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원자로 내부구조물의 유체흐름에 의한 진동 : 해석 및 실험

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(Flow Induced Vibration of Reactor Internals Structure : Analysis and Experiment)

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Abstract

A series of vibration assessment programs has been performed for Yonggwang Nuclear Power Plant Unit 4 (YGN 4) in order to verify the structural integrity of the reactor internals for flow induced vibration prior to its commercial operation. The structural analysis was done to provide the basis for measurement and the theoretical evidence for the structural integrity of the reactor internals. The actual flow induced hydraulic loads and reactor internals vibration response data were measured and recorded during pre-core hot functional testing of the plant. Then, the measured data have been reduced and analyzed, and compared with the analysis results such as the frequency contents, stresses, strains and displacements. It is concluded that the structural analysis methodology performed for vibration response of the reactor internals due to the flow induced vibration is appropriately conservative, and also that the structural integrity of YGN 4 reactor internals to flow induced vibration is acceptable for long term operation.

1. Introduction

The reactor internals shown in Fig.1 are the complex structures inside the reactor vessel of PWR type nuclear power plant. The reactor internals consist of the core support barrel, the lower support structure, the core shroud, the in-core instrumentation assembly, the upper guide structure barrel assembly, the CEA(Control Element Assembly) shroud assembly and the top hat. The reactor internals has a very important role in supporting and protecting the reactor core including nuclear fuels. Significant amount of static and dynamic hydraulic loadings are applied to the reactor internals structure during the various transient and normal operating conditions over the 40 years service life of the reactor. So, the reactor internals should be designed to avoid any excessive vibration due to the flow induced hydraulic forcing function by the coolant. A series of vibration assessment programs [1] has been performed for Yonggwang Nuclear Power Plant Unit 4 (YGN 4) reactor internals. The purpose of the vibration assessment program is to verify the structural integrity of the reactor internals due to flow induced vibration prior to commercial operation. This vibration assessment program consists of 4 stages : Analysis, Measurement, Inspection and Evaluation. The overall flow chart is shown in Fig. 2. We will discuss each stage of the vibration assessment program in the following sections.

2. Analysis

The purpose of the analysis stage is to predict the dynamic response of the reactor internals due to flow induced loads before the vibration test, and to provide the basis for the measurement and inspection. The methodology used to calculate the dynamic response is divided into 3 parts : calculation of hydraulic loads or forcing function, analysis of the structures to determine their modal characteristics e.g. natural frequencies and mode shapes, and finally, calculation of the response e.g. displacements, strains and stresses. The resulting information on the frequencies, stresses, strains and displacements are going to be compared with the actual measurement data.

2.1 Flow Induced Hydraulic Loads

The flow induced dynamic loads are classified as either deterministic or random according to their variation with time. The deterministic and random components are assumed to be uncorrelated. A complete description of the deterministic and random loads includes information on magnitudes, frequencies and spatial distributions. Deterministic loads are due to harmonic variations in fluid pressure caused by the reactor circulating pumps(pump pulsation). These pulsations propagate throughout the system as acoustic waves. The peaks of the pump pulsations occur at multiples of

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the pump rotor (20 Hz) and blade passing (120 Hz) frequencies. A combination of mathematical analysis and experimental data are used to determine the magnitude, frequencies and distributions of the deterministic loads. Random loads are generated by flow turbulences. All random loads are assumed to be stationary and ergodic. The power spectral densities (PSD) representations in the form of pressure squared per unit frequency versus frequency are developed. As an example, Fig. 3 shows the predicted random turbulence PSD curve for core support barrel at the inlet nozzle elevation. Spatial distributions are described by specifying areas or lengths over which these loads are coherent.

2.2 Structural Analysis Method

The FEM models which describe the structural assemblies are used to obtain the structural response to different loading conditions. Classical modal analysis methods are used to get the dynamic response. Forced response to deterministic and random excitations is obtained using the method of mode superposition.

2.2.1 Core Support Barrel (CSB)

The in-air natural frequencies and mode shapes of the CSB were calculated by an axisymmetric shell finite element code. Then the frequencies in water were computed considering the hydrodynamic effects. The normal mode method is used to obtain the structural response to deterministic forcing functions. Fig. 4 shows the CSB beam and shell mode shapes. The random response analysis calculates the response to the turbulent component of the flow. A lumped mass and beam finite element model of the CSB is developed using the ANSYS code [2]. This model is excited by two PSDs which represent the pressure fluctuations of the turbulent flow in the coolant annulus at different locations, i.e., inlet nozzle area and the other area.

2.2.2 Upper Guide Structure (UGS)

The complete UGS assembly, including UGS barrel, tube bank and CEA shroud is modeled as a lumped mass beam model, which is shown in Fig. 5. The model is used with the STARDYNE code [3] to perform modal analysis as well as deterministic and random response analyses. The UGS tube bank assembly, including support plate, guide tubes and fuel alignment plate, and a typical single CEA guide tube in the UGS tube bank are also modeled and analyzed. Predicted values of strain in the guide tubes and displacement at the UGS support plate are calculated and compared with the measured values.

2.2.3 CEA Shroud Assembly

The CEA shroud assembly, including tubes, webs, tie rods, rings and snubbers is modeled using ANSYS for random and deterministic analyses. The finite element model of symmetric half is shown in Fig. 6. Single CEA shroud tubes with 3 or 4 webs attached are also modeled for components response analysis. The assembly and components responses are combined to predict the responses at the instrumentation locations.

3. Measurement

The objective of the measurement stage is to obtain sufficient data to confirm analyses performed in the previous stage at various conditions such as steady state and transient operations. This confirmation requires data related to both the flow induced hydraulic loads and dynamic response of the structural components.

3.1 Sensors

The sensors for the vibration measurement consist of 6 biaxial accelerometers, 8 pressure transducers and 16 strain gages. Every sensor receives thorough testing to ensure correct operation in the high pressure (2250 psi) and high temperature (564 deg F) water environment condition inside the reactor. The location and purpose of each sensor are described in Table 1. The sensor locations are selected considering the risk of damage to the reactor internals structure during site installation of the sensors, their leads, and the hardware to protect them from flow induced vibration.

3.2 Data Acquisition

The schematic of the data acquisition system (DAS) is shown in Fig. 7. The DAS consists of Signal Conditioners, Data Acquisition Equipment and On-Line Monitoring Equipment. The data acquisition was performed for total 21 test points, which are listed in Table 2. These test points are selected to measure various operating conditions including steady state, transient and background noise conditions. The data acquisition was done at two different frequency ranges (0-500 Hz for high frequency and 0-50 Hz for low frequency readings) for each test point. The sampling frequencies were 1600 Hz and 160 Hz, respectively. All recordings acquired 204,800 samples for each of 36 sensor channels. For those test points identified as transient, only the high frequency recordings actually contain the transient condition because the low frequency recordings were made after the transient condition occured. A two channel spectrum analyzer and an oscilloscope were utilized for on-line monitoring the signals during the tests.

4. Inspection

The reactor internals were inspected in detail before and after the hot functional testing to check if there was any evidence of excessive vibration, loose parts, or other anomalies. In general there was no such an evidence.

5. Data Reduction and Evaluation

Data was reduced in real time to get the root mean square(rms) values for both the responses and hydraulic loads during the tests. The rms values of the response were checked to determine if the response was within the acceptance limits based on ASME code and design features. After completion of the testing, Power Spectral Densities (PSDs), Cross PSDs, Coherence and Phase plots were obtained for all of the individual sensors and/or some pairs of the sensors for all test points. Also, additional calculation was done to separate random and deterministic portions of response PSDs. Comparison between predictions made in analyses stage and measured data was performed for CSB, UGS and CEA shroud.

5.1 Core Support Barrel

Breaking total CSB motion into deterministic and random responses shows that CSB motion is dominated by random response. The first CSB beam mode frequency, which is predicted to be 6.5 - 8.06 Hz, was shown as about 7.5 Hz in biaxial accelerometer at the bottom of CSB. This is further corroborated by the strong coherence with the strain gage data at the upper section of CSB. The predicted CBS shell modes of cos 2θ and cos 3θ, are 16.6 Hz and 22.3 Hz, respectively. There are indications of the CSB shell modes in the strain data in the predicted range even though the response level is very low. The CSB response data was also examined during pump transients, i.e., pump starts and stops. There was no resonance response as the pump frequency changed as expected in the analysis stage. Also, the CSB response stresses are low compared to predicted value as shown in Table 3. Fig. 8 shows the auto PSD of the accelerometer signal at the bottom of CSB.

5.2 Upper Guide Structure

Generally the measured hydraulic forcing function values are smaller or comparable to the predicted values. The responses of the two accelerometers at the UGS Support Plate show peaks at 11 to 13 Hz which are comparable to prediction. The Cross PSD and Coherence plots for the two accelerometers data confirm the lateral type responses at these frequencies. The first lateral mode of the UGS Tube Bank was predicted to be about 26 Hz. This is comparable to the peaks in the above accelerometers data, and the Cross PSD and Coherence between the accelerometers and strain gages at the guide tube. The first mode of the guide tubes is seen in the response peaks at 150 - 170 Hz shown for strain gages at the guide tubes, which is in good agreement with the predicted values. Response strains in the guide tubes show much lower than the predicted values. Maximum displacement of 8.35 mils for the UGS support plate is higher than the predicted value, but still below the acceptance limit of 12 mils. The larger measured response displacement is due to the additional rigid body motion of the UGS caused by hydrodynamic coupling with the CSB, which does not cause any additional dynamic stress of the components as shown by the lower than predicted strain responses in the tube bank. The UGS response stresses are low compared to predicted value as shown in Table 3. Fig. 9 shows the cross PSD between the accelerometer and strain gage signals at the UGS plate and the guide tube, respectively.

5.3 CEA Shroud Assembly

The predicted pump induced and random turbulence pressures are generally matches or envelopes the measured values. The CEA Shroud assembly mode frequencies, which are about 10-22 Hz and 25-50 Hz ranges, are shown in good agreement between the measured and predicted values. The response of individual CEA Shroud tubes and webs shows that the predicted natural frequencies (130-200 Hz range) are in good agreement with the measured values and that the response strains (less than 14 $\mu\varepsilon$ rms) are quite lower than the acceptance level as predicted. The CEA Shroud assembly response stresses are low compared to predicted value as shown in Table 3. Fig. 10 shows the auto PSD of a strain gage response at the CEA Shroud tube.

6. Conclusions

The following conclusions were obtained through the finite element analysis and vibration test program of the YGN 4 reactor internals structure :

a) The measured natural frequencies agreed well with the predicted frequencies.
b) The predicted and measured response displacements, strains and stresses were smaller than the acceptance values. The analysis method was appropriately conservative.
c) There was no indication of loose parts, debris, abnormal corrosion products or excessive motion of the reactor internals before and after the hot functional testing.
d) All design limits of Section III of the ASME code have been satisfied including the fatigue allowables.

Based on the above conclusions, the structural integrity of YGN 4 reactor internals to flow induced vibration is acceptable for long term operation.

References

1. U.S.Nuclear Regulatory Commission Regulatory Guide 1.20, Rev.2, May 1976.
2. ANSYS Ver.5.1, Swanson Analysis System Inc., 1994.
3. STARDYNE , General Microelectronics, 1986.

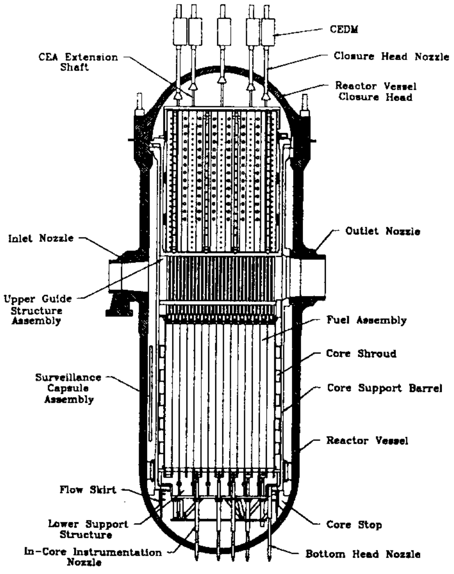

Fig. 1 YGN 4 Reactor Internals Structure

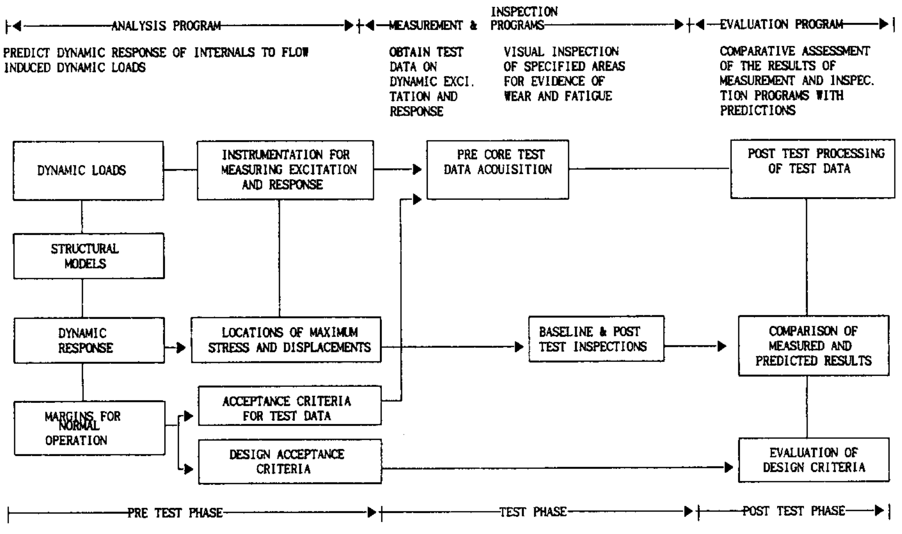

Fig. 2 Flow Chart for YGN 4 Reactor Internals Comprehensive Vibration Assessment Program

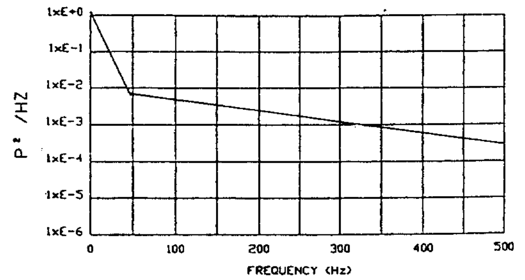

Fig. 3 Power Spectral Density Distribution for Random Turbulence on the Core Support Barrel at the Inlet Nozzle Elevation

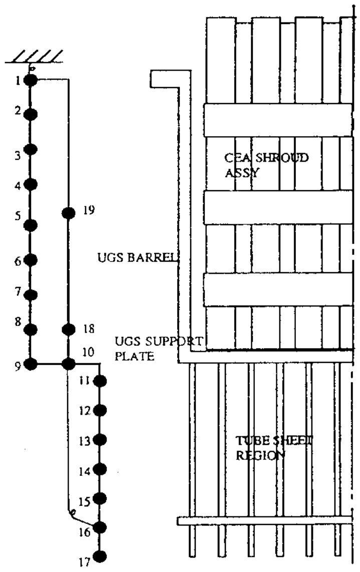

Fig. 5 UGS Assembly Model

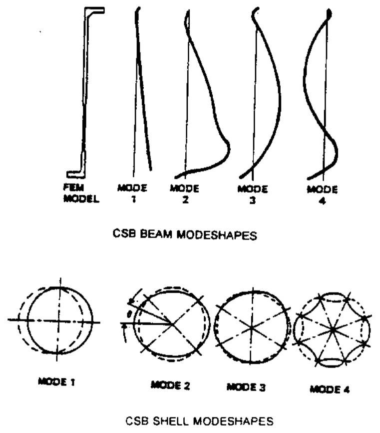

Fig. 4 CSB Beam and Shell Mode Shapes

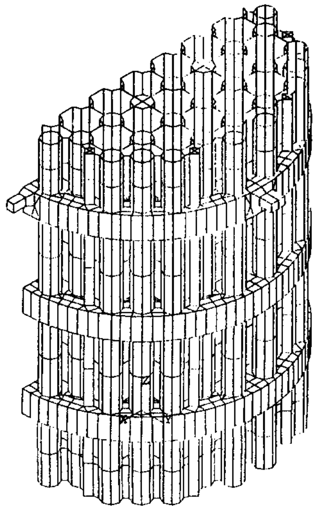

Fig. 6 Finite Element Model of CEA Shroud

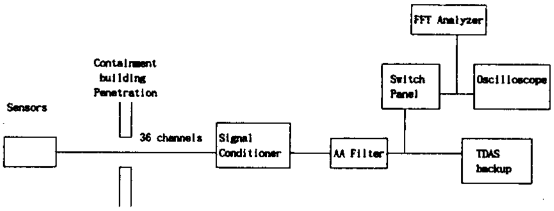

Fig. 7 Schematic of Data Acquisition System

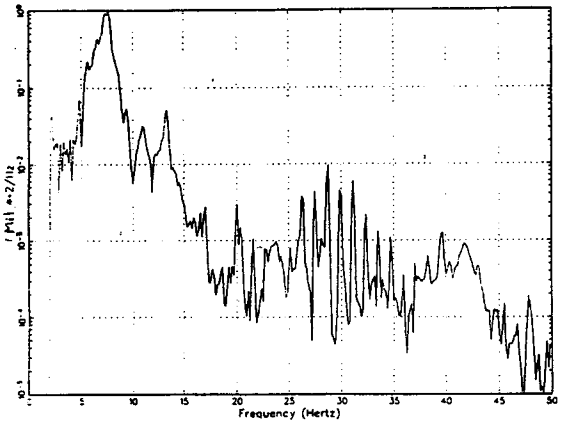

Fig. 9 Cross PSD between Acceleration at UGS Plate and Strain at Guide Tube

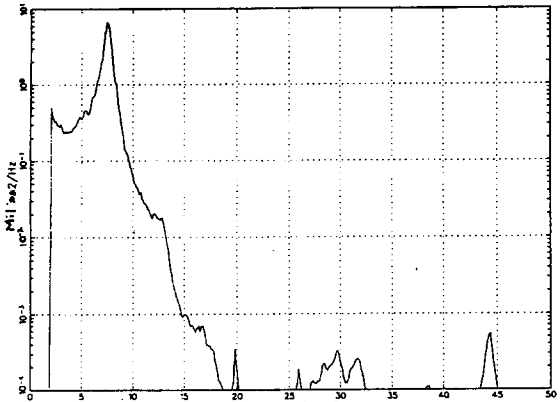

Fig. 8 Auto PSD of Acceleration at Bottom of CSB

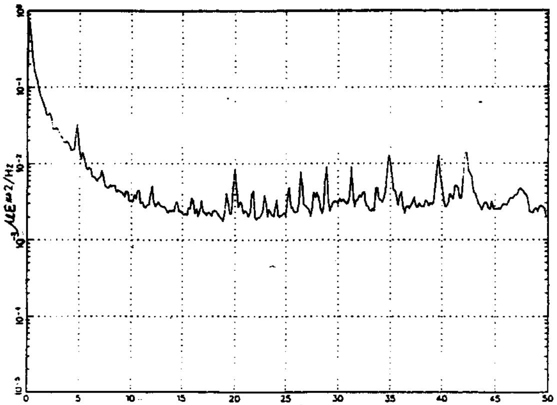

Fig. 10 Auto PSD of Strain at CEA Shroud Tube

Table 1 Sensor Locations and Purposes

Sensor	Location (number)	Purpose
Accelerometers	Near Top of CEA Shroud (2) Near Bottom of UGS Plate (2) near Bottom of CSB (2)	Acceleration at Tubes Acceleration at UGS Support Plate Acceleration at Snubber Elevation
Pressure Transducers	Near Top of CEA Shroud (6) Bottom of UGS Plate (2)	Pressure on CEA Shroud Pressure on Underside of UGS Support Plate
Strain Gages	Near Top of CEA Shroud (8) Near Top of UGS guide tubes (4) Near Top of CSB (2) Near Middle of CSB (2)	Strains at Tubes and Webs Guide Tube Bending Stresses Bending Strain at Upper Flange Circumferential Strain due to shell mode

Table 3 Predicted and Measured Values of RMS Dynamic Stresses at 4 Pumps, 564 °F (unit : psi)

Component	Location	Calculated	Measured
CSB	Upper Flange (0°)	315	67
	Upper Flange (90°)	175	96
	Midplane (0°)	55	12
	Midplane (90°)	35	13
UGS	Guide Tube	720	109
CEA Shroud	Peripheral Web	455	183
	Tube btwn Webs	405	291
	Interior Web	290	112
	Tube at Web	405	165

Table 2 Reactor Internals Vibration Test Points

YGN CVAP NO.	CONDITION	TEMP. °C	RCP				TEST TYPE
			1A	1B	2A	2B	
0*	Noise	65.6	NO	NO	NO	NO	Steady State
1	Pump Start	65.6	NO	NO	S	NO	Transient
2	Pump Start	93.3	S	NO	O	NO	Transient
3	Pump Start	93.3	O	NO	O	S	Transient
4	Pump Stop	126.7	O	NO	O	Sp	Transient
5	Steady State	126.7	O	NO	O	NO	Steady State
6	Steady State	126.7	O	NO	O	O	Steady State
7	Steady State	126.7	NO	NO	NO	O	Steady State
8	Steady State	182.2	O	NO	O	O	Steady State
00*	Noise	182.2	NO	NO	NO	NO	Steady State
9	Steady State	260	O	NO	O	NO	Steady State
10	Steady State	260	O	NO	O	O	Steady State
11	Pump Start	260	O	S	O	O	Transient
12	Steady State	260	O	O	O	O	Steady State
13	Steady State	295.5	O	NO	O	O	Steady State
14	Pump Stop	295.5	O	NO	O	Sp	Transient
15	Steady State	295.5	NO	NO	O	NO	Steady State
000*	Noise	295.5	NO	NO	NO	NO	Steady State
16	Pump Start	295.5	O	NO	O	S	Transient
17	Steady State	295.5	NO	NO	O	O	Steady State
18	Steady State	295.5	O	O	O	O	Steady State

NO = Not Operating
O = Operating
S = Start
Sp = Stop