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A Study on the Structural Integrity of an Auxiliary Feed Water Pump in a Nuclear Power Plant

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원자력 발전소 보조급수펌프의 구조 건전성에 관한 연구

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ABSTRACT

The auxiliary-feed-water pump (AFWP) used to supply water during a station black out situation at nuclear power plants should meet the seismic qualification regulations stipulated in IEEE Std 323 and 344, so as to withstand earthquakes or dangerous situations. Here, we establish a model for the estimation of the structural integrity of this type of pump. If the natural frequency that results from a modal analysis is less than 33 Hz, we adopt a dynamic analysis, instead of a static analysis. A dynamic analysis was carried out taking into consideration seismic conditions such as the floor response spectra (FRS), an operation-base earthquake (OBE), and a safe-shutdown earthquake (SSE). Finally, an analytical estimation of the structural integrity of an AFWP is made through a comparison of calculated values and allowable values. If the result is less than the allowable stress, the pump is deemed to have good structural integrity. In addition, future studies will involve a stability check for rotor accidents that may occur during the operation of the pump.

Key Words : Auxiliary Feed Water Pump (AFWP), Nuclear Power Plant, Structural Integrity, Analytical Estimation

1. Introduction

South Korea has many nuclear power plants. But the country is not safe from earthquakes. Nuclear facilities will always need to be prepared for an emergency accident. Therefore, they require more rigorous and precise seismic and structural integrity analysis in comparison to other industrial facilities [1]. If an accident occurs in a nuclear power plant, its operation will stop automatically. But because nuclear fission does not stop, water must be supplied continuously. The nuclear fuel is kept cool because continuously circulating water is supplied to the facility interior. An AFWP is used to cool the heated water. This pump must maintain integrity in

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Table 1 Load conditions

Operating condition	Load combination
Normal	Dead Weight + Nozzle load
Upset	Dead Weight + Nozzle load + OBE load
Faulted	Dead Weight + Nozzle loads + SSE load

an emergency situation so that the worst problems can be prevented.

A study on the analytical estimation of structural integrity for a main control board in a nuclear power plant was performed by Jung et al [6]. A study on the design of a tilting pad journal bearing, considering rotor stability, was performed by Jo [7]. Also, a heat-up calculation for an AFWP room at Ulchin units 3 and 4 for loss of HVAC accidents was performed by Yoon et al [8]. And seismic qualification of the main control board for a nuclear power plant was performed by Byeon et al [9].

Such theoretic stability analysis for nuclear structure research is in progress, but systematic individual researches have not been done. Therefore, a comprehensive study is needed on the safety of the pump shaft and the seismic safety verification of a AFWP. In this paper, a three-dimensional finite element model was constructed using ANSYS in order to verify the structural integrity of an AFWP of a nuclear power plant for earthquake load conditions. If a first natural frequency as a result of the mode analysis is greater than 33Hz, static analysis will be performed. When the first natural frequency is less than 33Hz, acceptable justification for static analysis cannot be provided, and a dynamic analysis will be required. And we will want to conduct a stability check for rotor accidents that may occur during pump operation.

2. Seismic Qualification Method

2.1 Analysis method

This is a method to analyze the behavior by mathematical model. A mathematical model of simple structural characteristics, like equipment or control panel, is used when possible, but realistically is impossible to test. The possible analysis methods are static analysis and dynamic analysis, depending on the structure of the devices and dynamic properties such as the complexity of the structure, and whether it has rigid or flexible characteristics. The form of the mathematical model is divided into a continuous model and discrete models. In recent years, a lot of dynamic analysis has used the finite element method by using a computer program such as ANSYS.

2.2 Seismic category

This classification is applied to those structures, systems, and components that are designed to remain functional during and/or following a safe shutdown earthquake. To be verified in this paper, an AFWP for SSE occurs when the ability to sustain as the class that corresponds to the seismic category I structures should be designed. Thus, the overall verification process is shown in Fig. 1.

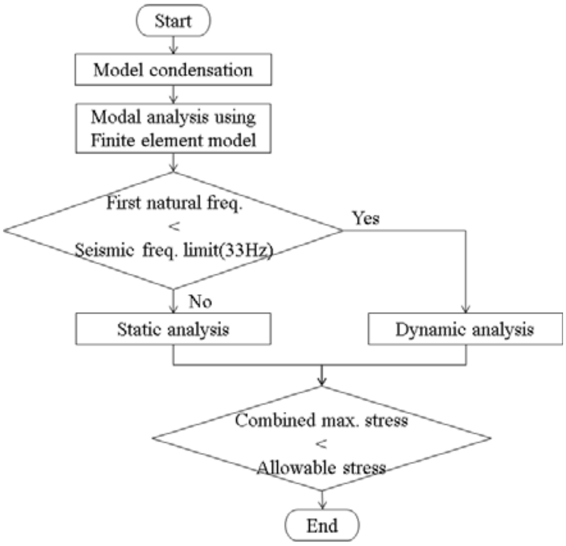


Fig. 1 Process of analysis method

To perform the seismic analysis we shall consider three kinds of conditions, as shown in Table 1. The normal case is a consideration of the dead weight and nozzle loads. And then, OBE and SSE will be applied by inputting the spectrum data.

3. Rotordynamic analysis

3.1 Rotor modeling

A rotor analysis for the rotating part was performed to verify that an AFWP meet the dynamic design requirements. To verify the stability of the rotor system, advanced rotating machinery dynamics (ARMD) modeling and analysis were used. The ARMD is a commercial rotor analysis tool and is available to analyze rotors and bearings at the same time. Figure 2 shows a finite element model applied to bearing stiffness at the place of installation of the magnetic bearing. For the total system, we made a rotor model having 39 elements and 40 nodes. The rotor is discretized to 2-node beam elements, and the characteristics of bearings are applied to the nodes at the centers of the bearing parts, respectively, as shown in Fig. 2. The rotor analysis was implemented to investigate the natural frequencies and mode shapes of the AFWP. The fundamental mode of an AFWP was found to be above 33Hz, which is not in the seismic range. Therefore, an AFWP is regarded as a rigid body within the frequency range up to 33Hz.

The bearing dynamic coefficients for rotor analysis are the input data shown in Fig. 3. Lubricant ISO VG 32 grade was used. The bearing stiffness is 2.7×10^{8} N/m and damping is 9.1×10^{4} N·s/m. And Fig. 3 shows the results of the journal bearing analysis and identifies the minimum film thickness. The minimum film thickness of journal bearing is more than 92.5µm which quite satisfy the required minimum film thickness about 8µm of the journal bearing.

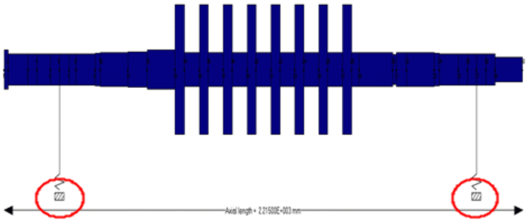
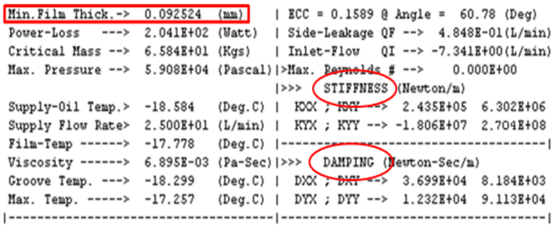


Fig. 2 Finite element model of a rotor



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Min.Film Thick.->  0.092524  (mm)     | ECC = 0.1589 @ Angle =  60.78 (Deg)
Power-Loss   --->  2.041E+02 (Watt)   | Side-Leakage QF -->  4.848E-01(L/min)
Critical Mass -->  6.584E+01 (Kgs)    | Inlet-Flow   QI --> -7.341E+00(L/min)
Max. Pressure -->  5.908E+04 (Pascal)|>Max. Reynolds # -->    0.000E+00
                                      |>>>  STIFFNESS (Newton/m)
Supply-Oil Temp.>  -18.584   (Deg.C) |  KXX ; KXY -->  2.435E+05  6.302E+06
Supply Flow Rate>  2.500E+01 (L/min) |  KYX ; KYY --> -1.806E+07  2.704E+08
Film-Temp ------>  -17.778   (Deg.C) |------------------------------------|
Viscosity ------>  6.895E-03 (Pa-Sec)|>>>  DAMPING (Newton-Sec/m)
Groove Temp. --->  -18.299   (Deg.C) |  DXX ; DXY -->  3.699E+04  8.184E+03
Max. Temp. ----->  -17.257   (Deg.C) |  DYX ; DYY -->  1.232E+04  9.113E+04
|-------------------------------------|------------------------------------|
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Fig. 3 Input data of journal bearing

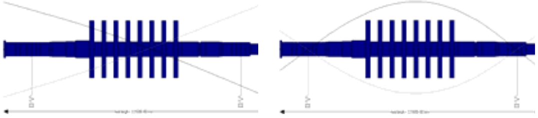
3.2 Rotor system stability

The operating speed of an AFWP is 3,600 RPM, which is used to analyze the rotor and bearing. As shown in the Table 2, the natural frequency of a first mode is 1,799.0 CPM (29.98Hz) at the operating speed of 3,600 RPM. Figs. 4(a) to 4(d) show the mode shape and each of the natural frequencies.

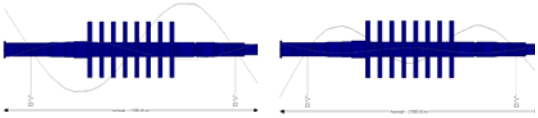
Figure 4(a) presents a rigid body mode as one of the results of the rotor analysis. So, the model of the real first mode can be found in Figure 4(b). The first flexible body modes of an AFWP occurs at 2,215 CPM (36.91Hz). Therefore, within 33Hz, the rotor systems can be regarded as a rigid body.

Table 2 Stability of a rotor

Mode	CPM (Hz)
Rigid body	1,799 (29.98)
First	2,215 (36.91)
Second	10,258 (170.96)
Third	24,976 (416.26)



(a) Rigid mode (b) First mode



(c) Second mode (d) Third mode

Fig. 4 Mode shapes

Flexible body mode occurs above 33Hz, so the stability of the rotor was secured. And do not overlap operating speed. So, the rotor system can be designed so that can avoid the critical speed.

3. Seismic qualification

3.1 Finite element model

A three dimensional model was constructed of an AFWP using a commercial finite element analysis program, ANSYS. Work was done to simplify as much as possible the parts needed for the analysis of the modeling, which consists of pumps, motors, and base. Figure 5 represents the completed finite element model of a AFWP. The three dimensional model was converted into a finite element model as shown in Fig. 5 to perform the modal analysis and seismic analysis.

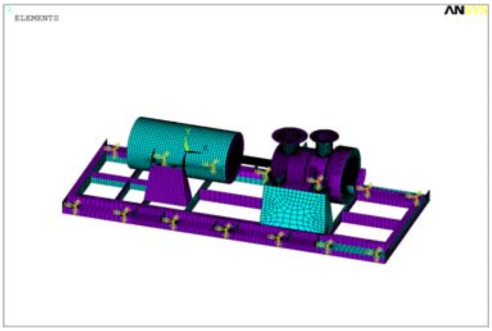


Fig. 5 Finite element model of AFWP

Table 3 Material properties

Material	SA-487 CA6NM	SA-36
Young's modulus	200 GPa	193 GPa
Poisson's ratio	0.3	0.28
density	7650 kg/m^3	7860 kg/m^3

The finite element model was created with the number of nodes 51,570 and elements 52,091. The finite element analysis model of the motor and pump shown in Table 3 was applied to the SA-487 CA6NM. Otherwise, the material property of the SA-36 was applied. A Shell63 element and multi-point constraint 184 (MPC184) elements were used for modeling. The shell63 element has six degrees of freedom at each 4 nodes: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. The MPC184 comprises a general class of multipoint constraint elements that apply kinematic constraints between nodes. In this paper, the rigid link is used to apply bolt confinement and nozzle loads.

3.2 Modal analysis

The modal analysis was performed before seismic analysis in order to verify the structural integrity for an earthquake. To decide on the analysis method, the structure was first determined to be either a rigid device or flexible device depending on the results of the mode analysis. The analytical model was constrained for all degrees of freedom at 14 points, because the structure is fixed to the floor using 14 anchor bolts. The boundary condition is shown in Fig. 5. The completed modal analysis is the shape shown in Fig. 6 and the results are shown in Table 4. In other words, from looking at the results, the first mode was 27.9 Hz, so it was considered to be a flexible device because the earthquake frequency was within 33Hz. So, a dynamic analysis should be performed.

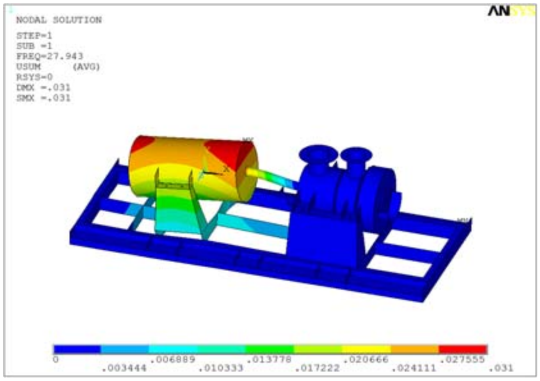


Fig. 6 First mode shape of AFWP

Table 4 Natural frequencies

Mode	Frequency (Hz)
First	27.9
Second	34.3
Third	47.4

3.3 Seismic analysis

A response spectrum analysis using ANSYS was performed. It may be that resonance is possible in the spectral data (seismic waves) because the mode analysis results represent that a first mode exists within 33Hz. And stress values can be calculated by Eq. (1) after entering a value that corresponds to the acceleration values.

$$\sigma = \sum_{n=1}^{N} |\sigma_n| = |\sigma_1| + |\sigma_2| + \cdots + |\sigma_N| \quad (1)$$

A nozzle load was determined using Eq. (2) and (3) respectively, a force and moment was applied value of total 6 components are described in Table 5. The suction and discharge parts in the analysis model, respectively, with a nozzle load applied, are shown in Fig. 7. Fr and Mr are defined as follows;

$$F_r^2 = F_x^2 + F_y^2 + F_z^2 \quad (2)$$

$$M_r^2 = M_x^2 + M_y^2 + M_z^2 \quad (3)$$

Based on the results of the mode analysis, an AFWP is flexible. Therefore a dynamic analysis is performed. To perform the dynamic analysis, load combinations are applied in Table 1. A normal analysis was performed by considering dead weight and nozzle loads. So, the OBE load and SSE load were applied through the floor response spectra curve occurrence in the developing region of nuclear power. To judge the structural integrity at nine important locations, allowable stress values and the stress analysis results were compared. Each of the location details are shown in Figs. 8 and 9.

The analysis result is shown in Figs. 10, 11 and 12, respectively. And to confirm, the value of stress intensity was compared with the allowable stress. Each part was compared with results is details classified depending on the type of applied properties in Table 6 and Table 7, respectively.

Table 5 Nozzle loads

Operating condition		Suction	Discharge
Normal	Fr [N]	56,423.0	34,233.9
	Mr [N·m]	20,350.8	9,410.6
Upset	Fr [N]	62,065.3	37,657.3
	Mr [N·m]	23,124.2	10,678.7
Faulted	Fr [N]	90,276.7	54,774.2
	Mr [N·m]	39,539.9	18,291.3

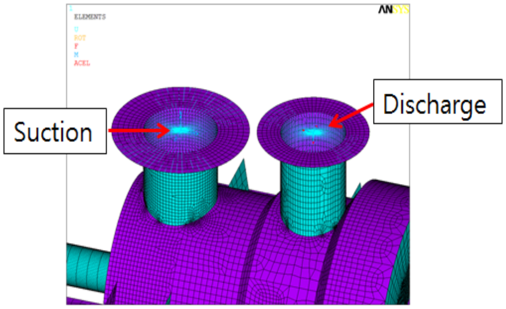


Fig. 7 Applied locations of nozzle load

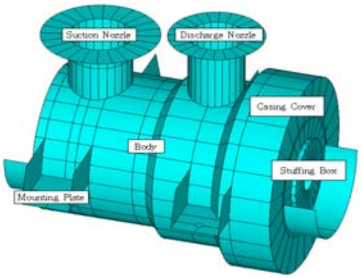


Fig. 8 Parts of pump

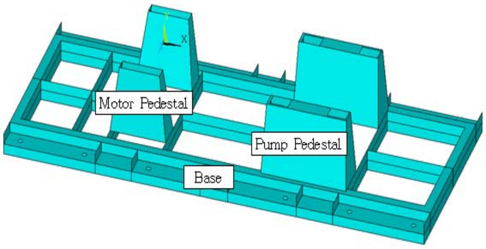


Fig. 9 Parts of base frame

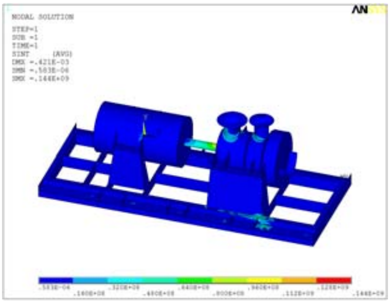


Fig. 10 Stress distribution of normal condition

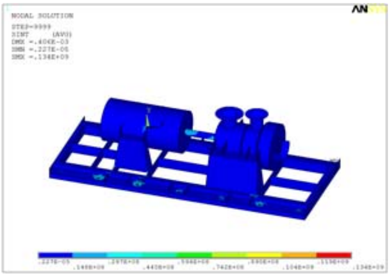


Fig. 11 Stress distribution of upset condition

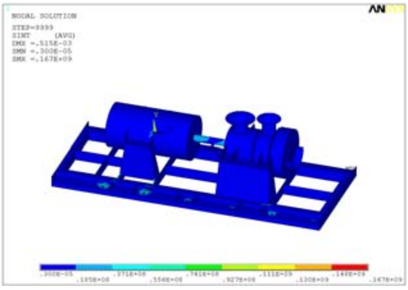


Fig. 12 Stress distribution of faulted condition

Table 6 Result of seismic analysis (SA-487 CA6NM)

Parts	Maximum stress [MPa]		
	Normal	Upset	Faulted
Suction nozzle	0.155	0.123	0.194
Discharge nozzle	0.275	0.199	0.295
Body/shell	0.758	0.404	0.538
Stuffing box	0.244	0.384	0.562
Casing cover	3.153	0.146	0.217
Mounting plate	1.800	7.404	10.54
Allowable stress [MPa]	324.7	357.2	357.2

Table 7 Result of seismic analysis (SA-36)

Parts	Maximum stress [MPa]		
	Normal	Upset	Faulted
Pump pedestal	8.1	10.3	11.2
Motro pedestal	5.9	13.1	16.3
Base	144.0	134.0	167.0
Allowable stress [MPa]	188.9	188.9	188.9

For each condition, as shown in Figs. 10 to 12, the maximum stress occurs in the part of the anchor bolt attached to the floor. The maximum stress for all conditions occurs at the base, as shown in Tables 6 and 7, which is less than the allowable stress.

4. Conclusions

In this paper, rotor analysis confirmed the stability of the pump shaft. We establish a model for the estimation of structural integrity. If the natural frequency that results from a modal analysis is less than 33 Hz, a dynamic analysis, not static analysis, is undertaken. A dynamic analysis was performed taking into consideration seismic conditions such as OBE, and SSE. Finally, an analytical estimation of the structural integrity of an AFWP is performed by making a comparison of the calculated value and the allowable value. Therefore, it was confirmed that an AFWP has sufficienct structural integrity for earthquake loads.

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