

A Study of Analytical Integrity Estimations for the Structure and Rotor System of an Emergency Diesel Generator

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ABSTRACT

This paper describes an integrity evaluation method for emergency diesel generator(EDG) and rotor part of EDG. EDG is a very important equipment in the nuclear power plant(NPP). EDG supplies electricity to the safety-related equipments for the safety shut down of NPP in an emergency situation of earthquake. The safety of the rotor part of EDG is also important during seismic impact from earthquake. The finite element modelling of the EDG including rotor part was constructed. The modal analysis of EDG was firstly performed. The first natural frequency was calculated and revealed higher than the cutoff frequency of seismic spectrum. Then the stress analysis was done to compare with the allowable stress. The safety of the rotor part was investigated by the finite element analysis of the rotor and journal bearing interaction to find film thickness and critical speed. The seismic load was applied to rotor part in a manner that the load was a weighted static load. Analysis results showed that the maximum stress was within the range of allowable stress and the film thickness is larger than the permissible minimum thickness, and the critical speed was out of the operating speed. Hence, the structural and dynamic integrity of EDG could be confirmed by the numerical analysis method used in this paper. However, dynamic analysis of a rotating rotor and supporting bearing with the seismic impact needs to be investigated in a more rigorous method since the seismic load to the rotating part complicates the behavior of rotating system.

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1. Introduction

Emergency diesel generator(EDG) is used in many industrial fields. Especially, in nuclear power plant(NPP), EDG is one of the most important equipments for the safety shut down of NPP in case of emergency such as earthquake. EDG supplies electricity to the safety-related equipments when all the electric powers were off. NPP after shut down still needs electricity to monitor, control the emergency situation and to remove the residual heat in the nuclear core vessel.

Several studies of NPP safety were summarized as follows. A study involving an analytical estimation of the structural health for a main control board in a nuclear power plant was performed by Jung et al.⁽¹⁾. Also, a heat-up calculation for the auxiliary feed water pump room at Ulchin Units 3 and 4 for a loss of HVAC accident was devised by Yoon et al.⁽²⁾. Methods to reduce operating vibration of EDG were proposed by Kim et al.⁽³⁾. Also, numerous studies for the stability of the rotor systems have been conducted on devices such as generators. A study of the design of a tilting pad journal bearing considering the degree of rotor stability was performed by Jo⁽⁴⁾. The effects of a generator retrofit operation on the torsional natural frequency of a turbine-generator train and a study of measurement results were performed by Lee et al.⁽⁵⁾. However, a stability study for EDG with seismic impact has not been studied yet. As shown in this paper, the structural integrity of EDG and also the stability of rotor during seismic

impact should be considered simultaneously.

Numerical model of EDG including the rotor part was formulated. Modal analysis was performed to find the natural frequencies to compare the cutoff frequency of the seismic response spectrum. The stress analysis of EDG was done and the stability of the rotor and bearing was studied to calculate the film thickness of the bearing and the critical speed of rotor.

2. Seismic Qualification Procedure

Three methods are recommended for the seismic qualification of the safety-related equipment: test, analysis and combination of test and analysis^(6,7). Analysis method is preferred when test can not be performed due to the lack of a seismic table capability. EDG is too a big and heavy equipment to be qualified by test.

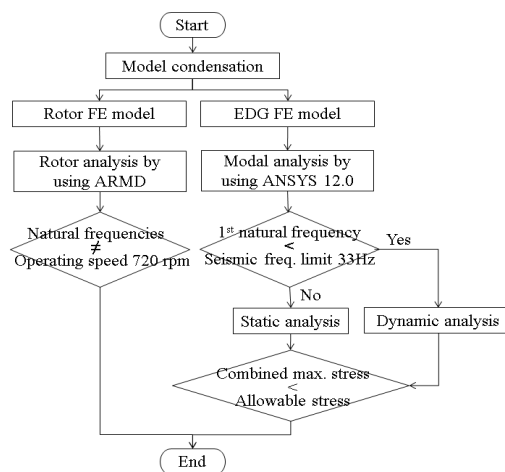


Fig. 1 Flow chart of an integrity evaluation technique

Firstly, modal analysis of EDG is performed. And the first natural frequency is verified as to whether it is within the seismic frequency range. Next, a determination is made as to whether a static analysis or a dynamic analysis is used depending on dynamic properties such as the complexity of the structure, i.e., whether it has rigid or flexible characteristics. The mathematical model is divided into a continuous model and discrete models.

In recent years, numerous seismic analyses have used the finite element method via a commercial computer program such as ANSYS. Numerical results are compared with the allowable stresses to assure the integrity of the structure. Secondly, a simple rotor system model is constructed using ARMD, and then a journal bearing analysis is performed to determine the dynamic characteristics. Here, the critical speed limit for the rotor system is determined by applying the calculated bearing characteristics. The overall estimation process for EDG and rotor part is shown in Fig. 1.

3. Seismic Qualifications

3.1 Finite Element Model of EDG

A three-dimensional(3D) model of EDG was constructed using ANSYS on the basis of 2D drawings. A finite element model was made using the Solid186 element. The EDG housing with the shaft, coil, starter and bearing was also modeled by finite elements. The total mass of the finite element model was compared with that of the actual EDG. As shown in Table 1, the mass difference is 0.03 % which is within 10 %. The finite element model was acceptable. The modeling of the finite element and boundary conditions for the generator are shown in Fig. 2.

EDG is fixed at the 8 base mounting points. The fixed points of EDG on the building structure were considered as boundary condition of translational(UX, UY, UZ) and rotational(ROTX, ROTY, ROTZ) constraints in the numerical analysis and

the rest part of the housing bottom is considered as simply supported. The rotor and bearing interface is considered to be connected by element coupling in the numerical analysis.

3.2 Modal Analysis of EDG

A modal analysis was undertaken before the seismic analysis in order to compare the first natural frequency of the EDG with the cutoff frequency of the seismic response spectrum imposed to the EDG. The structure of EDG can be considered as rigid or flexible according to the comparison result.

As shown in Fig. 3, the first natural frequency

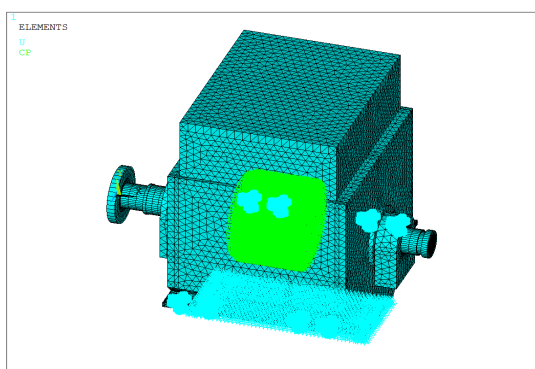


Fig. 2 Boundary conditions of the EDG

Table 1 Comparison of the total masses

Actual body	Finite element model	Error(%)
23,500 kg	23,493 kg	0.03

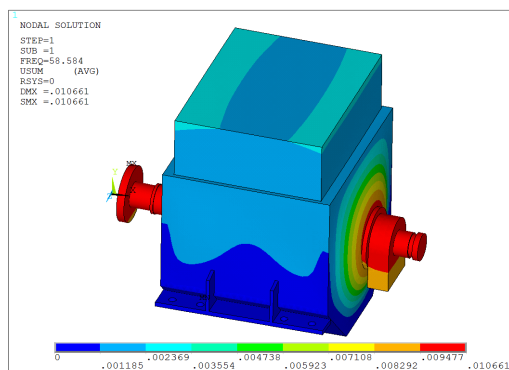


Fig. 3 First natural frequency and mode shape

of the EDG from the result of the modal analysis was 58.6 Hz, which is larger than the cutoff frequency of the seismic spectrum, 33 Hz. Therefore, the EDG structure was considered as a rigid body and the static analysis for stress was performed with maximum seismic load as an input force.

3.3 Seismic Analysis of EDG

The EDG was considered rigid based on the result from the modal analysis. Therefore, a static analysis was performed. In this case, the seismic

forces are determined by multiplying the mass of the equipment by the maximum dynamic acceleration value. Normal, upset, and faulted load conditions were considered. The applied *g* levels include a 10 % margin, as shown in Table 2.

Allowable stress levels of materials for EDG are shown in Table 3. The calculation results of the maximum stresses and allowable stresses for EDG material are summarized in Table 4.

For the normal, upset and faulted conditions, the maximum stress, as shown in Fig. 4 to Fig. 6, occurs in the part of the foot bolt which is attached to the floor. The maximum stresses and the allowable stresses are compared in Table 4. All the maximum stresses are much less than the allowable stresses to show the structural integrity of the EDG.

Table 2 Loading conditions

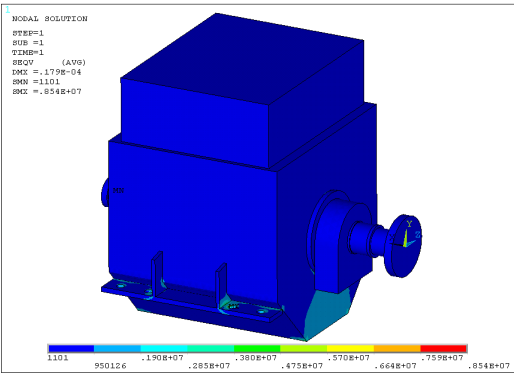
Operating conditions	Directions	Applied <i>g</i> levels [<i>g</i>]
Level A (normal)	E-W	0
	N-S	0
	V-S	1
Level B (upset)	E-W	0.495
	N-S	0.495
	V-S	1.33
Level D (faulted)	E-W	0.99
	N-S	0.99
	V-S	1.66

Table 3 Material and allowable stress

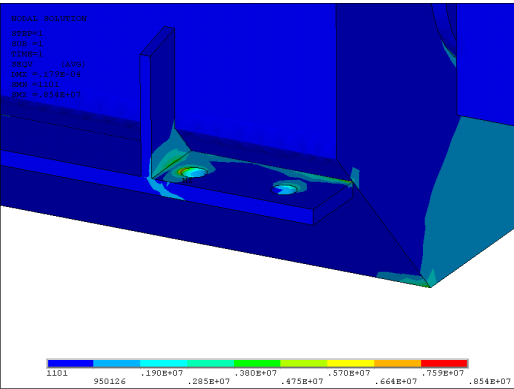
Material	Tensile yield strength, <i>S_y</i> [MPa]	Level A allowable stress, 0.6 <i>S_y</i> [MPa]	Level B allowable stress, 1.33 × 0.6 <i>S_y</i> [MPa]	Level D allowable Stress, 0.95 <i>S_y</i> [MPa]
KS B 1002-86	392.7	235.6	313.4	373.1

Table 4 Static analysis results

Operating conditions	Parts	Material	Max. stress	Allowable stress
Level A (normal)	Base foot bolt	KS B 1002-86	8.5	235.6
Level B (upset)	Base foot bolt	KS B 1002-86	39.3	313.3
Level D (faulted)	Base foot bolt	KS B 1002-86	72.1	373.0

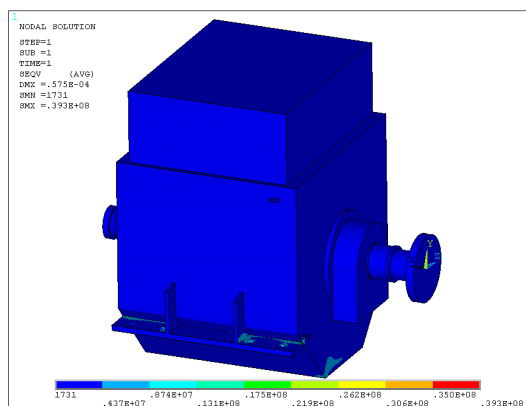


(a) Entire stress distribution

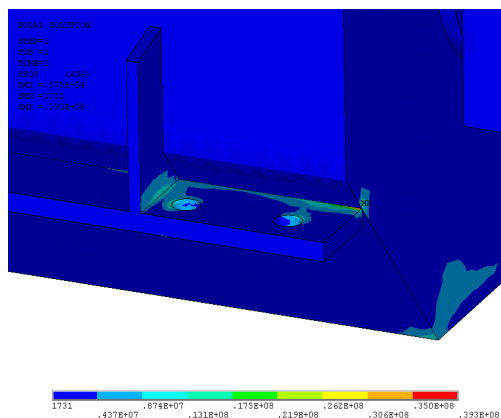


(b) Detailed maximum stress

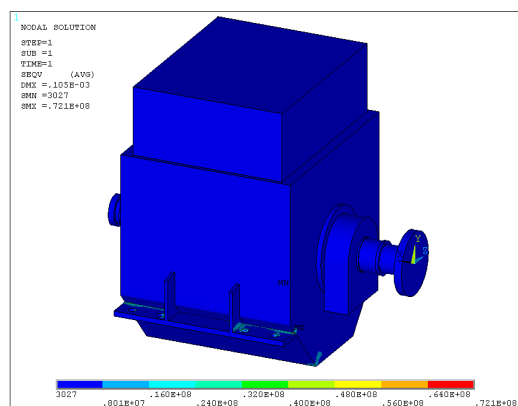
Fig. 4 Maximum stress in the normal condition



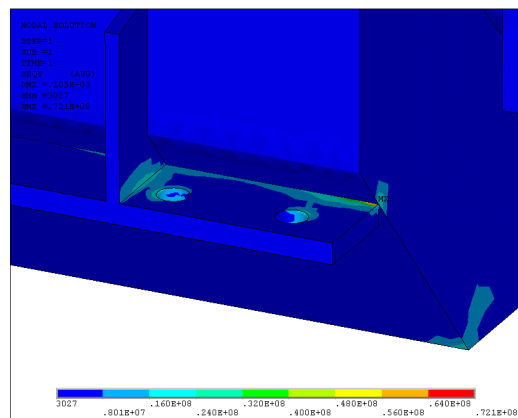
(a) Entire stress distribution



(b) Detailed maximum stress

Fig. 5 Maximum stress in the upset condition

(a) Entire stress distribution



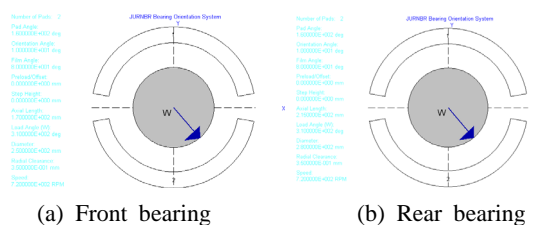
(b) Detailed maximum stress

Fig. 6 Maximum stress in the fault condition

4. Rotor Dynamic Analysis

4.1 Journal Bearing Analysis

An analysis to determine the dynamic characteristics of journal bearings in the rotor system for an emergency diesel generator under the normal condition is performed using a commercial software, ARMD. Figure 7 and Table 5 show the basic configuration of the journal bearing, including the diameter, length, clearance, pad angle, load angle and operating speed. After the finite element model is completed, the lubrication condition is defined. Table 6 shows the calculated stiffnesses and damping coefficients for the front and rear journal bearings.

**Fig. 7** Analysis model of the journal bearing**Table 5** Input data of the journal bearing analysis

Properties	Front bearing	Rear bearing
Ori. angle	10 deg	10 deg
Axial length	170 mm	215 mm
Load angle	310 deg	310 deg
Diameter	250 mm	280 mm
Radial clearance	0.35 mm	0.35 mm
Operating Speed	720 rpm	720 rpm

4.2 Critical Speed Analysis

ARMD is used for the stability analysis of the EDG. Figure 8 shows the two-dimensional(2D) mathematical model constructed using the finite element method. This model includes an operating shaft that is supported by journal bearings. The rotor system consists of 40 elements and 41 nodes.

The rotor system is discretized to two-node beam elements, and the characteristics of bearings are applied to the nodes at the centers of the bearing parts in each case, as shown in Fig. 8.

The stability of the rotor systems is investigated through a stability map analysis of the rotor system considering the stiffness and damping of the designed journal bearings in the Fig. 8.

Table 6 Characteristics of journal bearings

Characteristics	Front bearing	Rear bearing
Min. Film Thick.(mm)	0.064310	0.079008
Power Loss(kW)	1.364	2.033
Supply Oil Temp.(°C)	70.005	70.004
Supply Flow Rate(L/min)	20.37	29.04
Film Temp.(°C)	72.241	72.341
Viscosity(Pa·s)	0.0295	0.0294
Angle(Deg.)	343.5	359.97
Stiffness K_{xx} (MN/m)	585.9	435.9
Stiffness K_{xy} (MN/m)	-166.9	-131.6
Stiffness K_{yx} (MN/m)	-447.4	-314.0
Stiffness K_{yy} (MN/m)	241.9	171.0
Damping D_{xx} (MN/m)	5.286	3.183
Damping D_{xy} (MN/m)	-3.620	-2.195
Damping D_{yx} (MN/m)	-3.602	-2.180
Damping D_{yy} (MN/m)	3.515	2.478

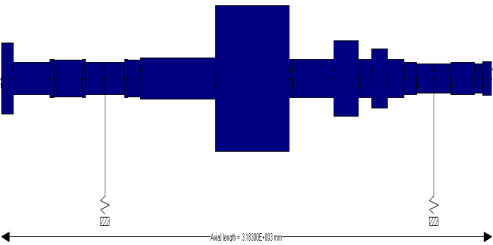


Fig. 8 Configuration of the rotor system

Table 7 and Fig. 9 show the data from each mode and the mode shapes, respectively the calculated natural frequencies are listed in the Table 8. It can be seen that each mode do not overlap the operating speed. From these results, no critical speed in the rotor system exists under the normal condition with no seismic loads.

4.3 Safety of Rotor Under Seismic Load

When seismic loads are applied to the emergency generator including the operating rotor system supported by journal bearings, it is very difficult to calculate the exact behavior of rotor with a simple analytic technique only due to the lots of nonlinearities such as journal bearing and another

Table 7 Mode data of the rotor system

Mode number	1	2	3	4
Speed(RPM)	7200	7200	7200	7200
Stiffness K_{YY} (MPa)	171.0	171.0	171.0	171.0
Freq.(CPM)	312.59	1090.5	3825.6	7334.7
C/Cc	0.96	0.60	0.08	0.42
LogDec	22.76	4.66	0.53	2.95

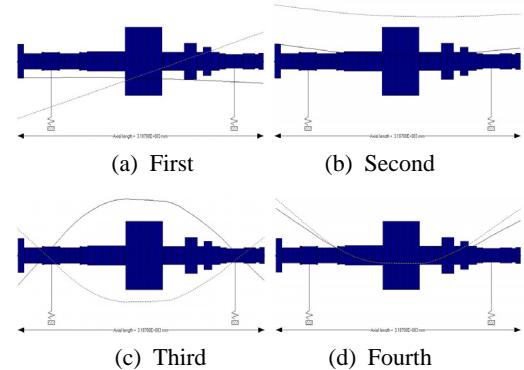


Fig. 9 Mode shapes of the rotor system

Table 8 Natural frequencies of the rotor system

Mode	CPM (=RPM)	Hz
First	312.6	5.2
Second	1090.5	18.2
Third	3825.6	63.8
Fourth	7334.7	122.2

dynamic load on the operating rotor.

In general, each seismic load depending on the occurring site has its size, orientation, frequency and duration independently. Since the behavior of structure and rotor for the generator may be changed by the size and orientation of seismic load if the load is suddenly applied in journal bearing, it is not easy to calculate the supporting loads and dynamic coefficients of the bearings.

However several things for the operating rotor under seismic loads may be estimated. The bearing load will be increased when the sudden seismic load is applied to the rotor. This may lead that the dynamic coefficients will be increased and that the natural frequencies of rotor will also be increased. If first mode is more than 33 Hz, the rotor will be safe for the resonance by the earthquake frequencies. If resonance is occurred for some of modes within 33 Hz and the amplitude is amplified, the bearing load will be also increased and the frequencies of rotor will be changed. So, it is estimated that the effect of resonance will

be attenuated even though seismic load is applied to the rotor.

If some of seismic loads are suddenly applied to the operating rotor, the leaning phenomenon will be produced. This may make the film thickness of journal bearing be thinner than that at the normal operation. At this point, the minimum film thickness should be maintained for the safety of rotor. How to apply the seismic load in the journal bearing-rotor system for calculating the minimum oil film thickness is typically same to that of the structure of generator. However, the experimental and analytic methods will be studied to apply seismic loads accurately.

Since the first natural frequency of the whole structure of generator, 58.6 Hz which is greater than 33 Hz, the film thickness is calculated by the greatest loading condition 1.66 g in the faulted conditions as shown in Table 2 and is compared to the minimum oil film thickness for ensuring the safety of rotor.

Table 9 shows the results of the journal bearing analysis and the minimum oil film thicknesses. As shown in Table 9, the minimum film thickness of the front journal bearing is above 45.7 μm , which satisfies the required film thickness of about 15 μm of the front journal bearing. As shown in Table 9, the minimum film thicknesses of the rear bearings are above 69.4 μm , which also satisfies the required film thickness of about 18 μm for these bearings. Therefore the rotor system will be safe under seismic loading condition.

5. Conclusion

In this paper, a finite element analysis for EDG was performed. Modal analysis for whole body of EDG was firstly carried out to find its natural frequencies. Since the first mode was larger than the seismic cutoff frequency, the static analysis was performed. The structural integrity of the EDG was assured because all the maximum stresses

Table 9 Film thicknesses of journal bearings

Characteristics	Front bearing	Rear bearing
Min. Film Thick.(mm)	0.045697	0.069418
Power Loss(kW)	1.706	2.276
Supply Oil Temp.(°C)	70.004	70.004
Supply Flow Rate(L/min)	20.40	27.73
Film Temp.(°C)	72.796	72.743
Viscosity(Pa·s)	0.02892	0.02897
Angle(Deg.)	337.50	347.05
Stiffness K_{xx} (MN/m)	1229.0	884.5
Stiffness K_{xy} (MN/m)	-351.3	-260.8
Stiffness K_{yx} (MN/m)	-986.6	-660.4
Stiffness K_{yy} (MN/m)	525.5	362.6
Damping D_{xx} (MN/m)	13.45	7.383
Damping D_{xy} (MN/m)	-8.929	-5.125
Damping D_{yx} (MN/m)	-8.895	-5.101
Damping D_{yy} (MN/m)	7.630	5.264

were much less than the allowable stresses

The rotating part of EDG which is the rotor supported by journal bearings, was also investigated to verify the safety. The rotor was safe for its critical speed calculated under a normal condition with no seismic load. The minimum film thicknesses of front and rear bearings under seismic loading condition were larger than the required film thickness.

The more rigorous method is necessary for considering the dynamic characteristics of seismic load in the analysis for safety of rotor and bearing safety.

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