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The Experimental Research of Flow-Induced Vibration of the Reactor Internal in 600 Mwe N.P.P

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ABSTRACT Qinshan Phase II N.P.P is the first 600MWe P.W.R power station designed by our institute, so it is necessary to carry out model experimental research of FIV of reactor internal. The scale model (1:5) designed according to scaling law. The test method, the test runs, the test data process and analysis were described in this paper. The fluctuating pressure force function that applied to the core barrel and a lot of the response parameters of internal structures were obtained. They are very important information for the further research of FIV of the P.W.R internal.

1. Introduction

During reactor operation, the coolant that flows through internal can induce vibration of internal structure, The flow-induced vibration (FIV) may induce structure fatigue failure or link piece loose and wear. As a result, an accident may take place, the plant must be shutdown and examined and repaired. Thus it may cause tremendous pecuniary loss.

According to past FIV failure experience at plant starts and during operation [1], the safety authorities want to protect the public against adverse consequences, to make sure the designer can control the design, to test new designs & even all sets of internals before operation; the utility wants to protect its investment and to extract the best performance out of it; the designer wants to check its designs and to get enough data for operating new plant. The researcher wants to get the fluctuating pressure force, because of the complexity of internal structure and flow field, it is difficult to get the fluctuating pressure force applied to barrel surface only from theoretical analysis at present, so reduced scale model test simulated operating condition is necessary.

The fatigue life of prototype core barrel of Qinshan Phase II will be estimated by the model test. The force function obtained from measured fluctuation pressure power spectral destiny (PSD) is the input load of prototype core barrel response for the theoretical calculation. A lot of test data for the same type reactor and the benchmark for vibration surveillance and diagnostics of prototype reactor were provided by the test.

2. Test model

2.1 Scaling law requirements

Scaling laws are the theoretical basis of model test. According to the scaling laws, only test data measured from model can be transformed correctly to prototype.

Three scaling laws from fluid Naive-Stoke dynamic equation were introduced

(1) Strouhal number $S_t=fL/V$

This number is the square root of the ratio of hydrodynamic fluctuating forces to fluid inertia forces.

(2) Euler number $E_u=P/\rho_f V^2$

This number is the ratio of fluid inertia forces to pressure fluctuating forces applied to the structure.

(3) Reynold number $R_e=VL/\nu$

This number is the ratio of fluid inertia forces to fluid viscosity forces.

Two scaling laws from cylindrical shell vibration equation were introduced

(4) Representation structure inertia property $\rho_s L^2 f^2/E$

(5) Representation structure dynamic property $PL/\delta E$

From boundary continue condition between shell and fluid $W/t=V_R$, We get another scaling law

(6) $V/\delta f$.

Here, f--frequency V--fluid velocity δ--vibration displacement

ρ_f--fluid specific mass ρ_s--structure specific mass

C was used to represent the ratio of prototype to model, for example, $C_L=L_p/L_m=5$, So called it the similarity number. All the similarity numbers corresponding. Six scaling laws in above should equal to 1, like $C_{st}=S_{tp}/S_{tm}=1$. So $C_\delta=C_L$ $C_f=1/C_L$ $C_v=1$, $C_{\rho s}=C_{\rho f}=1$, $C_P=C_E=1$ have been obtained. It is required that the flow velocity in the model is the same as in the reactor ($C_v=1$). The material and fluid density of the model are the same as of the reactor. So test data was satisfied for $C_\delta=C_L$, $C_f=1/C_L=1/5$, $C_P=1$, $C_\sigma=1$.

The vibration frequencies of the model will be 5 times of the frequency of the prototype and the strain of the model is the same as of the prototype.

But $C_{Re}=1$ is not satisfied, this is mainly due to the scale ratio of the flow velocity and the low viscosity of the reactor primary coolant in hot condition. in most cases, the Reynolds number in the model is far above the threshold level at which the Strouhal number varies, this last number that characterizes the vortex-shedding phenomenon is kept on model.

2.2 Model design

Considering simulation of small link pieces, restriction of test loop flow rate, manufacture cost and many transducers installation, We decided that use 1:5 scale model.

The core barrel, baffle, thermal shield, upper plate, lower plate, upper support assembly, hold down spring etc. have been carefully scaled down on the model including their connection condition. For the fuel assembly, only mass and stiffness were simulated, the vessel thickness was reduced a little according 1/5-prototype size. The support of vessel was simulated to assure rigidity. The size and shape of down-comer annular between vessel and core barrel was simulated, See Fig.1. The deformations of hold down spring and the hold force that applied to core barrel was simulated also.

3. Test methods

3.1 Test loop

The test loop consists of a 1/5-scale model of the reactor for a 2 loop PWR, pressurizer, some valves and instruments. Flow rate is $2 \times 1040\text{m}^3/\text{h}$. Pump head is 65m. Internal diameter of main piping is 300mm.

3.2 Measuring and analysis system

Measuring system consists of U.S.A concurrent computer and Britain CDS software, 96 channels signal could be acquired simultaneously and analyzed signal in line or off line.

3.3 Transducers installation

Twenty accelerometers (PCB WM352 B67), twenty-five dynamic pressure transducers (PCB 113Ml96), twenty displacement sensors were installed in internal structure, and many of them were equally spaced around one circumference line and one axial line of the core barrel.

Eight strain gauges were installed at barrel flange root; two force sensors were located on radial support key near vessel lower flange and used to measure the impact force between core barrel and vessel.

4. Test runs

Table 1 lists all test runs and its purpose. On each run, all transducers acquire signal simultaneously and save data in disk.

Table 1. Test runs and the purpose

Item	Case	Flow rate t/h	Purpose
1	Two pump operation 0.5Vp	1010	Fluctuating pressure distributing at barrel surface. Pressure and response signal varied with flow rate increased. Correlation in various transducers signals. Fatigue analysis use strain signal Statistical analysis of all signal
2	0.6 Vp	1212	
3	0.7 Vp	1414	
4	0.8 Vp	1617	
5	0.9 Vp	1819	
6	0.96 Vp	1940	
7	1.0 Vp	2021	
8	1.03 Vp	2080	
9	Single pump operation 0.6Vp	606	Pressure distributing in single pump operation Response signals in single pump operation compared with normal operation
10	0.9 Vp	909	
11	0.98 Vp	990	
12	1.03 Vp	1046	
13	Transient Valve open--shutdown	0-1940-0	Transient response research Signal various trends with flow velocity continuously
14	Valves open	0-2080	
15	Pump shutdown	2080-0	
16	Two pump operation 1.0Vp	60 hours operation	Fatigue qualification test, accumulated vibration numbers of barrel over 7E6

5. Signal processing and analysis

5.1 Different length signal on different duration have been analyzed, the R.M.S value is always the same. The probability distributing functions are typical normal distribution. The auto correlation function is also the same. So the FIV of core barrel is stationary ergodic random vibration cause by fluctuation flow. Statistical analysis method has been used to describe the signal.

5.2 There are some peaks in PSD curve of acceleration response, the abscissa of peak values are 36Hz; 102Hz; 149Hz; 237Hz, separately corresponding to beam mode (7.2Hz), shell mode (n=2, 20.4Hz; n=3, 29.4Hz; n=4, 47.4Hz) of prototype core barrel, see Fig.2.

The PSD curve of fluctuation pressure is smooth relatively, but the exciting frequency of pump doesn't appear, see Fig.3.

5.3 The distributing of fluctuation pressure and acceleration at core barrel have been obtained. At circular section near inlet nozzle, the maximum fluctuation pressure appears at the location corresponding to inlet nozzle, but at middle circular section of core barrel, the pressure distribute nearly equally, the distributing of acceleration response is as ellipse shape. At axial section, the maximum fluctuation pressure appears at a little distance below inlet nozzle.

The RMS value of fluctuation pressure, strain, impact force were increased with flow rate increased, see Fig.4.

5.4 The maximum value and RMS value of measuring signal by statistical analysis were given in Table 2, the response value of barrel in single pump operating is less than two pump operating. Acceleration of vessel is less than barrel, but the vibration of loop is large than core barrel. Vertical vibration of upper internal structure is very small.

Table 2 The maximum value of measuring signal by statistical analysis

Parameter	Symbol	Unit	Case	Maximum	RMS
Fluctuating pressure	P_{21}	10^{-3}MPa	$1.03V_p$	63	14.2
Barrel strain	SG_4 Axial	με	$0.9V_p$	17.8	4.0
(circular)	SG_5	με	$0.9V_p$	10.9	2.45
Impact force	F_{46}	N	$1.03V_p$	3135	
	F_{48}	N	$1.03V_p$	2023	
Barrel displacement	D_{13}	10^{-3}mm	$1.0V_p$(loosen)	52	11.6
	D_{11}	10^{-3}mm	$1.03V_p$	9.4	2.12
Acceleration	$G_{41\,\mathrm{Barrel}}$	m/s^2	$1.03V_p$	8.2	1.84
(vessel)	G_{36}	m/s^2	$1.03V_p$	0.8	0.20
(loop)	G_1	m/s^2	$1.03V_p$	16.0	3.65
(Upper internal)	G_{59}	m/s^2	$1.03V_p$	1.4	0.3
(Guide tube)	G_{58}	m/s^2	$1.03V_p$	4.45	1.0

5.5 Rain flow method of CDS fatigue software has been used to process signals. To check whether the bolts settled in barrel will loosen or not during operation, it is necessary to do real link bolts vibration qualification test by using barrel acceleration Gp and appearing numbers Np. From model test data Gm, Nm, we can get Gp, Np according to scaling laws.

$$G_p = \frac{1}{5} G_m$$

$$N_p = \frac{1}{5} N_m (1 \times 60 \times 24 \times 365 \times 40) = 4.2 \times 10^6 N_m$$

Here: Gp, Gm is acceleration peak-peak value of prototype and model barrel. Np is the number corresponding to prototype FIV during 40 years operation. Nm is the number corresponding to model FIV test during one minute.

5.6 Fatigue analysis

Elastic high-cycle fatigue evaluation has been carried out according to ASME code. First, rain flow method was used to calculation cycle numbers Nm corresponding to strain value in 30.1s strain time history of barrel model. Then, strain value was transferred to stress value and prototype stress σ_p equaled model stress σ_m and concentration factor was 2, then σ_p equaled two times model stress σ_m. Nm appeared in 30.1s model test was transferred to Np appeared in 40 years life. The value in barrel flange root stress and the cycle numbers were given in Table 3

$$Np=1/5 \times Nm \times (40 \times 365 \times 24 \times 3600/30.1)=8.38 \times 10^6 Nm$$

Table 3. The stress in barrel flange root and the cycle numbers.

Stress value (MPa)	2.84	4.24	5.68	7.10	8.52	9.94	11.3	12.7	14.2
Cycle numbers	2.56E9	1.15E9	9.14E8	7.21E8	3.86E8	2.0E8	1.34E8	8.38E6	1.68E7

According to ASME code section Ⅲ, Division 1-Appendices, Table Ⅰ-9.2.2, fatigue curve A stress value corresponding to the maximum cycle numbers 1E11 is 163.4MPa. In fatigue curve C, the maximum cycles number 1E11 corresponding to stress value is 93.8Mpa. Stress value is only reduced 1.4Mpa with cycle numbers extending from 1E9 to 1E11. So, the barrel stress in table 2 is very small, it's fatigue cycle numbers may be ∞, and the damage factor will be $D \approx 0$.

From above analysis, the barrel vibration by FIV is a low stress high cycle fatigue phenomenon, fatigue life of barrel is more than 40 years operating life of plant.

5.7 It is necessary to transform measured fluctuating pressure PSD to force function as input load of barrel response calculation [2], pressure load function at various location of barrel and various flow velocities can be expressed:

$$G(f,\alpha,\zeta) = G(0,\alpha) \bullet G(\zeta) \bullet G(f) \qquad (1)$$

$$G(f) = \frac{10^2}{10^2 + f^2} \qquad (2)$$

$$G(0,\alpha) = G(f,\alpha,\zeta) \Big|_{\substack{G(\zeta)=1 \\ f=0}} = \left(1.26\alpha^2 - 0.43\alpha + 0.24\right)^2 \times 10^{-6} \qquad (3)$$

$$G(\zeta) = \left(18.3\zeta^3 - 32.6\zeta^2 + 13.9\zeta + 0.5\right)^2 \qquad (4)$$

Here, G(f) is frequency function, G(o, α) is flow velocity function, G(ζ) is position function. $\alpha = v/v_p$, f is frequency, $\zeta = Z/L$, Z is barrel axial coordinate, Z=0 is in barrel flange position, L is length of barrel.

Pressure load PSD function of prototype transformed from model test result according to scaling law can be expressed:

$$G(f,\alpha,\zeta)_p = \frac{4}{4+f^2} G(0,\alpha) G(\zeta) \qquad (5)$$

$$G(0,\alpha)_p = \left(2.82\alpha^2 - 0.962\alpha + 0.537\right)^2 \times 10^{-6} (MPa)^2 / Hz \qquad \alpha = \frac{V}{V_p} \qquad (6)$$

$G(\zeta)_p$ is the same as $G(\zeta)_m$.

5.8 The maximum acceleration, stress, displacement of prototype transformed from model test result according to scaling laws have been compared with calculated response results from specific software and input pressure load function. The compared result was listed in Table 4. Calculation results are larger than test result, so they are conservation.

Table 4 Comparison between test results and calculation results in prototype

Parameter (Maximum)	Displacement (10^{-3}mm)	Acceleration (m/s^2)	Axial stress (MPa)	Circular stress (MPa)
Case	1.0Vp	1.03Vp	0.9Vp	0.9Vp
Test	260	1.64	4.5	3.5
Calculation	300	2.0	5.4	4.3

5.9 After two pumps normal flow rate operating for fatigue qualification test of 60 hours, the accumulated vibration numbers of barrel arrived 7.6×10^6. Removing head vessel and hanging out upper internal, There are no wears in hold-down spring and barrel flange. Lifting up barrel assembly, bolts and link pieces at shield, former, baffle weren't loosened.

6. Conclusion

6.1 The FIV test of scale model designed according to scaling laws has carried out simulated actual reactor different operating case. The experiment result shown that there is no fatigue in the root of core barrel flange during the plant service life.

6.2 There are beam mode and shell mode vibration of the core barrel due to FIV, beam mode, the frequency is 7.2Hz, for shell mode, the frequencies are 20.4Hz, 29.8Hz for n=2,3 respectively. They are very important reference data for .vibration monitor of prototype reactor [3].

6.3 The core barrel is subjected to fluctuation random exciting, the test result provided important force function, which could be used in dynamic response calculation of internal due to FIV.

6.4 There is not any loosen for link pieces after fatigue qualification test.

6.5 Two force transducers located at barrel radial support key provide the impact force time history, if there were 0.04mm gap between the key and vessel, the force would be maximum, see Fig.5.

References

[1] R.Assedo Model Experimentation and Analysis of Flow Induced Vibrations of PWR Internals Nuc.Eng .& Des .27(1974)

[2] Yao Weida etc. Study Analysis for Flow-induced Vibration of the Core Barrel of PWR, 10th SMiRT, 1989.8.

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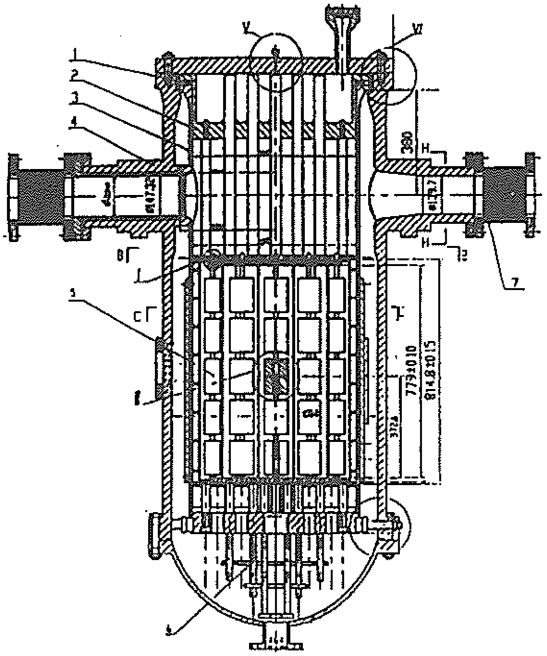


1. Hold down spring
2. Upper internal
3. Low internal (barrel)
4. Vessel
5. Fuel assembly model
6. Bottom mounted instrumentation
7. Corrugated pipe

Fig.1 longitudinal section of test model

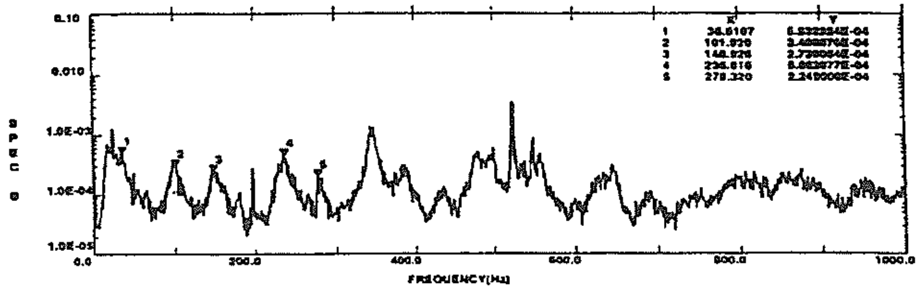


Fig.2 Acceleration PSD curve

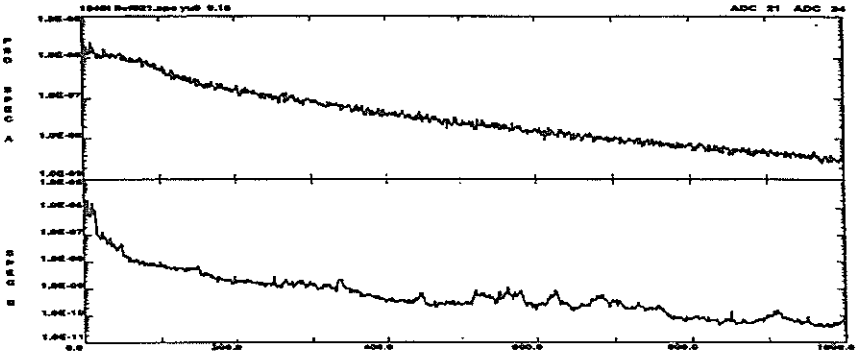
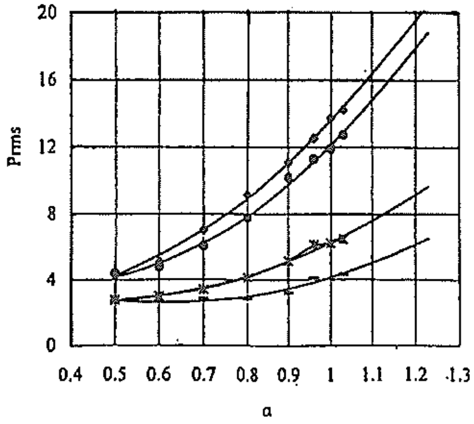


Fig.3 Two fluctuation pressure PSD curves



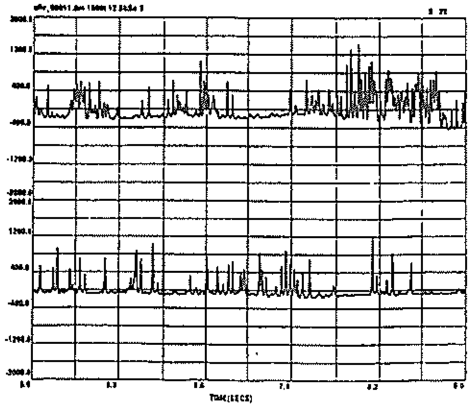


Fig.4 Fluctuation pressure vary with flow rate increased	Fig.5 The time history curve of two impact force transducers