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Study on the Dynamic Characteristics of High-slenderness Ratio Components of Sodium-Cooled Fast Reactor

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1. Introduction

The main components of the sodium-cooled fast reactor (SFR) assembly should be designed to maintain structural integrity against horizontal and vertical seismic loads of 0.3 g of safe shutdown earthquake (SSE). In general, the frequency characteristics of the seismic load that may occur have a high response in the low frequency range. The frequency range of these seismic loads is likely to be in the natural frequency range of main components with high-slenderness ratio installed in SFR. Thus, there is a possibility of resonance between the frequency of the seismic load and the natural frequencies of the structures. Therefore, it is necessary to identify structures that are expected to be vulnerable to seismic loads through dynamic characteristics analysis of major high-slenderness ratio components.

In this study, high-slenderness ratio components were selected from the main components installed in the reactor assembly of the prototype generation-IV sodium-cooled fast reactor (PGSFR), and the dynamic characteristics of the selected high-slenderness ratio components were analyzed through modal analysis. In addition, the possibility of resonance between the frequency of the seismic load and the natural frequency of the selected high-slenderness ratio components was analyzed to identify the structures expected to be vulnerable to the seismic load.

2. High-slenderness Ratio Component and Analysis Model

This chapter describes the selection of high-slenderness components among the main structures constituting the reactor assembly of the PGSFR and the establishment of finite element analysis models for dynamic characteristics analysis of the high-slenderness ratio components.

2.1 High-slenderness Ratio Components Selection

Among the components constituting the reactor assembly, the primary heat transfer system (PHTS) pump, intermediate heat exchanger (IHX), and decay heat exchanger (DHX) supported on the reactor head are high-slenderness ratio structures with long lengths and narrow cross-sectional areas as shown in Figure 1 [1]. In general, the buckling load of the high-slenderness structure is lowered, and the transverse natural frequency of the structure is also lowered. Therefore, there is a high possibility of structural weakness because the seismic load in the low frequency range and the natural frequency of the structure coincide with each other, which can cause resonance.

The value representing the level of slenderness of the structure is the slenderness ratio and can be expressed as follows [2].

$$\lambda = \frac{L}{r} = \frac{L}{2a\sqrt{\frac{I}{A}}}$$

where,

λ = slenderness ratio
L = structure length
r = minimum radius of gyration
I = section moment about the centroid axis
A = section area

The slenderness ratio of the PHTS pump, IHX, and DHX was calculated according to the above equation, and the results are shown in Table 1.

Table 1 : The slenderness ratio of PHTS pump, IHX, and DHX

	PHTS pump	IHX	DHX
L [m]	16.47	18.57	12.16
I [m^4]	0.00081	0.03630	0.00116
A [m^2]	0.025	0.027	0.036
r [m]	0.180	0.367	0.179
λ	103.17	44.82	68.05

As shown in Table 1, the slenderness ratio of PHTS pump, IHX, and DHX all showed a high value of 40 or more, and in particular, the PHTS pump showed the highest value. Except for the three structures presented, the other structures constituting the reactor assembly were expected to have a very low slender ratio compared to the proposed three structures because the length compared to the cross-sectional area was short even if the slender ratio was not calculated [1]. Therefore, the PHTS pump, IHX, and DHX were selected as the main high-slenderness ratio components.

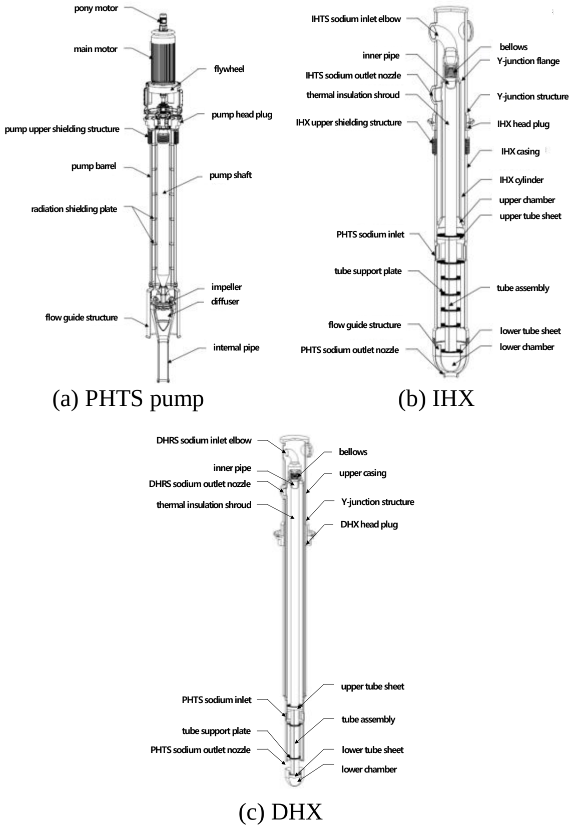


Fig. 1. Selected high-slenderness ratio components (PHTS pump, IHX, and DHX)

2.2 Analysis Model

In order to know the dynamic characteristics of the selected high-slenderness ratio components, it is necessary to construct a finite element analysis model and perform a modal analysis. Analysis model construction was performed using Inventor, SCDM and ANSYS [3~5]. The finite element analysis models of PHTS pump, IHX, and DHX are shown in Figure 2~4. The upper part of the PHTS pump is supported on the reactor head and the lower part is supported at the internal pipe. Since the PHTS pump is partially submerged in the cold pool sodium coolant inside the reactor assembly, the fluid added mass was applied to the submerged outer surface using the FAMD code [6]. For the surface containing the sodium coolant in the inner surface, the mass of the sodium coolant was evenly distributed and applied. Figure 5 shows the constraint boundary conditions and the location and values of the fluid added mass application of the PHTS pump.

The upper part of the IHX is supported on the reactor head and the lower part is supported by the separation plate. Since the IHX is partially submerged in the hot pool sodium coolant inside the reactor assembly, the fluid added mass was applied to the submerged outer surface using the FAMD code [6]. For the surface containing the sodium coolant in the inner surface, the mass of the sodium coolant was evenly distributed and applied. Figure 6 shows the constraint boundary conditions and the location and values of the fluid added mass application of the IHX.

The upper part of the DHX is supported on the reactor head. Since the DHX is partially submerged in the cold pool sodium coolant inside the reactor assembly, the fluid added mass was applied to the submerged outer surface using the FAMD code [6]. For the surface containing the sodium coolant in the inner surface, the mass of the sodium coolant was evenly distributed and applied. Figure 7 shows the constraint boundary conditions and the location and values of the fluid added mass application of the DHX.

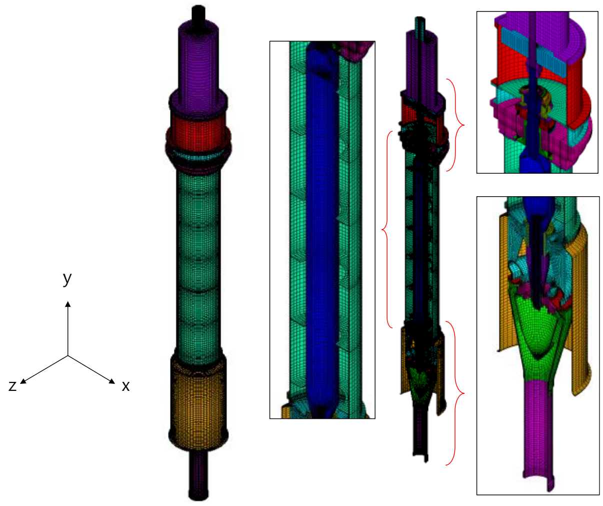


Fig. 2. Finite element analysis model of PHTS pump

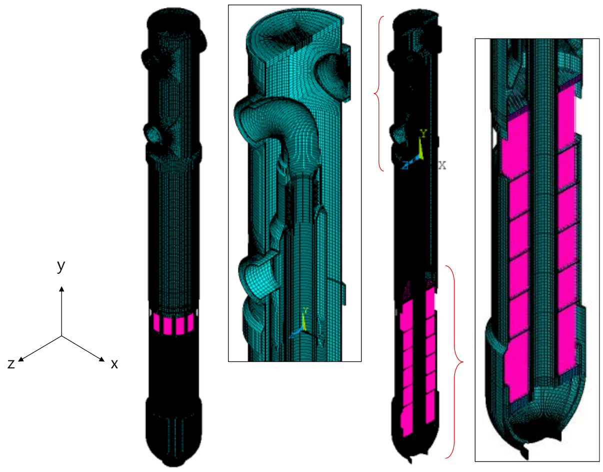


Fig. 3. Finite element analysis model of IHX

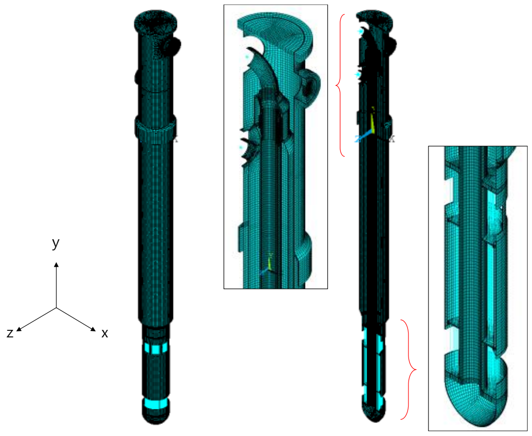


Fig. 4. Finite element analysis model of DHX

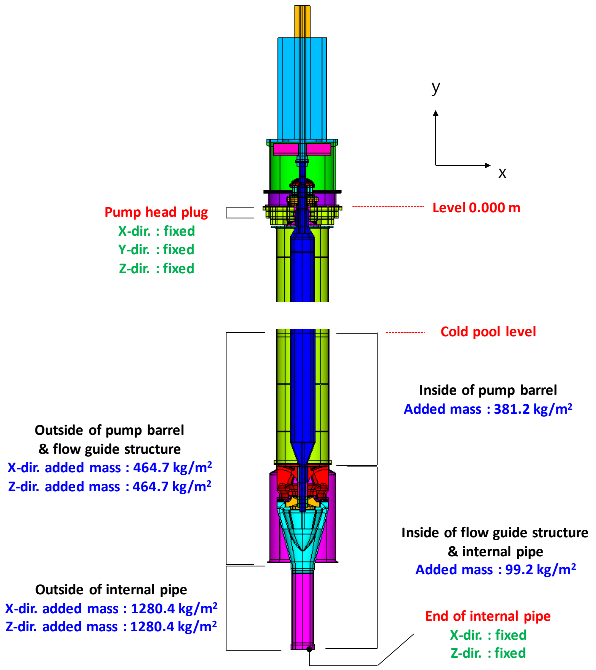


Fig. 5. Constraint boundary conditions and fluid added mass boundary conditions of the PHTS pump

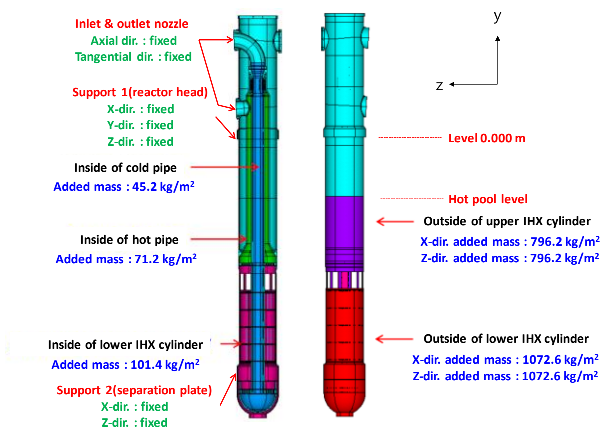


Fig. 6. Constraint boundary conditions and fluid added mass boundary conditions of the IHX

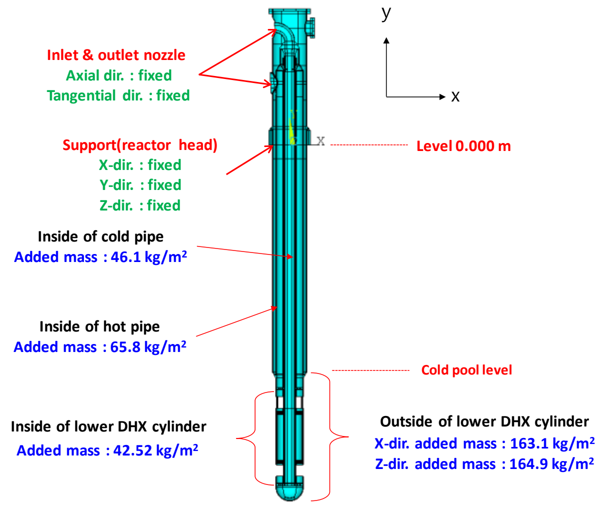


Fig. 7. Constraint boundary conditions and fluid added mass boundary conditions of the DHX

3. Dynamic Characteristics Analysis

In this chapter, modal analysis for dynamic characteristic analysis was performed on the finite element models described in Chapter 2 by using ANSYS [5]. In addition, the possibility of resonance with the natural frequency of each component derived from the modal analysis and the frequency of seismic load was analyzed.

3.1 Modal Analysis

When performing modal analysis, sufficient natural vibration modes and modal parameters were extracted to include the excitation frequency range (0-100 Hz) of the floor response spectrum (FRS). The major natural frequencies and modes for each direction derived from modal analysis of the PHTS pump, IHX, and DHX are shown in Table 2~4 and Figure 8~10, respectively.

Table 2 : The major natural frequencies of the PHTS pump for each direction

Direction	MODE	Freq.[Hz]	Participation factor
X (horizontal)	1	5.08	219.18
	17	37.26	96.08
Z (horizontal)	2	5.08	219.18
	18	37.26	96.08
Y(vertical)	8	23.46	233.07

Table 3 : The major natural frequencies of the IHX for each direction

Direction	MODE	Freq.[Hz]	Participation factor
X (horizontal)	3	24.27	170.08
	57	89.13	91.50
Z (horizontal)	4	24.39	168.29
	58	89.35	99.36
Y(vertical)	9	42.97	39.39

Table 4 : The major natural frequencies of the DHX for each direction

Direction	MODE	Freq.[Hz]	Participation factor
X	2	5.38	59.71
(horizontal)	12	32.77	29.33
Z	1	5.36	59.59
(horizontal)	11	31.99	-31.20
Y(vertical)	29	67.65	-60.86

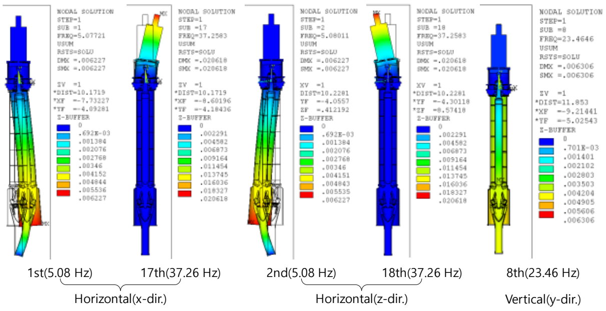


Fig. 8. Major mode shape of PHTs pump

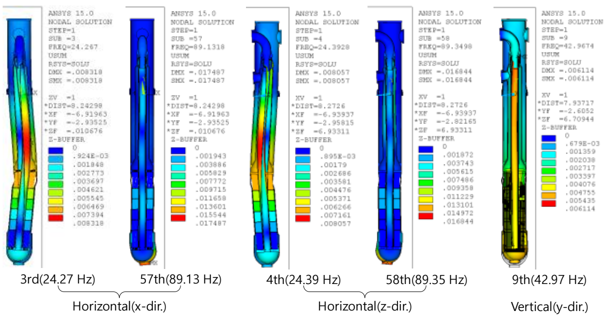


Fig. 9. Major mode shape of IHX

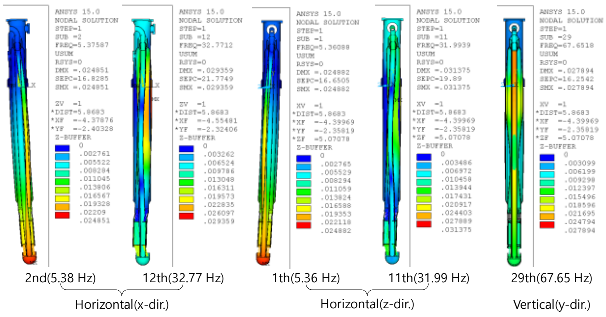


Fig. 10. Major mode shape of DHX

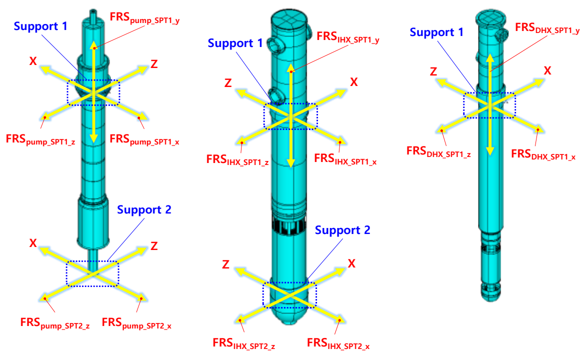
3.2 Resonance Possibility Analysis

The seismic load on the PHTS pump is applied at two locations, support 1 (x, y, z) supporting the PHTS pump at the top and support 2 (x, z) supporting at the bottom, as shown in Figure 11(a). And, the seismic load on the IHX is applied at support 1 (x, y, z) supporting the IHX at the top and support 2 (x, z) supporting at the bottom, as shown in Figure 11(b). Next, the seismic load on the DHX is applied at support 1 (x, y, z) supporting the DHX at the top, as shown in Figure 11(c).

First of all, the possibility of resonance was analyzed by comparing the FRS for each direction acting on support 1 and 2 of PHTS pump with the natural frequency of the PHTS pump [7]. As shown in Fig. 12, the possibility of resonance with the natural frequency of the PHTS pump is expected to be low in the critical frequency range of support 1-x direction (7.9 Hz to 11.3 Hz), support 1-z direction (7.8 Hz to 11.4 Hz), and support 1-y direction (7.4 Hz to 10.2 Hz). On the other hand, the possibility of resonance with the natural frequency of the PHTS pump is expected to be high in the critical frequency range of support 2-x direction (4.3 Hz to 6.0 Hz) and support 2-z direction (4.4 Hz to 6.3 Hz)

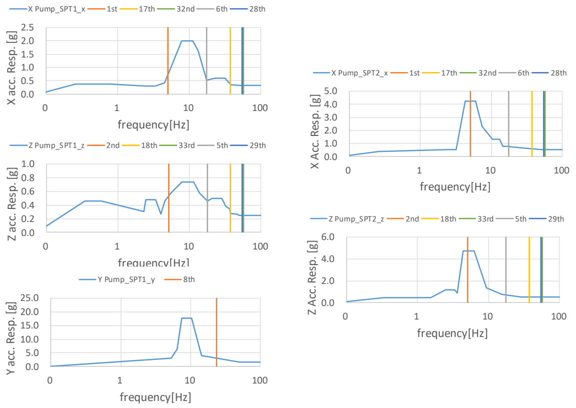
Next, the possibility of resonance was analyzed by comparing the FRS for each direction acting on support 1 and 2 of IHX with the natural frequency of the IHX [8]. As shown in Fig. 13, the possibility of resonance with the natural frequency of the IHX is expected to be low in the critical frequency range of support 1-x direction (7.9 Hz to 11.0 Hz), support 1-z direction (6.7 Hz to 12.4 Hz), and support 1-y direction (7.4 Hz to 10.2 Hz). The possibility of resonance with the natural frequency of the IHX is also expected to be low in the critical frequency range of support 2-x direction (2.4 Hz to 5.9 Hz) and support 2-z direction (2.5 Hz to 6.2 Hz)

Lastly, the possibility of resonance was analyzed by comparing the FRS for each direction acting on support 1 of DHX with the natural frequency of the DHX [8]. As shown in Fig. 14, the possibility of resonance with the natural frequency of the DHX is expected to be low in the critical frequency range of support 1-x direction (6.9 Hz to 13.2 Hz) and support 1-z direction (6.7 Hz to 12.4 Hz).



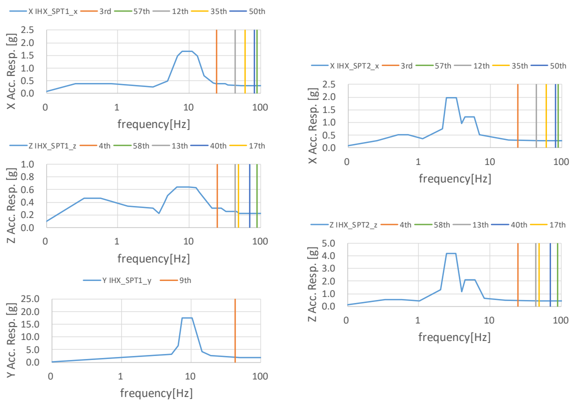
(a) PHTS pump (b) IHX (c) DHX

Fig. 11. Seismic load direction and location acting on each component



(a) Support 1 (b) Support 2

Fig. 12. Comparison of the natural frequency and FRS of the PHTS pump



(a) Support 1 (b) Support 2

Fig. 13. Comparison of the natural frequency and FRS of the IHX

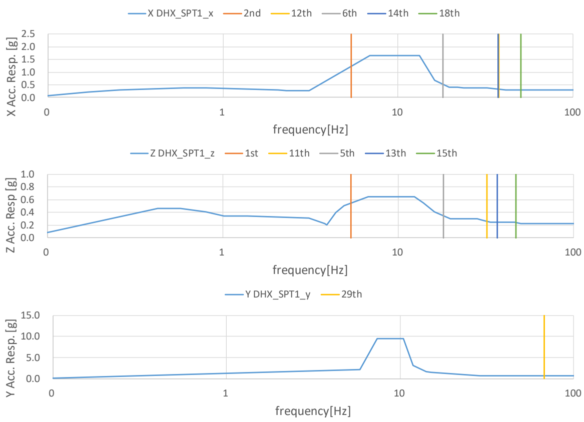


Fig. 14. Comparison of the natural frequency and FRS of the DHX (Support 1)

4. Conclusions

In this study, the PHTS pump, IHX, and DHX, which are expected to be vulnerable to horizontal seismic load, among the major components constituting the PGSFR reactor assembly were selected based on the slenderness ratio. Modal analysis was performed to analyze the dynamic characteristics of the components selected as high-slenderness ratio structures, and modal parameters such as natural frequency and participation factor obtained as a result of the modal analysis were calculated. In order to evaluate the seismic risk of each component, the possibility of resonance between the seismic load frequency acting on each component and the natural frequency of each component was analyzed. As a result of the analysis, in the case of the PHTS pump, it was expected that the critical frequency range of the horizontal seismic load acting on support 2 and the natural frequency of the PHTS pump would be highly likely to resonate. In order to ensure the seismic integrity of the PHTS pump in the future, a resonance avoidance design is required, and it will be conducted through follow-up research.

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