SEISMIC ANALYSIS OF NUCLEAR POWER PLANT CANNED MOTOR PUMP UNIT BASED ON INTEGRAL CALCULATION METHOD

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ABSTRACT

The canned motor pump is a device in one of the most important loops in the nuclear power plant system and key technology research project, of which the seismic requirements shall be checked by Category A. It is required that the structural integrity and electric drive assembly performability of the unit can be ensured during or after operating basic earthquake (OBE) or safe shutdown earthquake (SSE). The author uses Ansys software workbench module to carry out appearance-based three-dimensional modeling, finite element meshing, intrinsic mode analysis, and carry out structural overall element analysis and calculation considering dead weight load and earthquake spectrum load. The results show that the unit major structure rotary and static parts, gear system, bearing parts, bolt and screw strengths meet the requirements and the structure maintains integrity, the relative deformation of the unit rotary and static parts shall be less than the specified value of gap among them, so as to keep the performability and not interfere with the operation. The appearance–based seismic analysis method not only can ensure the calculation accuracy, but also can greatly reduce the workload in calculation and checking, has a certain learning value.

KEYWORDS

Nuclear power plant, Canned motor pump, Ansys integral calculation, Earthquake spectrum analysis

1. INTRODUCTION

The canned motor pump is a device in one of the most important circuit in ACP100+ nuclear power plant system and key technology research project and a valve turning speed governing fully enclosed actuator (hereinafter referred as Canned Motor Pump Drive Assembly). The seismic category shall be considered as 1A, if the performance is ineligible, the unit vibration swing may exceed the allowable value, which will result in high dynamic stress on rotary parts and support system, collision and friction among rotors and stators may occur, which will result in wear and damage, and thus do great harm to the system safe and reliable operation and even lead to accidents in the nuclear power plant. It is required that the structural integrity and electric drive assembly performability of the unit can be ensured during or after operating basic earthquake (OBE) or safe shutdown earthquake (SSE). In recent years, in seismic aspects the researches of scholars at home and abroad mainly focus on nuclear power plant building and equipment static performance[1~3], there are fewer literatures relating to the pump equipments[4~6], and the classical equipment seismic calculation methods mainly include equivalent static method, time history analysis method and response spectrum method. The response spectrum method，which features simple calculation principle, mature theory and considered dynamic characteristics of structure, can determine the structure dynamic response to random load. With sufficient parameters of vibration mode, based on integral analysis, in this article the response spectrum method is applied for seismic calculation of ACP 100+ nuclear power plant system canned motor pump drive assembly.

2. SEISMIC REQUIREMENTS AND MODELS

2.1 Operating characteristics

The canned motor pump drive assembly impellers rotate synchronously with the motor. The structure of canned motor pump drive device is shown in *Figure 1*. The assembly mainly consists of pump main parts (static) (14 and 18), pump main parts (rotary) (13), gear system (24,27 and 30), bearing parts(15,30 and 31) and bolts (21). The basic design parameters are shown in *Table 1*. The material mechanical properties of various parts are shown in *Table 2*. Under earthquake and other load cases, it is required that the major structure static and rotary parts, bearing system, bearing parts, bolt and screw strengths meet the requirements and the structure maintain integrity; the relative deformation among the rotary parts and static parts of the assembly shall be less than the specified value of the gap among them and the performability maintains.

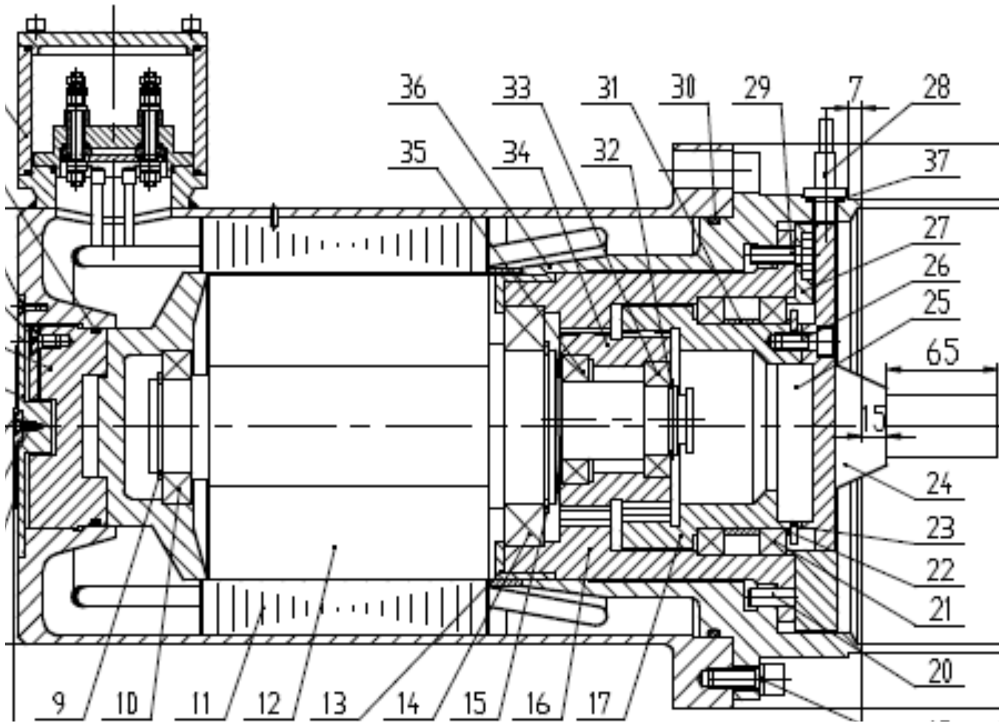


Figure 1 - Canned Motor Pump Drive Assembly Structure

Table 1 - Assembly Ratings

Rated Power (kw)	Rated Speed (r/min)	Air gap (mm)	Allowable air-gap offset (%)
300	1480	1	10%

Table 2 - Material Mechanical Properties of Various Parts

Name	Material and Modulus of Elasticity E /N•m-2	Poisson's Ratio μ	Yield Stress σ s/MPa	Tensile Strength σ b/MPa	Allowable Stress Sm/MPa	Allowable Stress under Seismic Condition Si/MPa
Pump Main Parts (static)	2.06×1011	0.27	460	980	245	368
Pump Main Parts (rotary)	2.06×1011	0.24	510	500	125	188
Gear system	2.06×1011	0.26	235	417	123	125
Bearing Part	2.06×1011	0.26	345	490	125	185
Bolt	2.06×1011	0.27	460	980	245	368

2.2 Structural model

The canned motor pump drive assembly is applied with solid element, beam element, quality element and spring element to build the model under unified consideration that the assembly composed by pump main parts (static), pump main parts (rotary), gear system, bearing parts, bolts and etc. In the calculation model, the pump main parts (rotary) are described by beam element, the total weight of the rotors and other parts are evenly put on the length of corresponding axis of various parts. The pump main parts (static) are described by 8-node Soild 45 element. The axial vents and other gaps of the stator yoke are just considered as simple mess decrement [7]. The support bearing of the canned motor pump drive assembly is applied with multi-point constraint method and is a simply-support structure, the fastener bolts and other parts are connected rigidly. The finite element model of the whole structure includes 3838 solid elements, 36 beam element, 24 quality elements, 64 spring elements, 5036 elements and 6756 nodes in all. The finite element model refers to Fig 2.

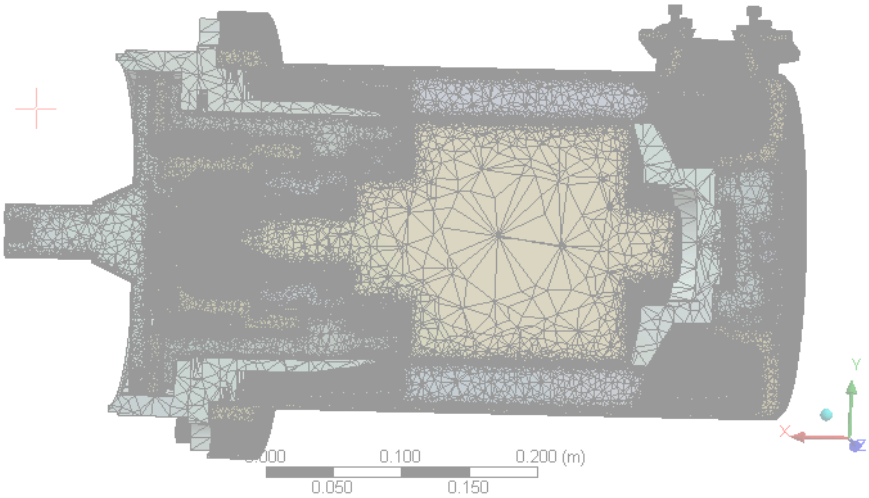


Figure 2 - Finite Element Mesh Model

3. THEORETICAL EQUATION

Through response spectrum concept, the response spectrum method not only considers the relationship between structure dynamic characteristics and seismic dynamic characteristics, but also makes full use of the static theory, skillfully staticizes the dynamic problem, makes the complicated earthquake action on structure and its effect calculation easy and simple [8-10]. Under seismic load, multi-freedom motion matrix equation [11-13] is:

$$M\ddot{x}+C\ddot{x}+K\ddot{x}=M\ddot{x}_g \tag{1}$$

Where, M refers to the structure mass matrix, C refers to the structure damping matrix, K refers to the structure rigidity matrix and x refers to the displacement vector.

The modal analysis is the basis of response spectrum method and dynamic transient and impact analysis and mainly solves the structure frequency and vibration mode. In dynamical property analysis without regard to damping, the free vibration master equation is:

$$M\ddot{x}+K\ddot{x}=0 \tag{2}$$

In modal analysis, the characteristic value represents the square of structure natural frequency (without regard to damp effect), the characteristic vector represents the vibration mode corresponding to that natural frequency .

The modal analysis simplifies the multi-degree-of-freedom system earthquake response into an independent single-degree-of-freedom system earthquake response for calculation. In case of horizontal earthquake, the horizontal earthquake action standard value at Particle i, Vibration Mode j in multi-degree-of-freedom system is:

$$F_{ij}=\alpha_j\gamma_jX_iG_i,\quad \text{i,j=1,2,...,n} \tag{3}$$

Where, F_{ij} refers to the horizontal earthquake action standard value, α_j refers to the earthquake influence coefficient; γ_j refers to the vibration mode participation coefficient; X_i refers to the horizontal relative displacement; G_i refers to the representative value of gravity load focusing on Particle i.

All of the earthquake actions of various vibration modes determined by the response spectrum method is the maximum value, while they do not always occur at the same time and moreover is not necessarily in same direction. Therefore, when solving the total effect S of earthquake actions, as the max absolute value is taken from various time-history responses during spectrum curve making, a larger result will be attained by simply adding the S_j. For this reason, the modalities are required to be combined. Considering the probability, the seismic code uses the method of Square Root of Sum of Squares (SRSS), calculates the structure earthquake action effect S_j according to the earthquake action standard value F_{ij} of multi-degree-of-freedom system Vibration Mode j Particle i, then it calculates the square root and square of S_j at the same position of various vibration modes as well as the total seismic effects of that position, i.e.

$$S = \sqrt{\sum_{j=1}^{n} S_j^2} \tag{4}$$

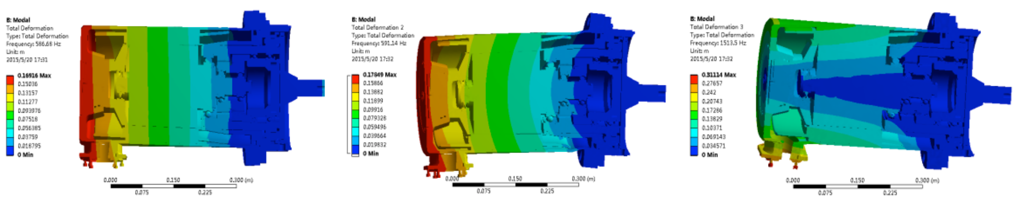
Where: S refers to the total seismic effect, S_j refers to the effect of action caused by Type j horizontal earthquake. In this article modal combination is applied with SRSS method and in the meanwhile the high order mode of which the seismic response is not more than 10% is neglected.

4. MODAL ANALYSIS

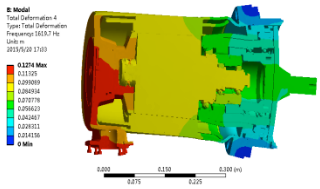
With modal calculation for the canned motor pump drive assembly and assembly basic structure mechanical property analysis, this has calculated the electric drive assembly overall 9-order mode. As seen in vibration mode Fig 3, the first two orders of the vibration mode of different parts of that electric drive assembly are the vibration mode of spindle. During modal analysis, the constraints are set single as possible as it can be, therefore the above modal calculation result is relatively conservative, the third and forth order of the vibration mode is in Y and Z direction, from the fifth to ninth order the vibration is in X direction. Table 3 shows: the first order natural frequency of various parts is greatly higher than 33Hz. In accordance with nuclear safety code HAF0215, methods including equivalent static method can be applied for assembly seismic analysis.

Table 3 - Integral natural frequency (Unit: Hz)

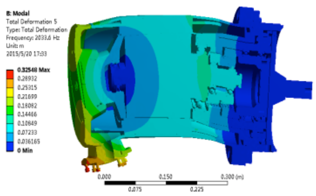
Order	1	2	3	4	5	6	7	8	9
Natural Frequency	586.68	591.14	1513.5	1619.7	2033.6	2064.2	2999.2	3097.6	3101.6



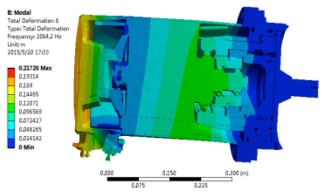
(1) First order mode *(2) Second order mode* *(3) Third order mode*



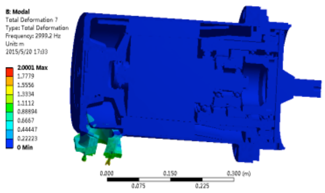
(4) Fourth order mode



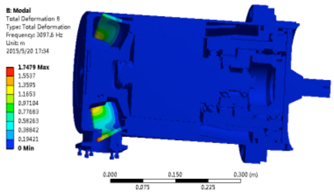
(5) Fifth order mode



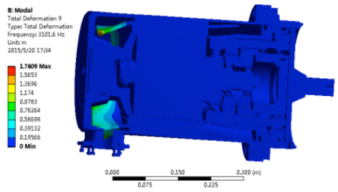
(6) Sixth order mode



(7) Seventhorder mode



(8) Eighth order mode



(9) Ninthorder mode

Fig 3 Electric Drive Assembly Integral Mode

5 CALCULATION AND ANALYSIS

5.1 Load and constraint

This calculation mainly considers the dead weight and earthquake response spectrum load and in the meanwhile rationally considers the resistance ratio. The dead weight load actually is a kind of mass force, including the assembly weight and medium weight, all loads act on the unit of every part of the canned motor pump drive assembly and belong to static load. *Table 4* is the response spectrum in horizontal direction (elevation:0.0m) and *Table 5* is the response spectrum in vertical direction (elevation:0.0m). As shown in *Table 6*, the main factors having influences on the resistance ratio during vibration are structure vibration mode, material characteristics, strain and vibration frequency. When defining the earthquake response spectrum, in nuclear power equipment codes of various countries different items are come up with quantitative damping ratio. This article applies a damping ratio of conservative 2%.

Table 4 - Response Spectrum in Horizontal Direction (Elevation: 0.0m)

Frequency(Hz)	Acceleration (g)				
	2%	4%	5%	7%	10%
0.2	0.04	0.04	0.03	0.03	0.03
2.50	0.47	0.36	0.31	0.28	0.25
3.50	0.47	0.37	0.34	0.31	0.27
5.58	1.02	0.70	0.62	0.51	0.43
7.80	1.02	0.70	0.62	0.51	0.43
9.14	0.85	0.59	0.50	0.41	
11.50	0.35	0.29	0.27	0.25	0.24
21.50	0.35	0.29	0.27	0.25	0.24
27.00	0.20	0.18	0.18	0.18	0.18
40.00	0.16	0.16	0.16	0.16	0.16
100.00	0.16	0.16	0.16	0.16	0.16

Table 5 - Response Spectrum in Vertical Direction (elevation: 0.0m)

Frequency(Hz)	Acceleration (g)				
	2%	4%	5%	7%	10%
0.2	0.03	0.028	0.03	0.025	0.023
2.30	0.33	0.24	0.22	0.18	0.16
8.25				0.21	0.19
13.1	0.38	0.26	0.24		
17.5					0.16
17.6	0.38	0.26	0.23	0.19	
20.0	0.15	0.14	0.14	0.14	0.14
31.50	0.092	0.092	0.092	0.092	0.092
100.00	0.092	0.092	0.092	0.092	0.092

Table 6 - Typical Item Damping Ratio

Item	Damping Ratio %	
	SSE	OBE
Welding Structure	4	3
Bolted Structure	7	5
Equipment, main Condenser Circulating System, parts	3	2
Pipeline System	4	3

Considering OBE and SSE standards, the calculation shall be relatively conservative, the three accelerations of the earthquake spectrum (2 mutually perpendicular horizontal accelerations and 1 vertical acceleration), i.e. for components in x, y and z three directions determine the acceleration by the earthquake response spectrum, then multiply a coefficient of 1.5. As shown in *Table 7*, when the load is SL-2 (limiting safety seismic motion), make 6g in the three directions simultaneously; under SL-1 (operating basis seismic motion), apply 4.8g specification requirement in three direction simultaneously, for gravity load, in a direction vertically downward, with the acceleration as 1g and g representing the acceleration of gravity =9.8m/s^2.

Table 7 - Part calculation constrains and load conditions

No	Name	Constrains	Load
1	Pump Main Parts (static)	Impose constraints on end and no constraints on rotation, thus the results are conservative	4.8g、6g Seismic load, self-weight load
2	Pump Main Parts (rotary)		4.8g、6g Seismic load, self-weight load
3	Fixation System		4.8g、6g Seismic load, self-weight load
4	Bearing Parts		4.8g、6g Seismic load, self-weight load
5	Bolt		4.8g、6g Seismic load, self-weight load

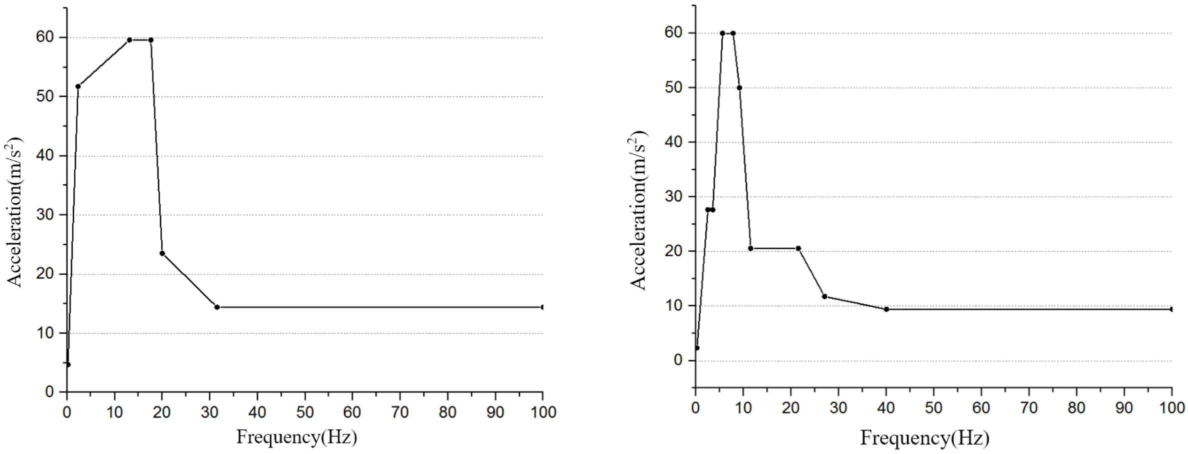
5.2 Load combinations and boundary conditions

The canned pump overall seismic analysis considers two kinds of load cases separately: (1) the loads under safe operation condition (Class B) are: dead weight+ torque+ OBE; (2) the loads under accident condition (Class C) are: dead weight+ torque +SSE. The operating conditions and stress criteria applied in the calculation are shown in *Table 4*. The material properties and acceleration of gravity given in the self-weight load will be calculated by the software itself, in a direction of vertically downward; the torque will be respectively applied at the both ends of the spindle in the opposite direction. Respectively calculate the seismic load in three directions for OBE and SSE load, combine by square root of sum of squares method, at last combine with the stress caused by other loads. *Table 8* shows the stress limits under different loads.

Table 8 - Stress Limit under Different Load

Operating Condition	Load Combination	Stress Limit
Class B	Dead Weight, Torque, OBE seismic load	σm≤1.1S σm (orσL) σb +≤1.65S
Class C	Dead Weight, Torque, OBE seismic load	σm≤1.5S σm (orσL) σb +≤1.80S

Under seismic load, calculate the earthquake response spectrum, with an elevation of 0.0m, a damping ratio of 2% and 6 times of load. *Figure 4* is the earthquake response spectrum input curves.



X direction Y direction

Figure 4 - Earthquake Response Spectrum Input Curve

6. RESULT AND SEISMIC PERFORMANCE ANALYSIS

6.1 Integrity analysis:

Under seismic load, with overall analysis, the calculations show that the max stress appears on the corresponding roller in the middle of the stator shield (in very small areas and cannot see it clearly), as 1.8MPa, mainly induced by large deformation in the middle of the stator shield; in case of much less than the allowable stress (roller main material tensile strength is 560MPa and the min allowable stress is 373MPa), it is as *Figure 5*. For max value refers to *Table 9*.

Table 9 - Integral Earthquake Response Spectrum Equivalent Stress Analysis (Max)

Equivalent Stress (Pa)	Equivalent strain (m/m)
1.8473e6	1.0429e-5

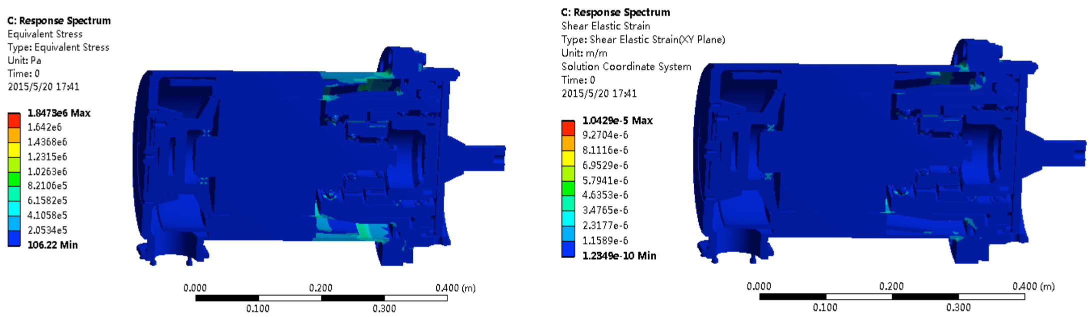


Figure 5 - Integral Earthquake Response Spectrum Stress

6.2 Performability analysis

During an earthquake response spectrum calculation, the integral deformation in rear cover position is larger, in the middle is smaller, in the output end is minimum and even, the value in X direction is relatively smaller, the deformation is relatively even, the value in Y and Z direction is smaller and increases locally, the max deformation in X direction is 5.5267e-7, 1.007e-6 in Y direction and 1.0789e-6 in Z direction, all of which are relatively smaller, it has no influences on the electric drive assembly performability. The distribution is shown in Fig 6 and the max deformation value is shown in *Table 11*.

Table 11 - Integral Earthquake Response Spectrum Deformation Analysis (Max)

Deformation in X direction (m)	Deformation in Y direction (m)	Deformation in Z direction (m)
5.5267e-7	1.007e-6	1.0789e-6

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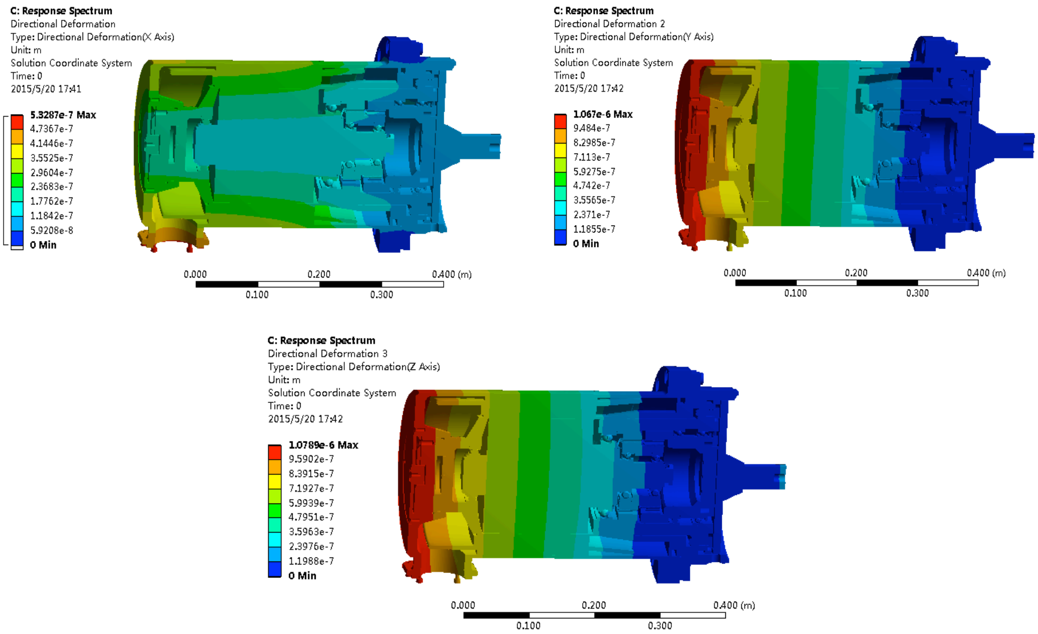

Figure 6 - Integral Earthquake Response Spectrum Deformation

6.3 Evaluation and conclusion

In accordance with nuclear power plant evaluation system, as shown in *Table 12*, based on integral calculation, the max calculated stress of the part is much less than the value required in evaluation criterion and qualified in the check. The seismic analysis of the canned pump requires that under the interaction of SSE seismic load, dead weight and other loads, the perfomability shall be maintained, the relative deformation between the rotor and stator shall be less than the gap between them, so as not to interfere with operation. Due to the strong integral structure rigidity, the absolute displacement of various parts is very small, the max displacement is in the upper cover position of the canned pump, with a value of 0.007mm. The displacement of the canned pump shaft is 0.006mm, mainly are rigid body displacement, the relative deformation between the stator and rotor of the canned pump is 0.007mm, less than 10% of the air gap, as shown in *Table 13*.

Table 12 Equipment Integrity Check

Position	Analysis Method	Load		Calculated Stress (MPa)	Evaluation Criterion (MPa)	Evaluation Result
Integral	Response Spectrum	4.8g Seismic Load	Self-weight Load	1.23	<347	Pass
		6g Seismic Load	Self-weight Load	1.84	<347	Pass

Table 13 - Integral Performability Evaluation Motor Designed Air Gap 1mm

Position	Analysis Method	Load		Deformation（%）	Evaluation Criterion	Evaluation Result
Integral	Response Spectrum	6g Seismic Load	Self-weight Load	X direction <1% Y direction <0.5% Z direction <0.5%	< Designed Air Gap 10%	Pass

Based on canned motor pump drive assembly integral analysis method, this article applies with response spectrum method for seismic calculation of ACP100+ nuclear power plant system canned motor pump drive assembly and draws the following conclusions, under self-weight and seismic load: the parts of the electric drive assembly (main part rotary and static parts, drive gear assembly, bearing and fasteners) meet the RCC-M requirements and can ensure that the integrity of the structure is maintained under safe shutdown earthquake. The deformation of assembly stator and rotor system and gear drive system under seismic load is less than the min operating air gap and meet the performability. The GB50267 Code for Seismic Design of Nuclear Power Plants, HAF102-2004 Regulation on Safety for Nuclear Power Plants Design and HAF103-2004 Regulation on Safety for Nuclear Power Plant Operation is met, the result accuracy is ensured and calculation work amount is greatly reduced. The results of this paper have a certain reference significance for seismic analysis of nuclear power plant canned motor pump unit.

ACKNOWLEDGMENT

The authors would like to thank Xihua University Natural fund (Z1510416)for their financial support, National Science Foundation (51279172).

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