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Study on Acoustic-Induced Vibration (AIV) by reactor coolant pump at secondary support structure

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ABSTRACT

The reactor coolant pump is the core equipment of nuclear power stations. During the operation of reactor coolant pump, acoustic pulsations are generated due to non-uniform flow within the reactor coolant pump and pass through the main pipe and coolant to the structure in the reactor. The acoustic pulsations can cause the

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vibration of the structure in the reactor, which is regarded as one of the main reasons of fatigue failure of the structure. In this paper, the finite element model of secondary support structure will be built and verified by test, then the pressure pulsations relation between the reactor coolant pump outlet and the secondary structure will be investigated, the pressure pulsation caused by the reactor coolant was calculated. Finally, the acoustic-induced vibration response of secondary support structure caused by the reactor coolant pump were obtained by harmonic analysis and high circle fatigue analysis will be done on the basis of the results. This study is helpful to understand the acoustic-induced vibration of the reactor coolant pump and to improve the hydraulic design of the reactor coolant pump.

Keywords: Acoustic-Induced Vibration, harmonic analysis, high circle fatigue analysis
I-INCE Classification of Subject Number: 30

1. INTRODUCTION

During the operation of reactor coolant pump, acoustic pulsations are generated due to non-uniform flow within the reactor coolant pump and pass through the main pipe and coolant to the structure in the reactor. According to the provisions of R.G.1.20 "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing" [1], it is required to evaluate the impact of pump-induced pulsation on the reactor internals and evaluate it together with other unfavourable flow-induced excitations. It is therefore necessary to evaluate the response and stress caused by pump pulsation together with the stress caused by other unfavourable flow induced excitation.

It can be seen from the flow vibration test of the reactor internals that the safety margin factor of the secondary support structure connecting bolt is relatively small. Therefore, this paper takes the secondary support structure as the research object, establishes the finite element model, and calculates the load and stress of the secondary support structure connecting bolt under the pump-induced pulsating pressure based on the measured pulsating pressure data of the pump inlet and outlet.

The finite element program used in the analysis is ANSYS[2].

2. STRUCTURE AND MATERIALS

The secondary support structure is used to limit the height of the reactor core drop and ensure that the control rod assembly can be inserted into the reactor core in the event of a reactor core drop accident, and can transfer the load of the lower part of the core barrel and the core component to the pressure vessel bottom plate; at the same time, it provides support and positioning for the mechanical buffer of the drive line, bears the impact force when the drive line is dropped.

The secondary support structure is composed of a secondary support cylinder, a support column assembly, a buffer plate, a measuring plate, a pressing assembly, a secondary support positioning key, and so on. The secondary support structure sits directly on the bottom of the pressure vessel and is positioned radially and circumferentially by a secondary support positioning key that is attached to the pressure vessel. The structural material is stainless steel, the modulus of elasticity is 195 GPa, the density is 7900 kg/m^3, and the Poisson's ratio is 0.3. The structure diagram is shown in Figure 1.

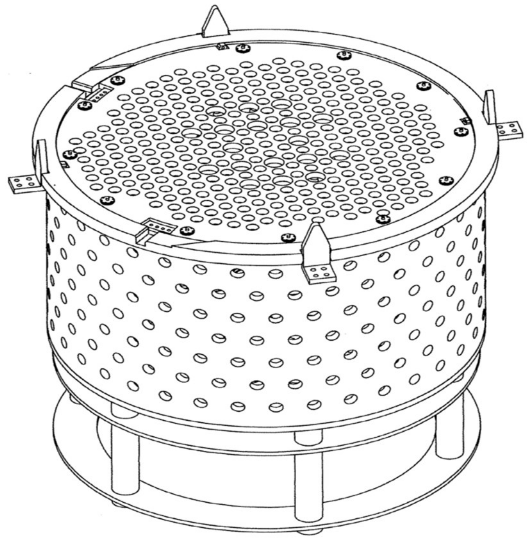


Figure.1 Schematic diagram of the secondary support structure

3. CALCULATION MODEL AND MODAL ANALYSIS

The secondary support structure model takes the intersection of the top plane of the secondary support flange and the central axis of the secondary support cylinder as the coordinate origin, the Y axis is vertically upward, the X axis points to the 0-degree direction of the secondary support cylinder, and the Z axis is determined according to the right-hand rule. Firstly, the model of the secondary support structure in the air is established. The shell93 element is used to simulate the secondary support cylinder, the buffer plate and the connecting plate, and the pipe16 element simulates the secondary support column. The secondary support structure model is shown in Figure 2. The secondary support structure is directly located on the bottom plate of the pressure vessel, and constrains the translational freedom of the bottom node of the secondary support column. The secondary support structure realizes radial and circumferential positioning by the secondary support positioning key fixed on the pressure vessel, and the boundary is simulated by a spring element. The spring stiffness is determined according to the frequency of the secondary support structure measured by the flow-induced vibration test of reactor internals. The radial and tangential spring stiffness is 3.4×10^7 N/m. The boundary conditions of the secondary support structure model are shown in Figure 3.

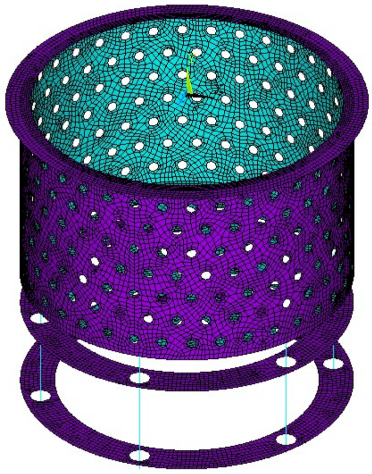


Figure.2 The finite element model of secondary support structure

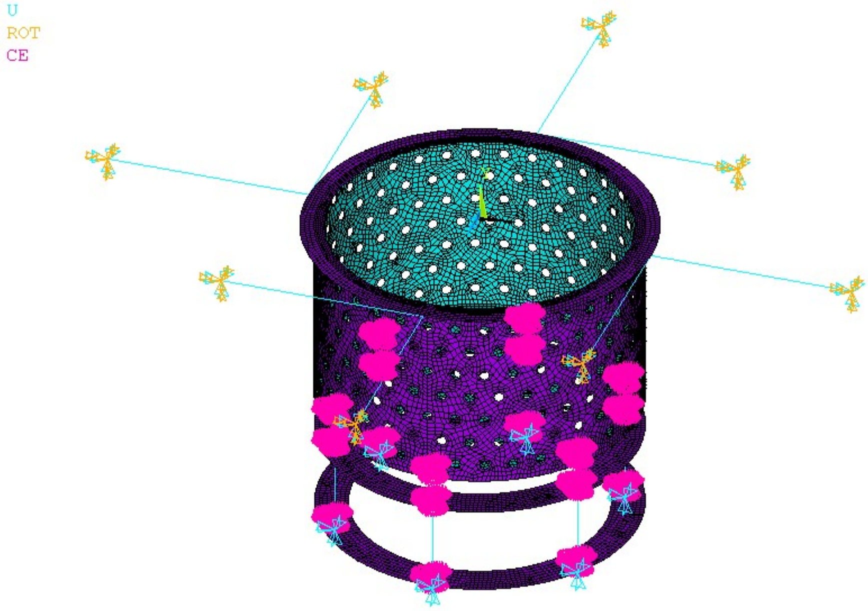


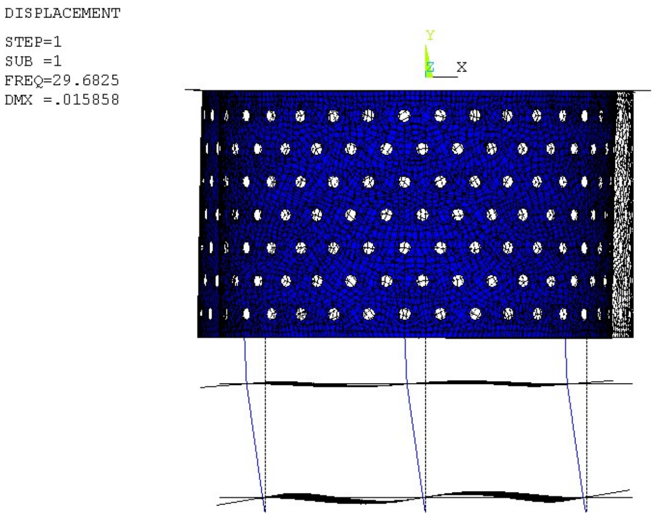
Figure.3 The boundary conditions of secondary support structure

The modal analysis method is used to analyse the vibration characteristics, and the results are compared with those of the flow-induced vibration test of the reactor internals. The comparison results are shown in Table 1. It can be seen from Table 1 that the deviation between the frequency calculated by the finite element model and the corresponding test measurement results is within 5%, and the finite element model can accurately simulate the natural vibration characteristics of the structure in the air.

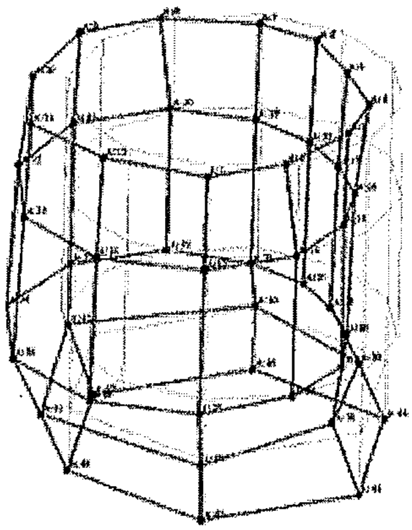
Table 1 Frequency of secondary support structure in air

Order	Calculated value / Hz	Test value / Hz	Deviation
1	37.06	37.25	-0.5%
3	45.32	44.00	3.0%

Based on the finite element model of the secondary support structure in the air, the finite element model of the secondary support structure in the water is established. The influence of water is considered by added mass. The results of the analysis are compared with those of the flow-induced vibration test of the reactor internals. The comparison results are shown in Table 2. The main modes related to the pump-induced fluctuating pressure response are shown in Figure 4 to Figure 6.



（a）Calculated value



(b) Test value

Figure.4 The boundary conditions of secondary support structure

It can be seen from Table 2 that the deviation between the frequency calculated by the finite element model and the corresponding test results is within 5%, and the finite element model can accurately simulate the natural vibration characteristics of the structure in water. The response of the secondary support structure caused by pump-induced pulsating pressure will be analysed using the finite element model in water.

Table 2 Frequency of secondary support structure in water

Order	Calculated value / Hz	Test value / Hz	Deviation
1	29.68	31.05	-4.4%
3	35.00	33.45	4.6%
4	57.64	-	-
6	100.49	-	-
13	216.08	-	-

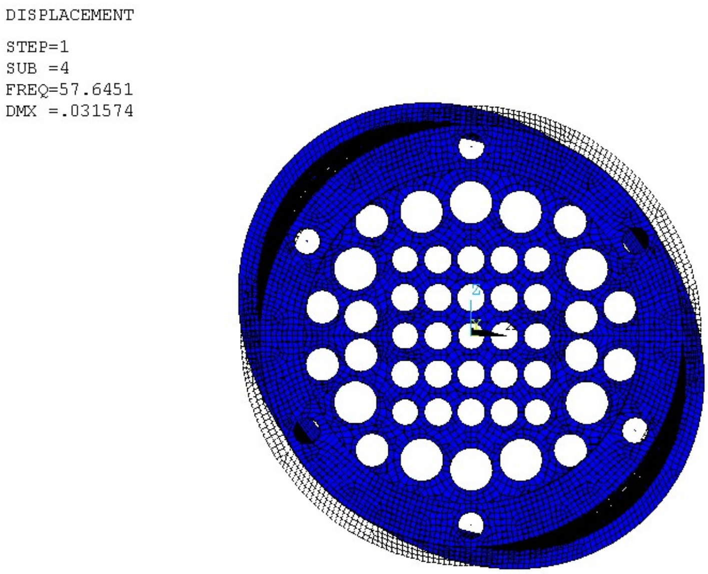


Figure.5 The fourth-order mode shapes of secondary support structure

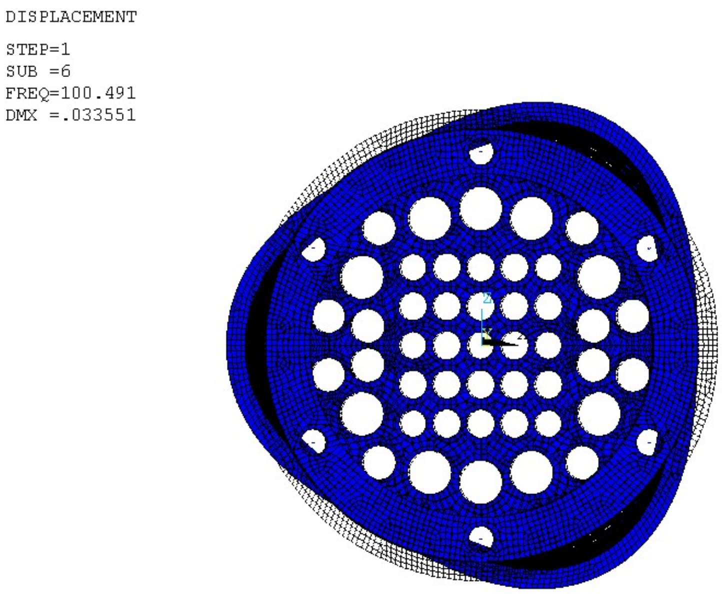


Figure.6 The sixth-order mode shapes of secondary support structure

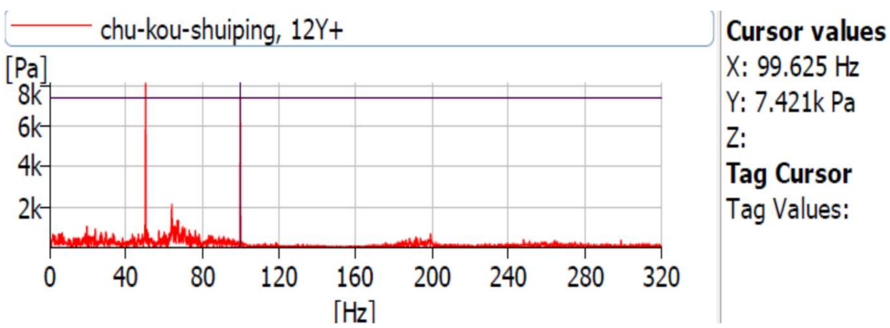
4. PUMP INDUCED PULSATION PRESSURE

Pump-induced fluctuating pressure acting on secondary support structure will be determined by the following two parameters: (1) the measured fluctuating pressure value at the pump outlet position; (2) the fluctuating pressure transfer coefficient (scaling coefficient) from the pump outlet position to the secondary support structure. The fluctuating pressure of the secondary support structure is finally obtained by multiplying the above two parameters.

According to the measured pulsating pressure spectrum data at the pump outlet, the peak value of the pulsating pressure corresponding to the characteristic frequencies (24.75 Hz, 50 Hz, 100 Hz, 200 Hz) of the pump is determined under the operating condition of 1600 m^3/s flowrate. The peak value of the pulsating pressure is shown in table 3, and the spectrum of the pulsating pressure is shown in Figure 7.

Table 3 Pulsating pressure amplitude at pump outlet

Frequency	Pulsating pressure amplitude / kPa
Shaft frequency 24.75Hz	1.00
Shaft frequency multiplier 50Hz	8.10
Primary blade frequency 100 Hz	13.88
Secondary blade frequency 200Hz	4.80



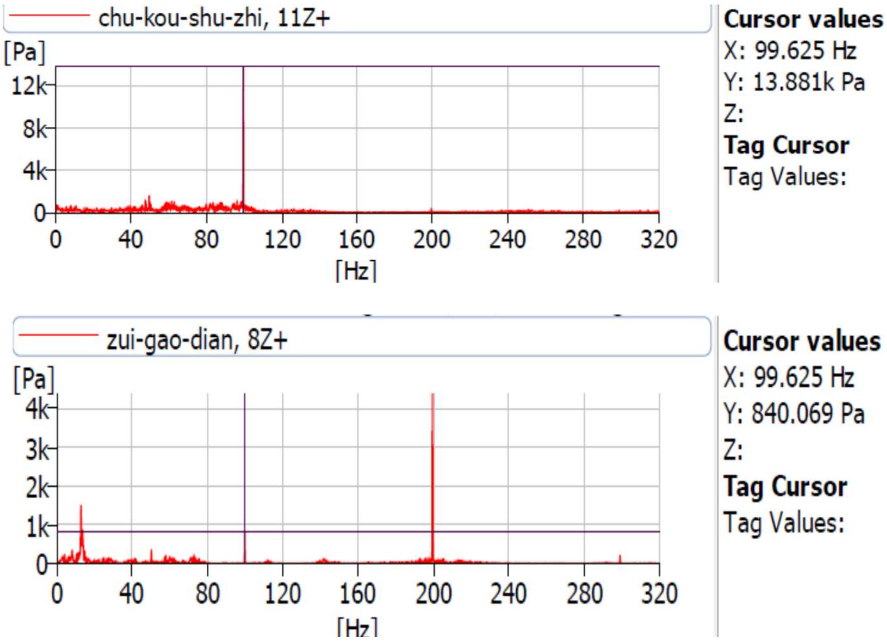


Figure.7 Measured spectrum data of fluctuating pressure

The pulsating pressure transfer coefficient from pump outlet to secondary support structure is calculated by ACSTIC software. Acoustic model of reactor coolant loop is established. The pulsating pressure response of the whole loop is calculated by applying unit pulsating pressure (1kPa) at the outlet of the pump. The pulsating pressure scaling coefficient of secondary support structure is obtained as shown in Table 4. Considering the uncertainties in the calculation, the scaling coefficient takes the maximum value in the range of (+10%) of shaft frequency, shaft frequency multiplier, primary blade frequency and secondary blade frequency.

Table 4 Pulsating pressure scaling coefficient of secondary supported structures

Frequency	Cylinder	Buffer plate
Shaft frequency 24.75Hz	0.09980	0.00866
Shaft frequency multiplier 50Hz	0.12297	0.02528
Primary blade frequency 100 Hz	0.02361	0.00309
Secondary blade frequency 200Hz	0.09482	0.03407

By multiplying the pulsating pressure scaling coefficient (Table 4) of the secondary support structure with the measured pulsating g pressure at the pump outlet (Table 3), the pump-induced fluctuating pressure of the secondary support structure is obtained, as shown in Table 5.

Table 5 Pump-induced pulsating *pressure of secondary support structure*

Frequency	Cylinder/kPa	Buffer plate/kPa
Shaft frequency 24.75Hz	0.09980	0.00866
Shaft frequency multiplier 50Hz	0.12297	0.02528
Primary blade frequency 100 Hz	0.02361	0.00309
Secondary blade frequency 200Hz	0.09482	0.03407

5. STRESS ANALYSIS

By applying the pulsating pressure load in Table 5 to the secondary support structure cylinder and the buffer plate, the response of pump-induced vibration on the secondary support structure is calculated using the harmonic analysis method.

Considering the uncertainty of frequency calculation, the frequency range of harmonic response analysis is in the range of (+10%) of shaft frequency, shaft frequency multiplier, primary blade frequency and secondary blade frequency. There are six supporting columns in the secondary support structure. Each supporting column is connected with the buffer plate by six M12 *30 bolts.

The load at the joint position of each support column and the baffle plate is extracted, and the pump-induced pulsating pressure load acting on the connecting bolt is used to calculate the stress. The bolt diameter is 10.106 mm. The stress amplitudes of the support column connecting bolts in the range of shaft frequency, shaft frequency multiplier, primary blade frequency and secondary blade frequency analysis are shown in Table 6. The number of support columns is shown in Figure 8. The total stress is the sum of the stress amplitudes in the range of shaft frequency, shaft frequency multiplier, primary blade frequency and secondary blade frequency.

6. STRESS ASSESSMENT

According to the provisions of R.G.1.20 "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing" [1], it is required to evaluate the impact of pump-induced pulsation on the reactor internals and evaluate it together with other unfavourable flow-induced excitations. Therefore, it is necessary to evaluate the stress caused by pump pulsation together with that caused by other adverse flow-induced excitations.

Table 6 The connection bolt stress of Secondary support column

Frequency	S1/MPa	S2/MPa	S3/MPa	S4/MPa	S5/MPa	S6/MPa
24.75Hz	3.33	3.51	3.33	3.33	3.52	3.33
50Hz	2.44	2.45	2.44	2.33	2.44	2.33
100Hz	1.09	0.40	1.09	1.08	0.30	1.08
200Hz	1.66	1.60	1.66	1.68	1.66	1.68
Total stress	**8.52**	7.96	**8.52**	8.42	7.92	8.42

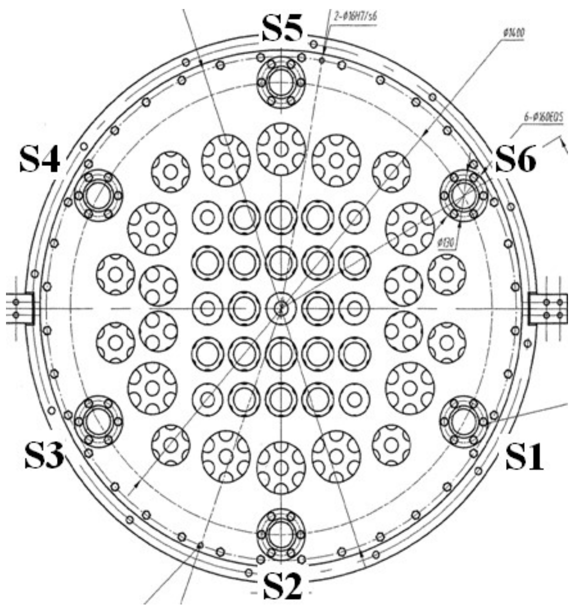


Figure.8 Number of secondary support column

In the flow-induced vibration test of the reactor internals, the measured stress of the connecting bolt of the secondary support column is 26.30 MPa, which is conservatively assumed to be the stress caused by other adverse flow-induced excitation. The total stress is 34.82 MPa by adding the stress caused by pump-induced pulsation, as shown in Table 7.

Under the action of pump-induced fluctuating pressure and other flow-induced excitation loads, the secondary support column connection bolts are evaluated by high cycle fatigue method. According to ASME[3] SECTION III, DIVISION 1-APPENDICES Table.1-9.2, the stress amplitude corresponding to the cycle number of stainless steel components is 93.7 MPa, and the stress of the secondary support column connection bolts is obviously less than the stress fatigue, which can meet the specification requirements.

Table 7 Stress Evaluation of Secondary Support Column Connection Bolts

	Pump induced pulsation stress / MPa	Other flow induced stress / MPa	Total stress / MPa	Stress fatigue Durable limit / MPa
Secondary Support Column Connection Bolts	8.52	26.30	34.82	93.70

7. CONCLUSION

In this paper, the finite element model of secondary support structure has been built and verified by test, then the pressure pulsations relation between the reactor coolant pump outlet and the secondary structure were investigated, the pressure pulsation caused by the reactor coolant was calculated. The acoustic-induced vibration response of secondary support structure caused by the reactor coolant pump were obtained by harmonic analysis and high circle fatigue analysis has been done on the basis of the results. The results show that the stress of the secondary support column connecting bolt under pump-induced pulsation pressure can meet the requirements of the specification. This study is helpful to understand the acoustic-induced vibration of the reactor coolant pump and to improve the hydraulic design of the reactor coolant pump.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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