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Aseismic Performance Evaluation of a PGSFR PHTS Pump

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INTRODUCTION

The sodium cooled fast reactor (SFR) is equipped with two mechanical type reactor coolant pumps that are used to circulate the sodium coolant in the primary heat transport system (PHTS) to transfer the heat generated in the core to the intermediate heat transfer system (IHTS). The reactor coolant pump must not lose its function for seismic load conditions. The reactor assembly, which includes the main equipment, needs to be designed to have no structural problems against potential seismic loads and to secure stability against seismic loads.

There have been various studies on seismic analysis methods, procedures, and evaluations to analyze the behavior of nuclear power plants (NPPs) according to seismic loads. Villasor (1976) proposed a seismic response spectrum analysis using a reduced seismic analysis model of a reactor coolant pump (RCP) installed in a NPP and verified the structural integrity of the RCP by analyzing and evaluating the results of dynamic stresses against a seismic load. Fujita et al. (1989) constructed axial symmetry analysis models of a liquid metal cooled fast breeder reactor (LMFBR) and performed seismic response analysis of a reactor assembly considering the fluid-structure interaction to study the vibration behavior of the main equipment, such as the intermediate heat exchanger (IHX), RCP, and reactor vessel. Jhung et al. (1996) studied the development of seismic design criteria for reactor vessels and internal devices for standardizing Korean nuclear power plants. Buongiorno et al. (2004) analyzed the vibration characteristics of a liquid metal cooled reactor vessel according to design changes and analyzed the stress intensity due to the seismic load acting on the reactor vessel. Chellapandi et al. (2007) studied the seismic behavior of the reactor vault of a pool type fast breeder reactor (PFBR) depending on whether the reactor vault was connected to the nuclear island connected buildings (NICB).

The prototype Generation IV sodium-cooled fast reactor (PGSFR), which was developed by the Korea Atomic Energy Research Institute (KAERI), is equipped with two reactor coolant pumps called PHTS pumps (You et al., 2016). A PGSFR PHTS pump must be designed to have sufficient structural integrity against horizontal and vertical seismic loads of a safety shutdown earthquake (SSE) of 0.3 g. Seismic response stresses are checked for the parts of the PHTS pump, and the design margin against a seismic load was calculated. Then a aseismic performance evaluation was performed on the seismic analysis results according to the service level D of ASME B&PV Sec. III Div. 5.

OVERVIEW OF THE PHTS PUMP

The overall shape and arrangement of the PGSFR reactor assembly which has a capacity of 150 MW SFR and the PHTS pump are shown in Figure 1. Two PHTS pumps are installed in the reactor vessel through the reactor head. The PHTS pump consists of a pump motor for driving the pump shaft with an impeller at the lower part, a pump head plug for supporting the pump on the reactor head, and an internal pipe for carrying the primary sodium coolant that flows through the impeller to the core. All parts of the

PHTS pump are made of 316SS, and the length of the PHTS pump including the internal pipe is about 16 m.

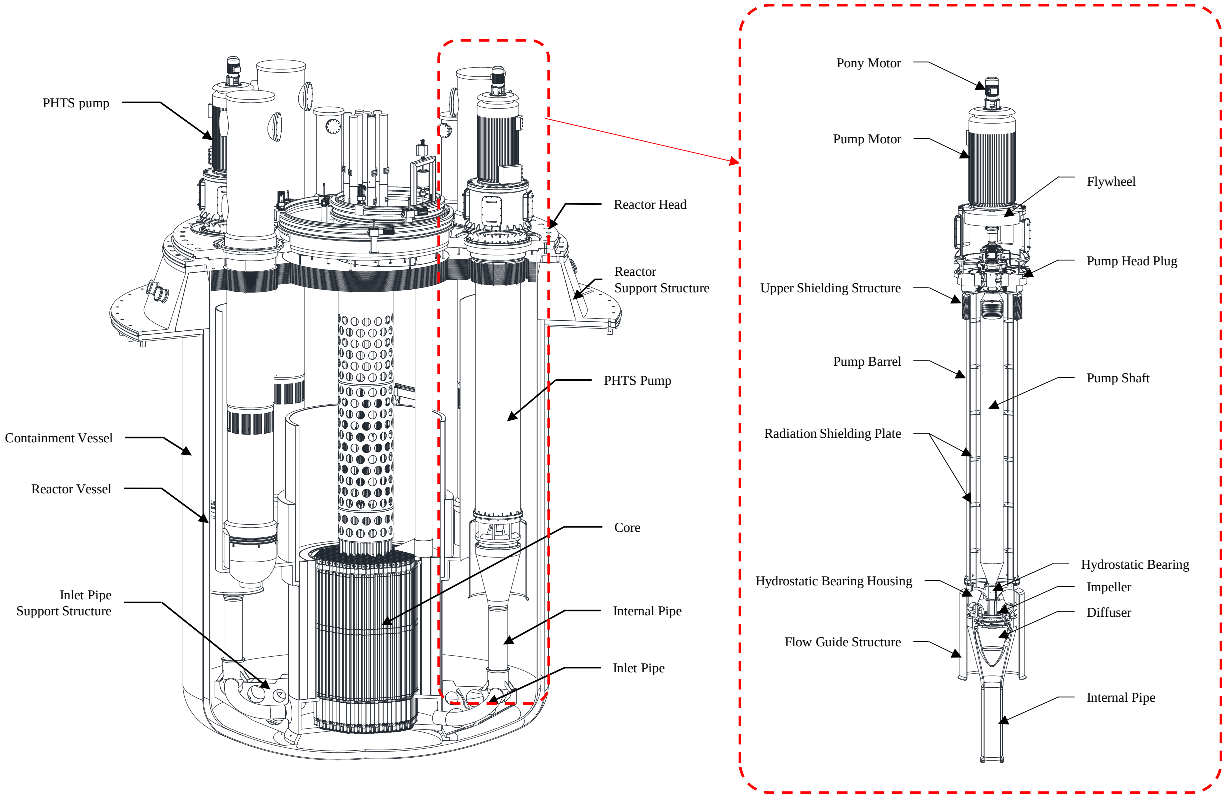


Figure 1. Overall shape and arrangement of the PGSFR reactor assembly and the PHTS pump

SEISMIC ANALYSIS

The PGSFR PHTS pump was designed to have sufficient structural integrity against a seismic load of SSE (0.3g), which means peak ground acceleration is SSE (0.3g). To verify the structural integrity of the PHTS pump, seismic analysis must be performed, the general procedure for seismic analysis is shown in Figure 2.

The square root sum of squares (SRSS) method is used to combine modes to calculate the dynamic stress for the seismic analysis, and the definition of the SRSS for the total modal response R_a is shown in equation (1) (ANSYS, 2013).

$$R_a = \left(\sum_{i=1}^{N}(R_i)^2\right)^{\frac{1}{2}} \quad (1)$$

where,

$$R_i = A_i \psi_i$$

The vibration mode to be used in the SRSS calculation must include a vibration mode that has an influence on the overall dynamic behavior for all directions of x, y, and z. For this, the significance level should be set sufficiently small. The significance level is the value obtained by dividing the mode coefficient of the corresponding vibration mode by the highest mode coefficient of the total of the vibration modes. In the SRSS calculation, the calculation is performed using only the vibration modes higher than the significance level.

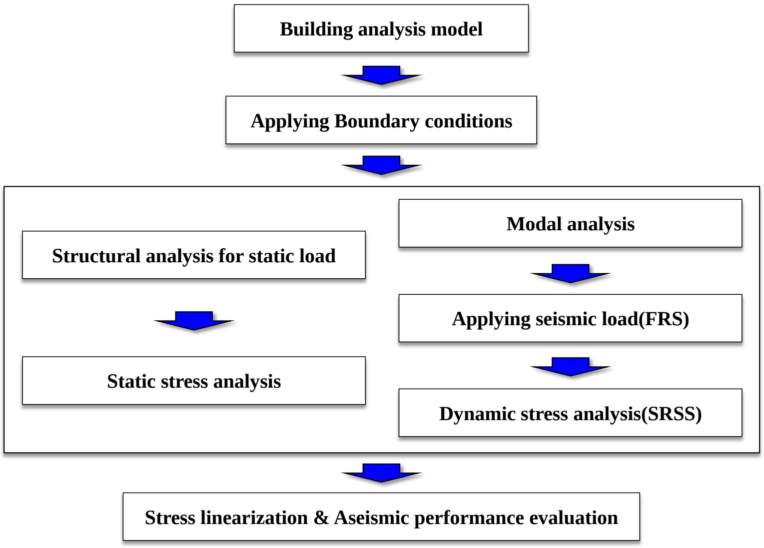


Figure 2. Procedure for seismic analysis

Analysis model

The analysis model of the PGSFR PHTS pump was constructed using ANSYS as shown in Figure 3. The analysis model consists of 534,880 SOLID185 elements, 59,680 SURF154 elements, and 688,425 nodes (ANSYS, 2013), and the material is type 316SS.

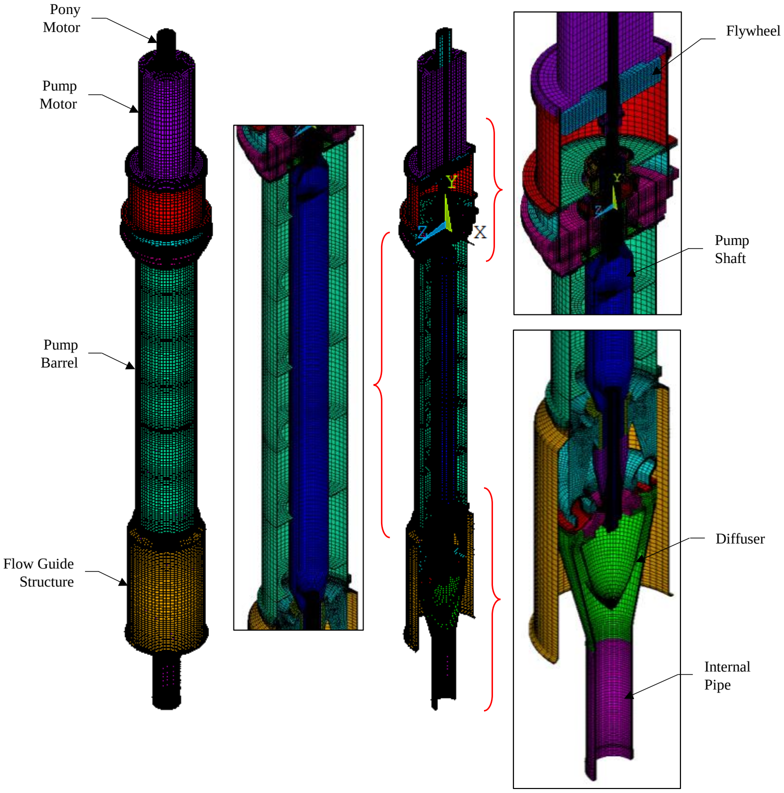
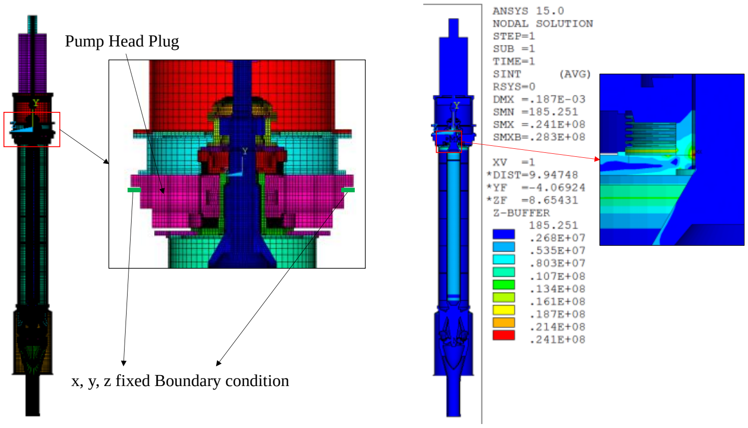


Figure 3. Finite element analysis model of PHTS pump

Static analysis

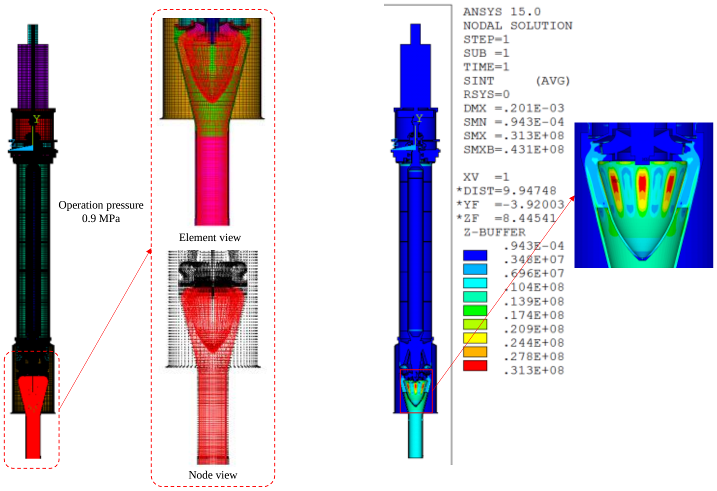
The dead weight and operating pressure are taken into account by the static loads applied to the PHTS pump. First, as a boundary condition for the dead weight analysis of the PHTS pump, the fixed boundary conditions are applied to the head plug of the upper part in the x, y, and z directions, and the gravity acceleration 9.8 m/s^2 is applied to the whole model. The boundary condition and the result of the dead weight analysis is shown in Figure 4, and the maximum stress occurred at the connection part of the pump barrel with a maximum stress intensity of 24.1 MPa.



<Boundary condition> <Stress intensity>

Figure 4. Boundary condition and result for the dead weight analysis of the PHTS pump

During PHTS pump operation, the sodium coolant flows into the flow guide structure and then flows into the internal pipe after the pass through impeller and diffuser. In this case, pressure (differential pressure 0.9 MPa) is applied to the diffuser and internal pipe as the boundary condition. Fixed boundary conditions are applied in the same way as in the case of the dead weight analysis as shown in Figure 4. The pressure boundary condition and results of the analysis with respect to operating pressure are shown in Figure 5. The maximum stress is generated in the lower diffuser part, and the corresponding stress intensity is 31.3 MPa.



<Pressure boundary condition> <Stress intensity>

Figure 5. Pressure boundary condition and analysis result of the PHTS pump during normal operation

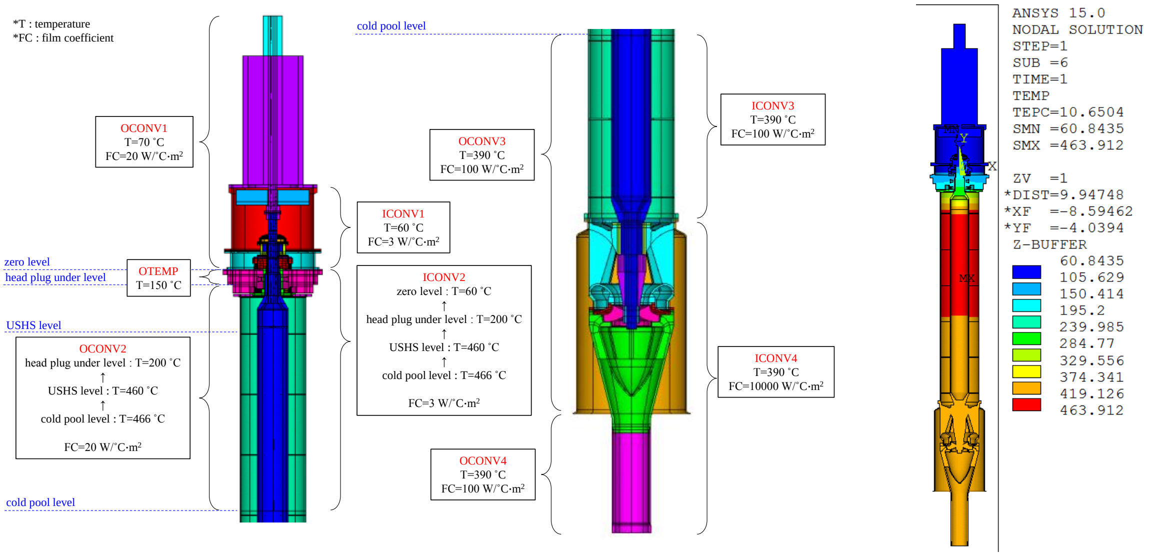
Heat transfer analysis

Heat transfer analysis for the PHTS pump was performed to obtain the temperature distribution of the pump during normal operation. The convection boundary condition was applied to all parts except the head plug, and the temperature boundary condition was applied to the head plug as shown in Figure 6. Details of heat transfer boundary conditions for each part are as follows.

From the engineering estimation, the following conditions are tentatively applied: a film coefficient of 3 W/℃·m^2 for the inner surface above the head plug (ICONV1), 20 W/℃·m^2 for the outer surface above the head (OCONV1), 20 W/℃·m^2 for the cover gas area under the head plug (OCONV2), 100 W/℃·m^2 for the liquid sodium area in a low velocity flow (ICONV3, OCONV3, OCONV4), and 10,000 W/℃·m^2 for the liquid sodium area in a high velocity flow (ICONV4) (Lee, 2017).

The cover gas temperature from the cold pool level to the upper shielding structure (USHS) level decreased linearly from 466 ℃ to 460 ℃, and the cover gas temperature from the USHS level to the bottom of the pump head plug decreased linearly from 460 ℃ to 200 ℃. In addition, the temperature of the part immersed in the cold pool was set at 390 ℃ (cold pool temperature), and the head plug supporting part of the PHTS pump was set at 150 ℃ (reactor head temperature) (Lee, 2017).

The temperature distribution of the PHTS pump during normal operation is shown in Figure 6 as a result of the heat transfer analysis of the PHTS pump.



<Boundary conditions> <Temperature distribution>

Figure 6. Boundary conditions and temperature distribution for the heat transfer analysis of the PHTS pump during normal operation

Dynamic structural characteristic

To determine the dynamic characteristics of the PHTS pump, the natural frequencies and the natural vibration modes need to be obtained through modal analysis of the PHTS pump, and the resonance with the seismic load acting on the PHTS pump needs to be analyzed.

The PHTS pump is partly submerged in the cold pool inside the reactor vessel, so the fluid added mass must be applied to the area in contact with the sodium coolant. The fluid added mass was applied using the FAMD code (Koo et al., 2003) for the outer surface submerged in the sodium coolant. For the inner surface, the fluid added mass was applied by uniformly distributing the mass of the sodium coolant. The location and value of the fluid added mass are shown in Figure 7, and 465 kg/m^2 on the OM1 (outside of the pump barrel and flow guide structure), 129 kg/m^2 on the OM2 (outside of the internal pipe), 381 kg/m^2 on the IM1 (outside of the pump shaft and inside of the pump barrel), and 99 kg/m^2 on the IM2 (inside of the flow guide structure and internal pipe, and inside and outside of the diffuser).

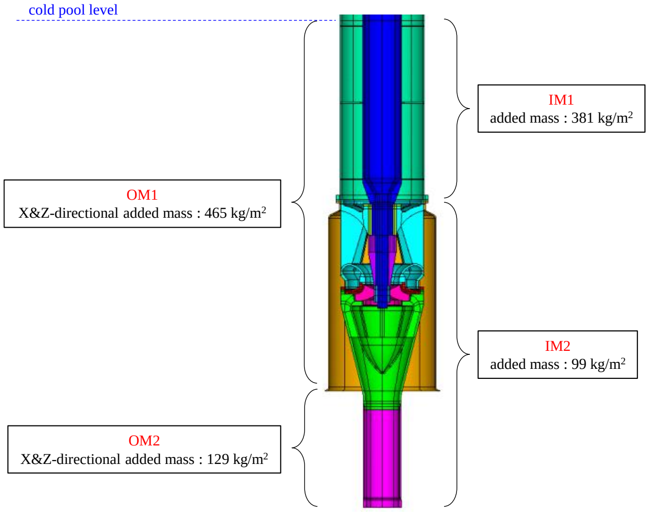


Figure 7. Locations and values of the fluid added mass of the PHTS pump

The seismic loads acting on the PHTS pump as the floor response spectra (FRS) for the seismic load of SSE (0.3g) applied in both head plug part and internal pipe connection part are shown in Fig 8.

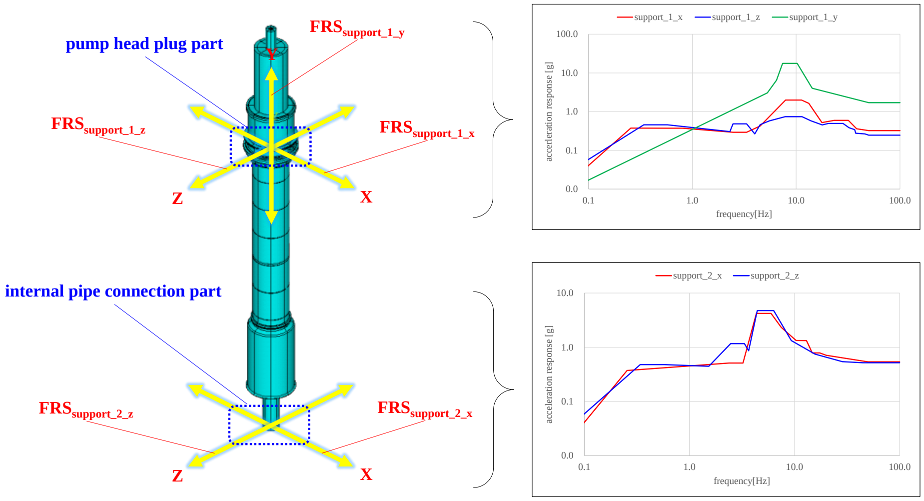
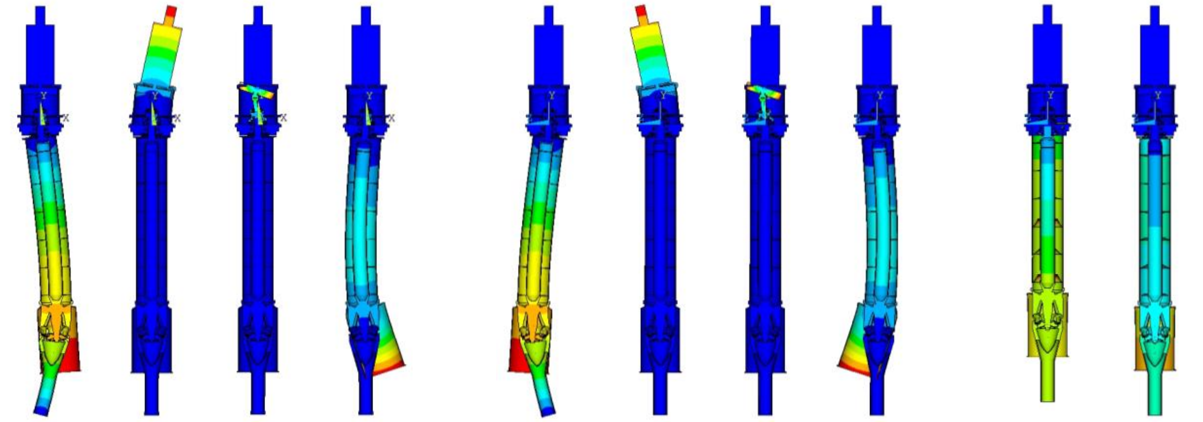


Figure 8. Directions and locations of the seismic load and FRSs acting on the PHTS pump

In the modal analysis, a total of 70 natural vibration modes and modal parameters were extracted to cover the excitation frequency range (0~100 Hz) of the FRS. The calculated modal analysis results indicated that the vibration mode, which can significantly affect the vibration response characteristics of an actual structure, is a mode with a high effective mass. Therefore, major modes and natural frequencies by directions were listed in order of the high effective mass ratio to the total mass, and major modes and frequencies below 100 Hz with a ratio of 1% effective mass to the total mass are shown in Table. 1. In addition, the major vibration mode shapes for the horizontal direction (x and z directions) and vertical direction (y direction) corresponding to Table 1 are shown in Figure 9.

Table 1: Major vibration modes and natural frequencies of PHTS pump by directions

Direction	Vibration mode	Natural frequency [Hz]	Ratio (effective mass to total mass) [%]
X (horizontal)	1	6.43	58.72
	15	37.26	12.12
	29	57.16	2.45
	6	17.73	1.05
Z (horizontal)	2	6.44	58.72
	14	37.26	12.12
	28	57.16	2.45
	5	17.73	1.05
Y (vertical)	8	25.44	64.92
	40	71.09	1.06



1st(6.43 Hz) 15th(37.26 Hz) 29th(57.16 Hz) 6th(17.73 Hz)

<x direction>

2nd(6.44 Hz) 14th(37.26 Hz) 28st(57.16 Hz) 5th(17.73 Hz)

<z direction>

8th(25.44 Hz) 40th(71.09 Hz)

<y direction>

Figure 9. Major vibration modes of PHTS pump

Seismic response spectrum analysis

The modal analysis results of the PHTS pump showed that the major horizontal direction (x, z direction) modes with the highest effective mass ratio to the total mass were the 1st and 2nd modes (transverse bending mode), and the natural frequencies were calculated as 6.43 Hz and 6.44 Hz, respectively. For the vertical direction (the y direction), the 8th mode was the mode with the highest effective mass ratio, and the natural frequency of the mode was calculated as 25.44 Hz.

A structural analysis with the seismic load of the PHTS pump was performed using the vibration modes with a significance level greater than 0.001 and the FRSs in Figure 8. The stress intensity caused by seismic loads in the PHTS pump was calculated by the SRSS method, and the results are shown in Figure 10.

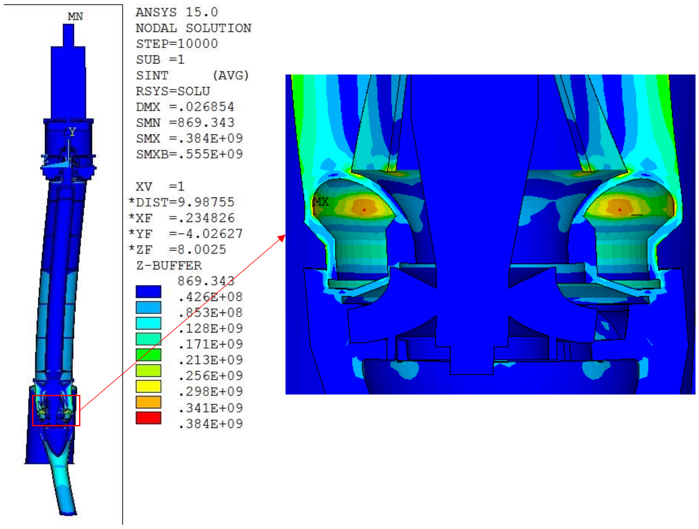


Figure 10. Stress intensity distribution of PHTS pump by seismic loads

As shown in Figure 10, the side of the hydrostatic bearing housing of the PHTS pump was predicted to be the most vulnerable to seismic loads with a stress intensity of 384 MPa. This was due to resonance between the transverse vibration mode of the PHTS pump (1st vibration mode in the x direction, 2nd vibration mode in the z direction) and the excitation frequency of the transverse FRS (x and z directions) acting on the internal pipe connection.

Aseismic performance evaluation

Aseismic performance evaluation was carried out per ASME B&PV Sec. III Div. 5 Service level D, taking into account of mechanical loads and SSE (0.3g). Three evaluation sections with high dynamic stresses were selected from the seismic response analysis of the PHTS pump, as shown in Figure 10. The ASME B&PV Sec. III Div. 5-HBA was applied because the metal temperatures of all selected evaluation sections were less than 425 ℃, which is a creep negligible temperature for stainless steel, and the aseismic performance evaluation results are shown in Table 3. For each evaluation section, the node close to the y-axis was set to the inner node. The evaluation results reveal that the aseismic performance was satisfactory in all evaluation sections even though the design margin in evaluation section 2 was as low as 6%.

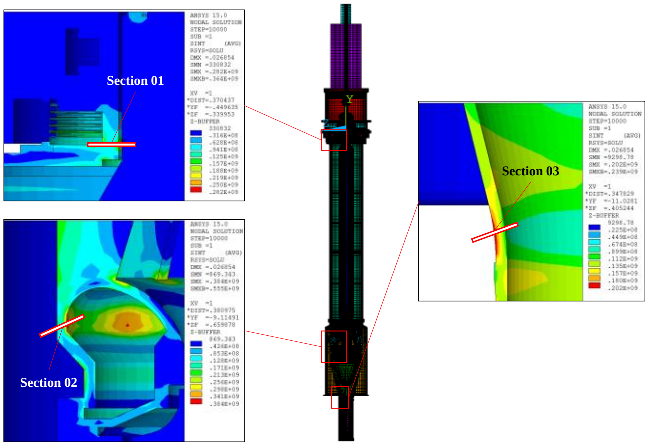


Figure 20. Aseismic performance integrity evaluation sections of the PHTS pump

Table 3: Structural integrity evaluation results of the PHTS pump for service level D

Section (node)	Linearized Stress	Calculated Stress [MPa]	Allowable Stress [MPa]	Design margin	T [℃]
1 (inner)	P_L	82.1	478.1	4.83	207.4
	P_L+P_b	141.5	478.1	2.38	
1 (outer)	P_L	82.1	474.2	4.78	214.3
	P_L+P_b	140.2	474.2	2.38	
2 (inner)	P_L	143.1	401.0	1.80	390.0
	P_L+P_b	377.0	401.0	0.06	
2 (outer)	P_L	143.1	401.0	1.80	390.0
	P_L+P_b	374.0	401.0	0.07	
3 (inner)	P_L	153.4	401.0	1.61	390.0
	P_L+P_b	209.8	401.0	0.91	
3 (outer)	P_L	153.4	401.0	1.61	390.0
	P_L+P_b	207.8	401.0	0.93	

CONCLUSION

In this paper, seismic analysis of a PGSFR PHTS pump under a seismic load of SSE (0.3g) was performed and an aseismic performance evaluation was performed according to ASME code.

For evaluating the aseismic performance of PHTS pump, we considered the static loads (dead weight, operating pressure) and dynamic load (seismic load). Three evaluation sections with high dynamic stresses were selected from the seismic response analysis of the PHTS pump, and an aseismic performance evaluation was performed on each evaluation section using linearized stresses according to ASME code. The evaluation confirmed that the stresses at all the evaluation sections satisfied the allowable stresses at the given temperature, and the PHTS pump had an aseismic performance against a seismic load of SSE (0.3g). In section 2, where the aseismic performance was evaluated to be low, research on improving the aseismic performance is needed in the future.

NOMENCLATURE

A_i	Modal coefficient for the ith mode
g	Gravity acceleration
i	Mode number
N	Total number of expanded modes
P_b	Primary bending stress
P_L	Local membrane stress
R_a	Total modal response
R_i	Modal response in the ith mode

T Temperature
ψ_i The ith mode shape

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