SEISMIC RESPONSE ANALYSIS OF REACTOR COOLANT PUMP IN NUCLEAR POWER PLANT

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ABSTRACT :

The reactor coolant pump in nuclear power plant is the only revolving equipment in the nuclear power plant. Its functional stability will directly affect the security of nuclear power plant. The coolant pump of a very nuclear plant is examined by using response spectrum analysis to analysis dynamic characteristics and responses aiming at finding the natural frequencies of vibration, modes of vibration and seismic responses, and any possible step which may cause damage of the whole system. The favorable spectrum and unfavorable one are investigated as well. The paper focuses on avoiding the detrimental effects caused by earthquakes, therefore may lay down a theoretical foundation for structural design and installation.

KEYWORDS: Seismic response, Dynamic characteristics, Frequencies of vibration, Nuclear power plant

1. INTRODUCTION

The energy is one of most serious problems which humans face. The use of nuclear power is the inevitable result and specific embodiment of human civilization and science technology unceasingly developing. The advantages of nuclear power are that the nuclear fuel volume is small; "burning" does not need the oxygen, no pollution and so on. We know, once leak accident occurs in the nuclear power station, it creates a large-scale destructive disaster possibly. So the use of nuclear power is also a double-edged sword, which demands that, humans must use nuclear power carefully. Then in unstable condition, especially in seismic condition, safe operation is very important. As for the nuclear power stations that, the reactor coolant pump is "the heart" of nuclear reactor and the only revolving equipment in the nuclear power station. Its security rank is the highest level. Therefore dynamic analysis in unsteady condition is extremely essential.

In this paper, we will carry out dynamic analysis for the main pump of nuclear power station in seismic condition.In recent years, people had the thorough understanding to the earthquake. The research on dynamic characteristic of system in seismic condition also had the corresponding progress. The development of seismic response analysis experienced two stages, static method, response spectrum analysis and dynamic method. Static method means that, supposing structure as absolute rigid body, acceleration of each part is same as the ground when earthquake occurs. Maximum value of acceleration is used into structure seismic design. Response spectrum analysis means to calculate the displacement and stress of system with combining the result of mode analysis and another known spectrum. Dynamic method means to idealize the analysis system, then solve the dynamic response of system to some seismic time-history record. Because static method absolutely neglects the distortion of system, does not take account of dynamic property, it isn't accord with real condition and has a large error. But response spectrum analysis can take place of time-history analysis, mainly used in determining the dynamic response of structure to random load or ratio load, for instance, earthquake, wind load, waves and so on. So seismic response analysis of reactor coolant pump in nuclear power plant adopts response spectrum analysis method. Input the earthquake wave by the form of earthquake spectrum from two directions, and then carry on seismic response analysis. The steps of seismic response analysis are that: establishing the dynamic model of system; the mode solving of system; obtaining the spectrum solution.

2. THE ESTABLISHMENT OF THE FINITE ELEMENT MODEL

The main water pump of nuclear power station is shown as Fig.1. The installment is that: there are three

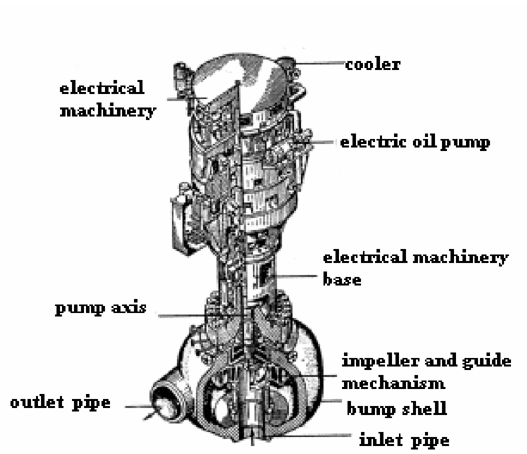


Figure 1 The outside structural drawings of coolant pump in nuclear power station

columns to support the pump body and the electrical machinery, simultaneously there are three tension bars fixed to the foundation at the pump housing crown. Three attenuators are fixed to the foundation in the electrical machinery ledger wall crown; there is a water inlet pipe in the pump housing base, an outlet pipe in the pump housing side. The structure of nuclear power is very complicated; therefore the establishment of mechanics model of nuclear power is more difficult. It's essential to carry on the suitable simplification to the mechanics model of nuclear power: Simplifying pump auxiliary platform, high-pressured cooling pumps, bearing seat, electrical machinery, thrust ring, impeller, impeller cover and so on as mass point; Simplifying connecting rod and column as the pole; Simplifying axis and electrical machinery ledger wall as the beam. The finite element model is shown as Fig. 2.

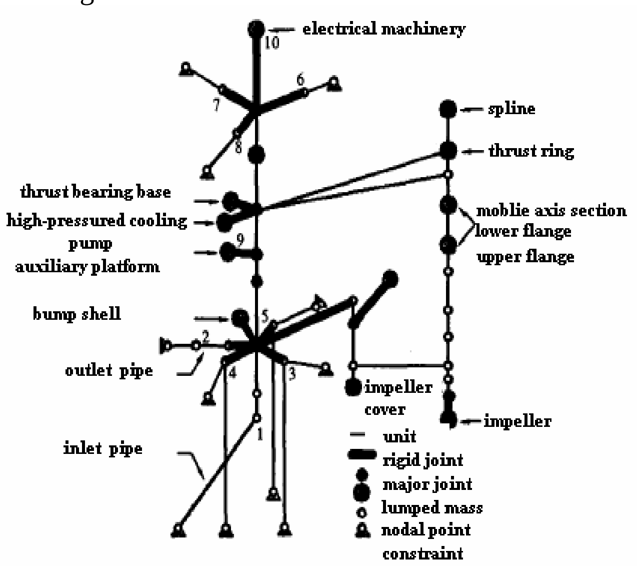


Figure 2 The finite element model of nuclear power

3. THE MODE OF NUCLEAR PUMP

Not considering the damping in the linear, using the following formula e to carry on the computation,

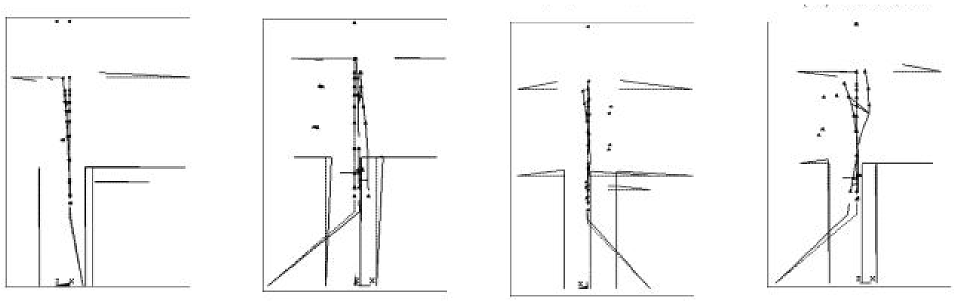
$$M\ddot{u} + Ku = 0 \tag{1}$$

In the formula,

$$u = \Phi_i \sin(\omega t + \varphi) \tag{2}$$

M, K —— the quality and rigidity matrix of system

ω_i , Φ_i —— the natural angular frequency and angle of the ith mode shape



(A) 17.255Hz (B) 26.616Hz (C) 52.670Hz (D) 67.089Hz

Figure 3 Some modes of structure

Substituting formula (2) into formula (1):

$$(-\omega_i^2 M + K)\Phi_i = 0 \tag{3}$$

The situation that we research is $\Phi = 0$, so:

$$\left| K - \omega_i^2 M \right| = 0 \tag{4}$$

Substituting rigidity matrix and nature plate matrix into formula (4), and then extracting various steps natural angular frequency of the nuclear pump:

$$f_i = \frac{\omega_i}{2\pi} \quad \text{(i=1,2,…..,n)} \tag{5}$$

Extracting the natural frequency by the formula (5), taking ω_i into formula (3) to extract various steps of mode shape Φ_i .

Select several steps of typical mode shapes,17.255HZ, 26.616HZ, 52.670HZ, 67.089HZ are shown in Fig.3, Various steps natural frequency values are shown in Table1. Dashed line represents the primary form and solid line represents mode shape. Several spots are mass points which connected to pump body rigidly.

First step mode shape: electrical machinery vibrates along X direction, pump housing keeps static.

Second step mode shape: electrical machinery vibrates along Z direction, pump housing keeps static.

Third step mode shape: pump axis makes bending vibration along X direction, the whole pump body has slight torsional vibration.

Table 1. Various steps natural frequency values

Step number	1	2	3	4	5	6	7	8	9	10
value	16.663	17.255	26.616	31.128	33.033	35.406	35.763	38.838	43.139	49.247

Step number	11	12	13	14	15	16	17	18	19	20
value	49.332	52.670	67.089	71.219	85.040	93.877	113.33	119.00	121.81	124.07

Fourth step mode shape: pump axis makes bending vibration along Z direction, having the biggest amplitude at the place of impeller.

Fifth step mode shape: pump axis makes bending vibration along X direction.
Sixth step mode shape: pump axis makes bending vibration along Z direction.
Seventh step mode shape: pump axis makes bending vibration along X direction.
Eighth step mode shape: pump axis makes bending vibration along Z direction, the whole pump has slight torsional vibration.
Ninth step mode shape: pump axis makes bending vibration along X direction, the whole pump has slight torsional vibration.
Tenth step mode shape: pump axis makes bending vibration in the quadrants of +X,-Z and -X,+Z.
Eleventh step mode shape: pump axis makes bending vibration in the quadrants of +X,+Z and –X,-Z.
Twelfth step mode shape: the whole pump vibrates vertically in the Y direction.
Thirteenth step mode shape: pump axis and electrical machinery base vibrate along X direction and pump axis makes bending vibration along Z direction.
Fourteenth step mode shape: electrical machinery base oscillates along Z direction and pump axis makes bending vibration along Z direction.
Fifteenth step mode shape: pump axis vibrates in the Y direction.
Sixteenth step mode shape: pump axis makes bending vibration and torsional vibration along Y axis.
Seventeenth step mode shape: pump axis makes bending vibration along Z direction.
Eighteenth step mode shape: pump axis and electrical machinery base make bending vibration in X direction
Nineteenth step mode shape: pump axis makes bending vibration along Z direction.
Twentieth step mode shape: pump axis makes bending vibration along X direction.

Looking from the natural frequencies and mode shapes above: Mode shapes of nuclear pump are mainly bending vibration of pump axis. Simultaneously a few mode shapes have slight torsional vibration. Because the structure of pump body is quite complicated and its base frequency is lower. Moreover every two steps frequencies are quite close.

The seismic spectrum which we used is acceleration spectrum, from three different directions, including one vertical spectrum and two lateral spectrums. Inputting two lateral spectrums separately along the positive direction of X axis and Z direction, then spectrum 1 rotates to the positive direction of Z axis and spectrum 2 rotates accordingly, keeping the angle of spectrum 1 and spectrum 2 at 90.Then solve the corresponding displacement response. The detailed spectrum values are shown in table 2-4.

Table2 response spectrum in vertical direction

F(Hz)	0.50	0.53	1.82	7.70	27.0	100.0
value	1.9	2.3	4.7	4.7	1.4	1.4

Table3 response spectrum in horizontal direction

F(Hz)	0.50	0.53	0.67	0.77	2.33	3.3	19.0	33.0	100
value	3.8	4.5	4.5	6.0	11.3	11.3	3.4	1.8	1.8

Table 4 response spectrum 2 in horizontal direction

F(Hz)	0.50	0.53	0.80	1.90	3.13	19.0	33.3	100
value	3.2	4.0	5.6	7.5	7.5	5.9	2.0	2.0

Introduce the principle of multi-degree of freedom system spectrum analysis briefly, u represents the total displacement of multi-degree of freedom system, u_r represents the relative displacement, u_g represents the absolute displacement, shown as Fig.3, the formula of motion can be obtained due to $u = u_g + u_r$

$$M\ddot{u}_r + C\dot{u}_r + Ku_r = -M\ddot{u}_g \quad (6)$$

In the formula
M----mass of system

C----damping of system
K----rigidity of system.
From the transformation of coordinates

$$u_r = \Phi_1\delta_1 + \Phi_2\delta_2 + ... + \Phi_n\delta_n = \Phi\delta \quad (7)$$

The following formula can be expressed as follows:

$$M\Phi\ddot{\delta} + C\Phi\dot{\delta} + K\Phi\delta = -M\ddot{u}_g \quad (8)$$

Multiplying the both sides of above formula by Φ^T :

$$M^*\ddot{\delta} + C^*\dot{\delta} + K^*\delta = F^* \quad (9)$$

In the formula

$$K^* = \Phi^T K\Phi \quad F^* = -\Phi^T M\ddot{u}_g \quad (10)$$

The above formula is decomposed into N numbers of independent single degree formula of motions.

$$\ddot{\delta}_i + 2\xi_i\omega_i\dot{\delta} + \omega_i^2\delta_i = \eta_i\alpha_m \quad (m = x, y, z) \quad (11)$$

In above formula

$$\ddot{u}_g = -\delta_m\alpha_m, \delta_m = Te$$

α_m ------acceleration value of foundation along m direction.

$$T = \begin{bmatrix} 100 & 0 & (Z-Z_0) & -(Y-Y_0) \\ 010 & -(Z-Z_0) & 0 & (X-X_0) \\ 001 & (Y-Y_0) & -(X-X_0) & 0 \\ 000 & 1 & 0 & 0 \\ 000 & 0 & 1 & 0 \\ 000 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

X, Y, Z ------- The coordinates of reference points
X_0, Y_0, Z_0 -------The coordinates of reference points after loading
e ----------Six dimensional unit vector
η_i --------mode participation coefficient,

$$\eta_i = \frac{\Phi_i^T M}{\Phi_i^T M\Phi_i}\delta_m \quad (13)$$

δ_m -------the Direction Vector of input spectrum
The displacement of ith step mode shape is:

$$\delta_i = \eta_i\alpha_{im} / \omega_i^2 \quad (14)$$

Substituting formula (14) into formula (7) , the displacement response of system is obtained .
The components in three directions are substituted into above formula separately to obtain the components of three directions, and then use the combination of mode shapes with square and square root to combine the response.

$$u_r = \left(\sum_{m=1}^{3} u_{im}^2 \right)^{1/2} \qquad u_{im} = \left(\sum_{j=1}^{N} u_m^2 \right)^{1/2} \tag{15}$$

In the formula

u_r ---------the computation of nodal total combination-response,

u_m ---------the combination-response value in m direction,

u_{mj} ---------the absolute value of the jth mode response in m direction,

N---------the total number of dynamic analysis

Substituting the seismic spectrum into above formulas, and also substituting Φ_i, ω_i into it to compute. Calculating one time for each $15°$ and discovering that the aroused vibrating frequency from different directions is different.
The frequency values are 16.663Hz, 17.255Hz, 26.616Hz, 52.670Hz at $0°,15°,30°,135°,150°,165°,180°$ and 16.663Hz, 17.255Hz, 26.616Hz, 3l.128Hz, 52. 670Hz at $45°,60°,75°,90°,105°$.
The frequency values at $120°$ are 16.663Hz,17.255Hz, 26.616Hz, 3l.128Hz,38.838Hz, 52.670Hz.Because the structure of pump is unsymmetrical, when input spectrums from different directions ,the frequencies are different. The various steps of aroused mode shapes are same with mode response frequencies, but amplitudes, velocities, accelerations and stress are different.
The key points of nuclear pump are 1~11,and their displacement responses are larger than other points. If the response displacements of these two points are larger than request of standard, the nuclear pumps can have the dangers even nuclear leakages. So it is essential to research the response displacement of these two points. The schematic diagram of each point's displacement according with variations of seismic spectrum's inputting angles is shown in Fig. 4.

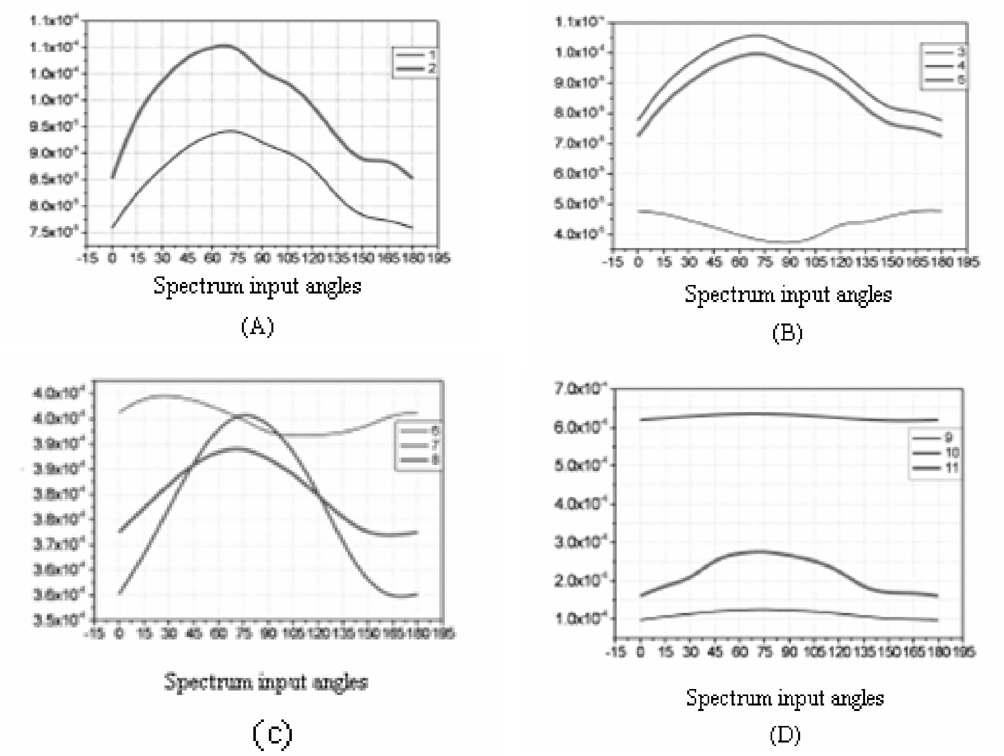


Figure 4 Changing curves of some points' displacement according with spectrum input angle

Looking from Fig. 4(A) we can know, the displacement response of input pipe is smaller than that of output pipe, andits response changes according with the changing trend of input directions of seismic spectrums. But the displacement response values are different, because the distance between input pipe and ground is shorter than that between output pipe and ground. In Fig. 4(B), the displacement response of point 3 is smaller. But the displacement responses of point 4,5 are larger and vibrating response trends are nearly same. So when vibrations happen, the response of cabinet can be regarded approximately as the torsional vibration across point 3. Because connecting methods of point 4,5 to the foundation are same and different from point 3. In Fig. 4(C), there are three attenuators fixed to foundation between electrical machinery and its ledger wall. The rigidities of three attenuators are same and lengths are different. The length of attenuator which connects to point 6 is largest and its displacement response is larger relatively in the most directions. The lengths of attenuators at point 7,8 are close ,so the displacement responses of point 7,8 have no essential difference. But response variations of point 8 according with inputting directions of seismic spectrums are steady than point 7. The changing trends of these three points are different regarding with unsymmetry of pump structure. In chart 4(D), the displacement response of electrical machinery according with inputting directions of seismic spectrums has no large change, but the total displacement response is larger; the displacement response of auxiliary platform according with inputting directions of seismic spectrums also has no large change, and the total displacement response is also smaller; the displacement response of impeller according with inputting directions of seismic spectrums has large change, so failure is easy to happen.
From above analysis we can know, the displacement responses of other points according with inputting directions of seismic spectrums have great changes except for auxiliary platform and electrical machinery. Some point has extreme value in the direction whose angle of spectrum 1 and X axis is 0 and some point has extreme value in the direction whose angle of spectrum 1 and X axis is 90.These phenomena are formed by unsymmetry of pump structure. Therefore these analyses may provide a theoretical reference for structural design and installation of nuclear power plant and reactor coolant pump.

4. CONCLUSIONS

The principle of seismic spectrum response analysis is elaborated, and this method is applied in dynamic analysis of nuclear reactor coolant pump. By mode analysis we can know, because structure of pump is more complicated, every two steps frequencies are quite close. Looking from seismic response analysis we know, the establishment of dynamic model is quite reasonable. The biggest displacement of impeller is 0.27801mm and the biggest displacement of impeller cover is 0.063631mm in seismic response. The gap between impeller and impeller cover is 1.25mm.Therefore the frictions between static parts and rotative parts won't happen in seismic condition. The vibration of motor is quite larger regardless of the direction from which seismic spectrum input, so the phenomenon that motor fling may happens in seismic condition. It is suggested that the direction which earthquakes happen frequently is put in at 45-75 angles of made shape.

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