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Comprehensive Vibration Assessment Program for Yonggwang Nuclear Power Plant Unit 4

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Abstract

A Comprehensive Vibration Assessment Program (CVAP) 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 vibrations prior to commercial operation. The theoretical evidence for the structural integrity of the reactor internals and the basis for measurement and inspection are provided by the analysis. Flow induced hydraulic loads and reactor internals vibration response data were measured during pre-core hot functional testing in YGN 4 site. Also, the critical areas in the reactor internals were inspected visually to check any existence of structural abnormality before and after the pre-core hot functional testing. Then, the measured data have been analyzed and compared with the predicted data by analysis. The measured stresses are less than the predicted values and the allowable limits. It is concluded that the vibration response of the reactor internals due to the flow induced vibration under normal operation is acceptable for long term operation.

1. Introduction

The reactor internals, which is shown in Fig. 1, are the structures within the reactor vessel other than the fuel and control assemblies, and instrumentation. 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 system function of the reactor internals is to support and protect the reactor core. Significant amount of static and dynamic hydraulic loadings are applied to the reactor internals structure during the various transient and normal operation 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. The Comprehensive Vibration Assessment Program (CVAP) has been performed for Yonggwang Nuclear Power Plant Unit 4 (YGN 4) reactor internals. The purpose of the CVAP is to verify the structural integrity of the reactor internals due to flow induced vibration prior to commercial operation. The YGN 4 CVAP consists of 4 programs : (a) Analysis program (b) Measurement program (c) Inspection program (d) Evaluation program. The overall flow chart for the YGN 4 CVAP is shown in Fig. 2. and each program will be discussed in the following sections briefly.

2. Analysis

The methodology used to calculate the dynamic response of the reactor vessel internal structures due to flow induced loads 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. displacement, strain and stress.

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, which peaks occur at multiples of 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 turbulence. 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. Spatial distributions are described by specifying areas or lengths over which these loads are coherent.

2.2 Structural Analysis Method

The mathematical 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. The random response analysis calculates the response to the turbulent component of flow. A lumped mass and beam finite element model of the CSB is developed using the ANSYS computer code. This model is excited by two PSD's which represent the pressure fluctuations of the turbulent flow in the coolant annulus for different locations.

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. The model is used with the STARDYNE computer code 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 in a 1/2 symmetry using ANSYS for random and deterministic analyses. 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 program is to obtain sufficient data to confirm predictions at the conditions of steady state and transient operations. This confirmation requires data related to both the flow induced hydraulic loads and dynamic response of the structural components. The measurement program was planned with adequate instrumentation, with appropriate data reduction to compare predicted and measured values of response and to verify the margin of safety for long term operation.

3.1 Instrumentation

The instrumentation for the vibration measurement program consisted of 6 biaxial accelerometers, 8 pressure transducers and 16 strain gages, located as follows:

- o 6 biaxial accelerometers
  - 2 near top of CEA shroud : Acceleration at Tubes
  - 2 near bottom of UGS plate : Acceleration at UGS Support Plate
  - 2 near bottom of CSB : Acceleration at Snubber elevation
- o 8 pressure transducers
  - 6 near top of CEA Shroud : Pressures on CEA Shroud
  - 2 on bottom of UGS plate : Pressures on underside of UGS Support Plate
- o 16 strain gages
  - 8 near top of CEA shroud : Strains at Tubes and Webs
  - 4 near top of UGS guide tubes : Guide Tube bending stresses
  - 2 near top of CSB : Bending strain at CSB Upper Flange
  - 2 near middle of CSB : Circumferential strain due to shell mode

The above selections and locations were based on the licencing body's position and on the minimization of the risk of damage to the internals during site installation of the sensors and 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. 3. The DAS consists of Instrument Signal Conditioners, Data Acquisition Equipment and On-Line Monitoring Equipment. The data acquisition was performed for 21 test points listed in Table 1 and 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.

4. Data Reduction and Evaluation

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 appropriately for all test points. Also, additional work was done to separate random and deterministic portions of response PSDs. Comparison of predictions and measured data was done for CSB, UGS and CEA Shroud.

4.1 Core Support Barrel

Breaking total CSB motion into deterministic and random response 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 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 CBS shell modes predicted, cos 2θ and cos 3θ, are 16.6 Hz and 22.3Hz, 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 stesses are low compared to fatigue endurance limit and predicted value as shown in Table 2.

4.2 Upper Guide Structure

Generally the measured hydraulic forcing function values are smaller or comparable to the predicted values. The response of the two accelerometers at the UGS Support Plate shows peaks at 11 to 13 Hz which is 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 is 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. However, if it is considered that the measured forcing functions in the tube bank area were considerably lower than predicted, the predicted guide tube responses are more in line with measured values. Maximum displacement 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 fatigue endurance limit and predicted value as shown in Table 2.

4.3 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 range, 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 are in good agreement with the measured values and that the response strains are quite lower as predicted than the acceptance level. The maximum measured value of displacement is larger than the predicted value, but still less than the acceptance level. The higher value is due to the rigid body motion, which does not increase the dynamic response stress. The CEA Shroud assembly response stresses are low compared to fatigue endurance limit and predicted value as shown in Table 2.

5. Conclusion

Evaluation of the analytical predictions, test measurements and visual inspection results has demonstrated the YGN 4 reactor internals structure is structurally adequate and acceptable for long term operation based on the followings:

1. All design limits of Section III of the ASME code have been met.
2. The acceptance criteria based on the ASME code fatigue allowables were not exceeded at all.
3. The measured natural frequencies agreed well with the predicted frequencies in all areas of the reactor internals.
4. The measured response displacements, strains and stresses were smaller than the acceptance values.
5. 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

Reference

1. U.S.Nuclear Regulatory Commission Regulatory Guide 1.20, Rev.2, May 1976, "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing".

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
OO*	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

Table 1 CVAP Test Points

Unit : psi

Component	Predicted	Measured	Fatigue Eudrance Limit
CSB	788	430	16500
CEA Shroud	2430	990	16500
UGS	6480	981	23700

Table 2 Peak Stresses and Fatigue Endurance Limits

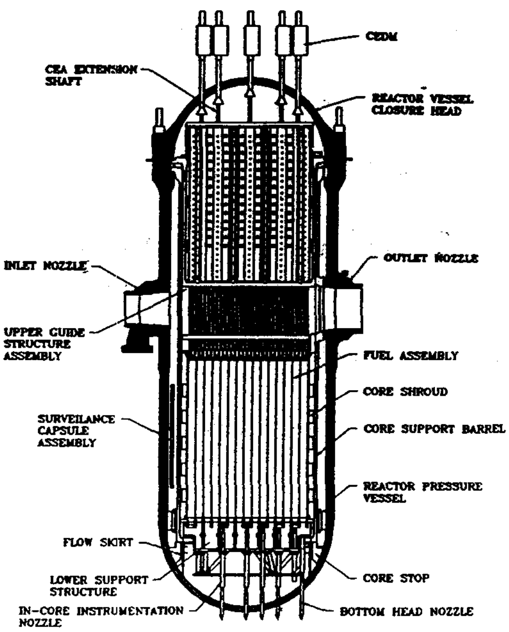

Fig.1 Reactor Internals

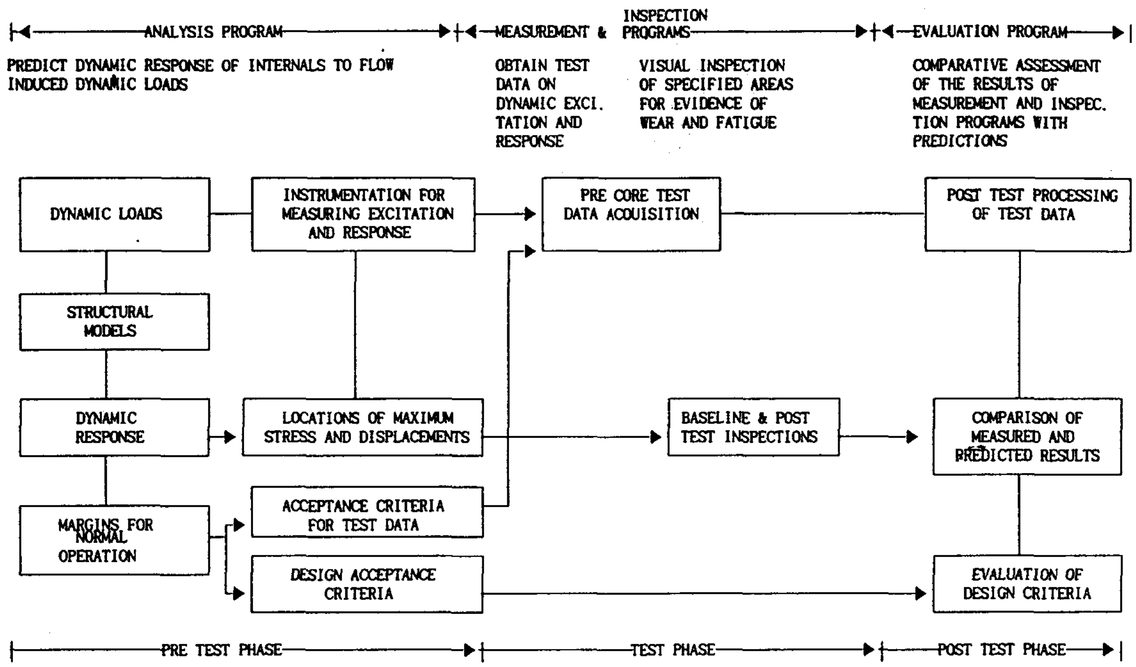

Fig.2 Comprehensive Vibration Assessment Program

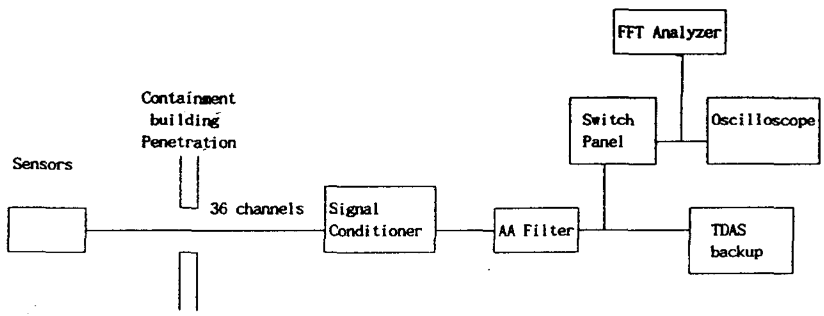

Fig.3 Schematic of Data Acquisition System