frac{1}{f_k^2 - r^2 + 2i\varsigma_s r f_k}\right)\right]\left[f_j^2 - r^2 + 2i\varsigma_s r f_j\right]}$$

(23a,b)

where $j=1, 2, \ldots, n$.

The equations (23a and b) are same as the equations developed by Abe and Fujino except the terms from the base excitations. If the natural frequencies of the substructures are equally spaced and the natural frequency of central substructure is tuned to the natural frequency of the primary system, the equation can be expressed as a function of the number of the substructures, n, and the frequency bandwidth, B defined as follows.

$$B=(n-1)\beta \tag{24}$$

where $\beta=(\omega_{j+1}-\omega_j)/\omega_c$, is frequency spacing and ω_c is the central frequency.

The natural frequency ratio f_j can be written as

$$f_j = \frac{\omega_j}{\omega_c} = 1 + \frac{B(2j-n-1)}{2(n-1)} \tag{25}$$

We can investigate the response characteristics of the system for the number of substructures and the frequency bandwidth.

Fig.5 shows the variations of the maximum displacement transmissibility of the primary mass with the variation of the value of B for $n=12$, $\mu_{tot}=0.0425$ and $\varsigma_p=\varsigma_s=0.02$. As can be seen from Fig.5 there exists optimum B minimizing the responses of the primary system

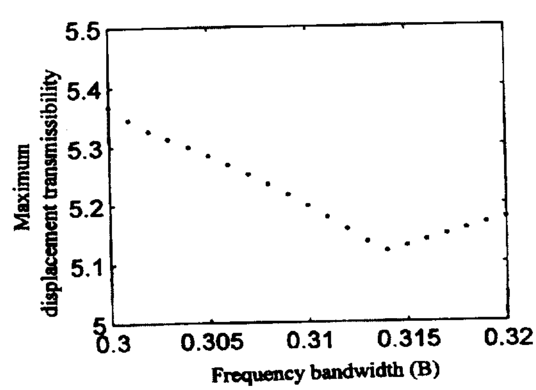

Fig. 5 Variation of the maximum responses of the primary system for variation of the frequency bandwidth of the substructures when n=12, $\mu_{tot}=0.0425$ and $\varsigma_p=\varsigma_s=0.02$.

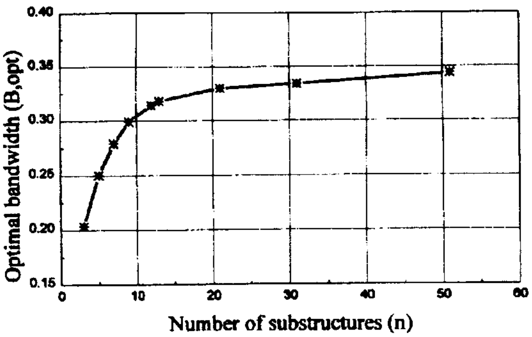

Fig. 6 Relationship between the number of substructures and the optimum frequency bandwidth when $\mu_{tot}=0.0425$ and $\varsigma_p=\varsigma_s=0.02$.

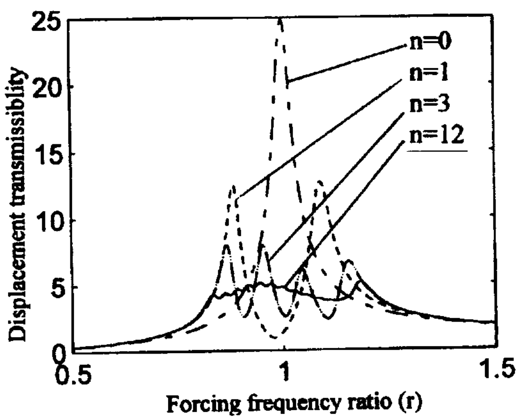

Fig. 7 Variation of the responses of the primary system for various optimal pair of n and B.

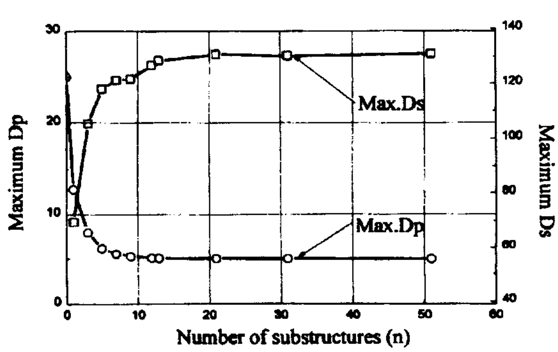

Fig. 8 Relationship between the number of substructures and the maximum responses of the system with optimum frequency bandwidth.

for the given n. Fig.6 presents the relationship between the optimal B and n for that case and Fig.7 shows the responses of the primary system for various optimal pair of n and B.

Fig.8 shows that one can reduce the response of the primary mass by increasing the number of substructures. However it can be seen that there is a limit value of n which would not reduce the responses much with further increaing of n.

For the reactor vessel and the CEDM system, we can suggest that the number of substructures of 12 is adequate. By applying the optimum B of 0.314 for n=12 to the design with equal mass distributions of the CEDMs, the responses can be reduced as presented in Fig.9. Fig.10 shows that the response reduction by applying optimum B but keeping mass distributions of the CEDM as the present design. By comparing Fig.9 with Fig.10, the responses of the primary system are not different much between the two cases. Considering the easiness of the incorporation to the practical design, the second case shown in Fig.10 may be favorable.

3. FEM Analyses

To verify the simplified mathematical model used in section 2 of this paper, the detailed finite element model of the reactor vessel and the CEDMs are developed as shown in Fig.11. The reactor vessel is modeled by the 81 massless beams, 6 linear springs and 2 lumped masses

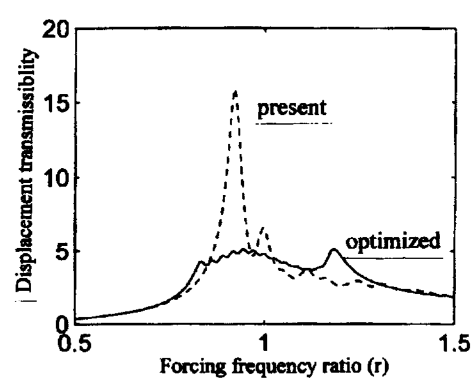

Fig. 9 Responses of the reactor vessel with optimized design of the CEDMs with equal mass distributions

and each CEDM is modeled by 2 massless beams and 2 lumped masses. There are 12 groups of CEDMs as presented in Table 1.

The harmonic base excitation analyses are performed by ANSYS code[7] and the steady state responses of the reactor vessel and the CEDMs are shown in Fig 12 and Fig.13, respectively, for the unit amplitude of exciting displacements. By comparing Fig.12 and Fig.13 with Fig.3 and Fig.4 obtained from analytical solutions, it can be concluded that the mathematical model developed in this paper to simplify the reactor vessel and the CEDM is simulates the real system very well.

To check whether the optimal design parameters for the CEDM are applicable to the

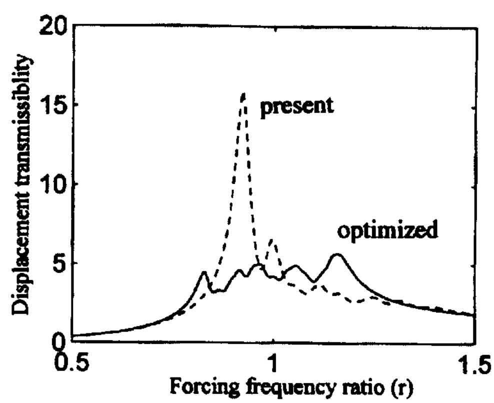

Fig. 10 Responses of the reactor vessel with changed design of the CEDMs with present mass distributions retained

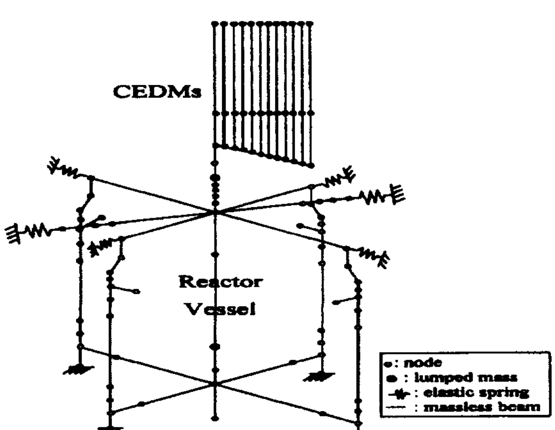

Fig. 11 Detailed RV-CEDM finite element model

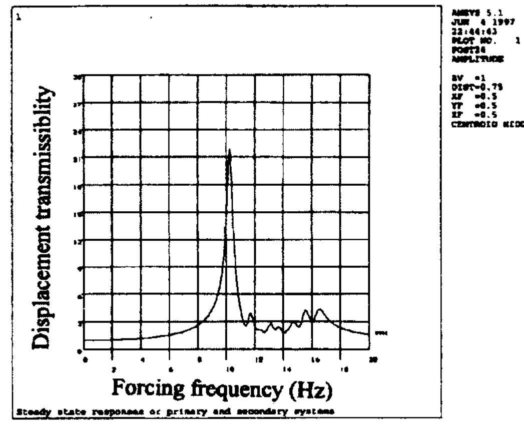

Fig. 12 Steady state response of the reactor vessel to the harmonic base excitions

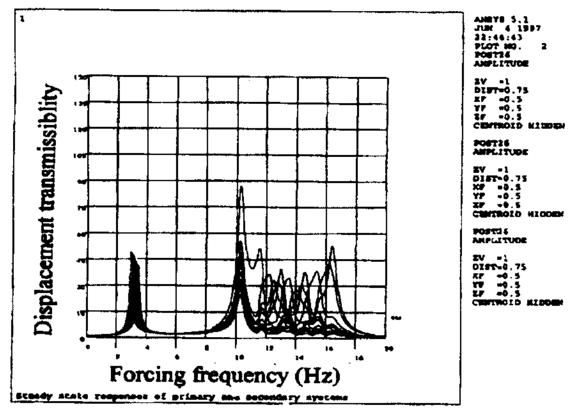

Fig. 13 Steady state response of the CEDMs to the harmonic base excitions

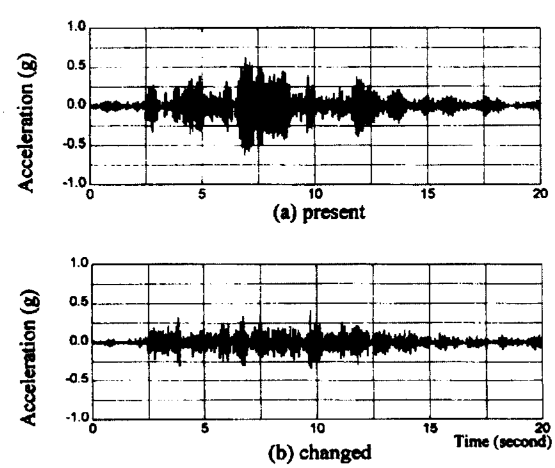

Fig. 14 Seismic acceleration responses of the reactor vessel for (a) present design and (b) changed design.

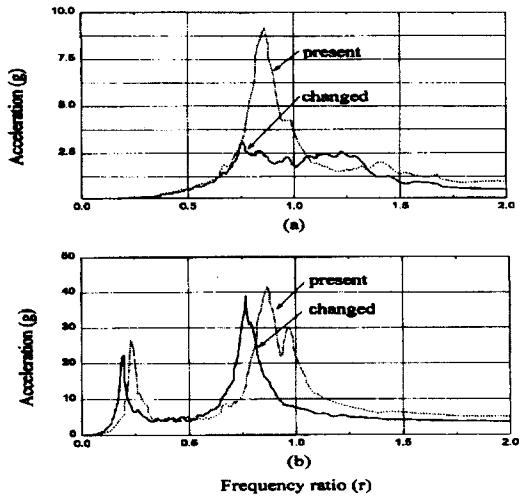

Fig. 15 Comparison of the acceleration response spectra between from the present design and from the changed design (a) at the reactor vessel and (b) at the CEDM

seismic excitations, the time history analyses are performed for the present design and the optimized design. Fig. 14 shows acceleration responses of the reactor vessel for (a) the present design and (b) the changed design to the typical seismic base excitations. It can be seen from Fig.14 that the seismic responses are reduced as for the case of the harmonic base excitations.

The acceleration response spectra at the reactor vessel and the CEDMs are compared in Fig.15 for the present and the changed design. It can be concluded that the optimal parameters presented in this paper will reduce the responses to the seismic excitations.

4. Conclusions

In this paper, the dynamic interactions between the reactor vessel and the control element drive mechanisms (CEDMs) of a pressurized water reactor are investigated. The mathematical model is developed to simplify the reactor vessel as a single degree of freedom system and the CEDMs as multiple substructures and to study the response characteristics of the system for various design parameters such as frequency ratios, mass ratios and damping factors. The explicit form of the frequency response equations are presented for the multiple substructures having different masses excited by the base displacement disturbances. The optimal distributions of the natural frequencies of the CEDMs are presented to reduce the responses of the reactor vessel. It is shown that the optimal design parameters are applicable to the seismic disturbances.

References

(1) Jin, C.E. and Kim, I.Y., 1991, "Dynamic Behavior of CEDM with Various Types of Seismic Support," Proc. Korea Nuclear Society, Spring Annual Meeting, pp. 579-590.

(2) Jin, C.E., Kim, I.Y., Shin, T.M. and Choi, T.S., 1997, "Dynamic Interaction Effects between the Reactor Vessel and the CEDM," 14th Structural Mechanics in Reactor Technology, Lyon, France (to be presented).

(3) Kim, I.Y. and Jin, C.E., 1997, "Optimal Design of CEDM Considering Dynamic characteristics," Computational Struct. Eng. Inst. of Korea (to be published).

(4) Igusa, T. and Xu, K., 1990, "Wide-band Response Characteristics of Multiple Subsystem with high Modal Density," Proc. 2nd int. Conf. Stochastic Struc. Dyn., Florida.

(5) Igusa, T. and Xu, K., 1992, "Dynamic Characteristics of Multiple Substructures with Closely Spaced Frequencies", Earthquake Eng. Struc. Dyn., 21, pp. 1059-1070.

(6) Abe, M. and Fujino, Y., 1994, "Dynamic Characterization of Multiple Tuned Mass Dampers and Some Design Formulas", Earthquake Eng. Struc. Dyn., 23, pp. 813-835.

(7) Swanson Analysis Co., 1996, *ANSYS user's Manual*, Ver.5.1.

Appendix

In equation (1) of this paper, the *M*, *C* and *K* are as follows:

$$M=\begin{bmatrix} m_p+\sum_{j=1}^{n} m_j & m_1 & m_2 & \cdots & m_n \\ m_1 & m_1 & & 0 & \\ m_2 & & m_2 & & \\ \vdots & 0 & & \ddots & \\ m_n & & & & m_n \end{bmatrix} \quad (A1)$$

$$C=\begin{bmatrix} C_p & & & & \\ & C_1 & & 0 & \\ & & C_2 & & \\ & 0 & & \ddots & \\ & & & & C_n \end{bmatrix} \quad (A2)$$

$$K=\begin{bmatrix} k_p & & & & \\ & k_1 & & 0 & \\ & & k_2 & & \\ & 0 & & \ddots & \\ & & & & k_n \end{bmatrix} \quad (A3)$$

In equation (13), the inverse of matrix A is as follows

$$A^{-1}=\frac{\prod_{j=1}^{n} g_j}{\det A}\begin{bmatrix} 1 & \frac{-L_1}{g_1} & \frac{-L_2}{g_2} & \cdots & \frac{-L_n}{g_n} \\ & \frac{1}{g_1}\left(G-\sum_{k\neq 1}\frac{L_k^2}{g_k}\right) & \frac{L_1L_2}{g_1g_2} & \cdots & \frac{L_1L_n}{g_1g_n} \\ & & \frac{1}{g_2}\left(G-\sum_{k\neq 2}\frac{L_k^2}{g_k}\right) & \cdots & \frac{L_2L_n}{g_2g_n} \\ & & & \ddots & \vdots \\ & (sym.) & & & \frac{1}{g_n}\left(G-\sum_{k\neq n}\frac{L_k^2}{g_k}\right) \end{bmatrix} \quad (A4)$$

where

$$\det A = G\prod_{j=1}^{n} g_j - \sum_{j=1}^{n}\left(L_j^2\prod_{k\neq j} g_k\right) \quad (A5)$$