Vibration Monitoring of Core Support Barrel in APR1400 Reactor Vessel Based on the NIMS-IVMS Data Evaluation

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1. Introduction

To have a better understanding of the vibration of Core Support Barrel (CSB) in APR1400 reactor vessel, KHNP and KEPCO E&C have jointly evaluated the NIMS-IVMS data of BNPP Unit 2. All of the OPR1000 and APR1400 nuclear power plants have been designed with the NSSS Integrity Monitoring System (NIMS), which has four subsystems, including the Internals Vibration Monitoring System (IVMS) [1].

This paper briefly describes the evaluation results of CSB beam mode and shell mode vibration for the APR1400 based on the engineering experiences and the evaluation methods described in ASME OM, Part 5 standard [2].

2. Methods and Results

The NIMS-IVMS, its monitoring methods, and data evaluation results are explained in this section.

2.1 IVMS Data Acquisition

As shown in Fig. 1, the sensors used for the NIMS-IVMS for BNPP Unit 2 are four channels of Ex-core Neutron Flux Monitoring System (ENFMS) detectors, which consist of three (upper/middle/lower) fission chambers per detector. The ENFMS detector signals are transmitted to the IVMS through the optical isolators.

The IVMS data were acquired during the power ascension test (at 100% reactor power) for the establishment of IVMS alarm setpoint. ASME OM, Part 5 standard classifies the IVMS inservice monitoring program as three phases; baseline, surveillance, and diagnostic phases [2]. The IVMS data described in this paper are parts of the baseline data, classified by ASME OM, Part 5 standard, acquired at the beginning of the first fuel cycle of a new plant, BNPP unit 2. The IVMS baseline data acquired at the BNPP will be used to establish reference data for use in the surveillance and diagnostic phases.

2.2 IVMS Data Reduction

The neutron noise (AC type) time history data acquired from the ENFMS fission chambers can be reduced and transformed to the various forms, including Normalized Cross-Power Spectral Density (NCPSD), Coherence (COH), and Phase (Ø).

The NCPSD provides a descriptor of commonality between two signals from the ENFMS detectors [2]. For the NCPSD calculation the signals from two ENFMS detectors, which are located on opposite sides of the core, are used in this paper. As shown in Fig. 1, the ENFMS channels 1&4 and 2&3 are the detector pairs located on opposite sides of the core.

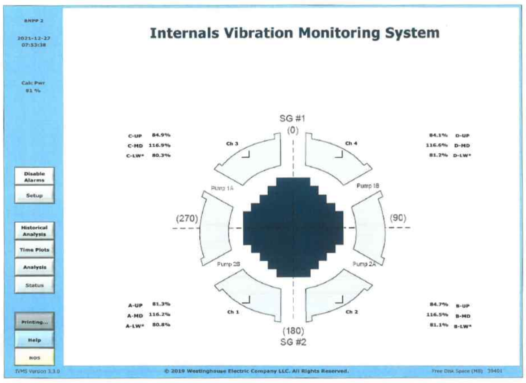

Fig. 1. IVMS Historical Analysis Main Screen for BNPP

The coherence between two signals x(t) and y(t) is a real valued function that is defined as [3][4]:

$$C_{xy}(f) = \{|G_{xy}(f)|^2\}/\{G_{xx}(f)G_{yy}(f)\}$$

Where $G_{xy}(f)$ is the cross-spectral density between x and y, and $G_{xx}(f)$ and $G_{yy}(f)$ are the auto spectral density of x and y, respectively. If the coherence is one (1.0), the two signals are said to be fully coherent, therefore the corresponding phase data are valid [2].

The IVMS phase data between two signals x(t) and y(t) provide the phase shift information. The indication of 180° and 0° phase shifts and the high coherence values at the frequency ranges of 180° and 0° phase shifts mean that there are high possibilities of beam mode and shell mode vibrations, respectively.

2.3 IVMS Data Evaluation Procedures

For our analysis of the beam and shell modes of CSB vibration, the following five steps for the IVMS evaluation and diagnosis are developed and applied:

1) Review the phase plot in detail in the minimum frequency band of 0.2 Hz to 20 Hz [2]. Identify the

frequency ranges of 180 and 0 degrees of phase shifts which are corresponding to the beam mode (i.e., cantilever mode) and shell mode of CSB vibration, respectively, on the phase plot.

2) Review the coherence plot, and identify the frequency range of high coherence value (0.5 to 1.0) within the phase shift ranges of 180 and 0 degree shifts, respectively, identified at Step 1).
3) Review the NCPSD plot, and identify the frequencies and magnitudes on the NCPSD at the points which are met with the criteria described in above Steps 1) and 2).
4) Review the results of Step 3), and compare them with the previous baseline data. If the decrease of CSB beam mode frequency and the increase of NCPSD magnitude at the CSB beam mode frequency were found, then review the NCPSD plot in the frequency range of 0.2 to 5 Hz whether the NCPSD magnitude is largely increased more than 20 dB.
5) Enter the diagnostic phase based on Steps 3) and 4) results. Based on ASME OM, Part 5, general criteria for entering the diagnostic phase are as follows [2];
   - A combined increase in CSB beam mode response of RMS amplitude and a simultaneous decrease in CSB beam mode resonance frequency, or
   - A large increase in low frequency neutron noise.

2.4 Evaluation of CSB Beam Mode Vibration

[Step 1] Analysis of Phase Plots

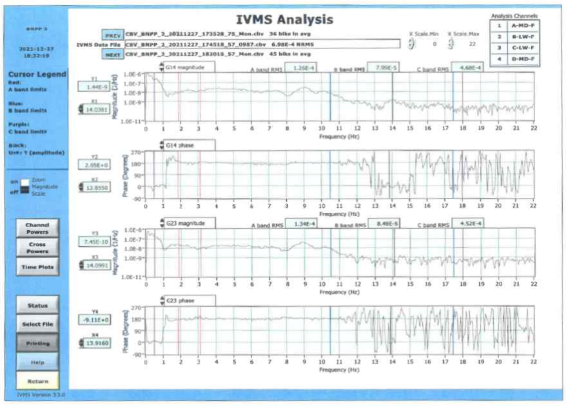

Fig. 2. IVMS Analysis Case 1 (NCPSD vs. Phase Shift)

Fig. 2 shows the IVMS historical analysis screen which presents the 180° phase shifts of acquired signals from the middle (MD) fission chambers in ENFMS CH.1&4(G14) and from the lower (LW) fission chambers of CH.2&3(G23) detectors in the frequency ranges of 2 to 11 Hz.

Fig. 3 also shows another case of the IVMS phase plots which present 180° phase shifts of acquired signals from different pairs of the ENFMS fission chambers in the frequency range of 2 to 11 Hz.

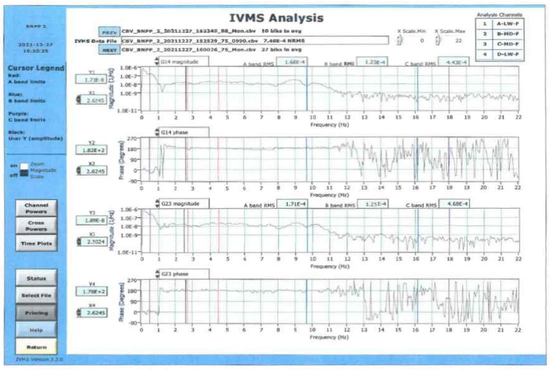

Fig. 3. IVMS Analysis Case 2 (NCPSD vs. Phase Shift)

[Step 2] Analysis of Coherence Plots

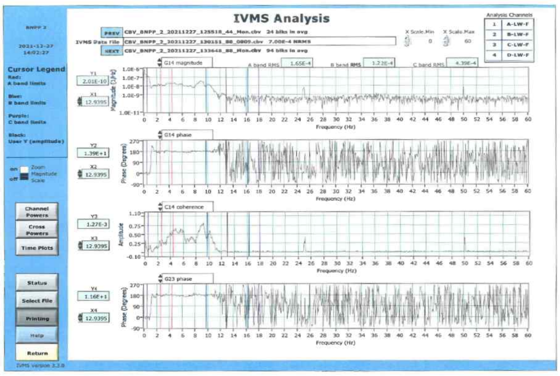

Fig. 4. IVMS Analysis of NCPSD(G14)/Phase/Coherence

Fig. 4 shows the IVMS historical analysis screen which presents the NCPSD, Phase, and Coherence plots simultaneously. As shown in Fig. 4, the highest value of coherence (more than 0.75) is found at 9.0 to 9.5 Hz within the frequency range of 180° phase shift of acquired signals from the pair of ENFMS channels A&D lower fission chambers.

[Step 3] Analysis of NCPSD Plots

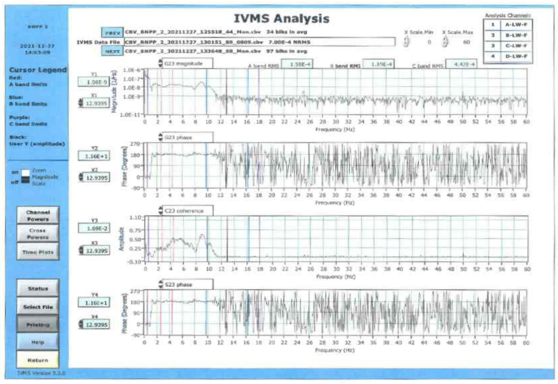

Fig. 5. IVMS Analysis of NCPSD(G23)/Phase/Coherence

Fig. 4&5 also shows the NCPSD plots. As shown in Fig. 4&5, there are high peak magnitudes at 9.0 to 9.5 Hz of frequency in the NCPSD plots. Therefore, we can conclude as follows:

- The IVMS analysis shows the CSB beam mode vibration in the frequency range of 9.0 to 9.5 Hz.
- The CSB beam mode vibrations are found in both directions of ENFMS detectors 1-to-4 and 2-to-3. However, it is found that the CSB beam mode vibrations in ENFMS detectors 1-to-4 direction is dominant based on its coherence value (≥ 0.75).

[Step 4] Compare with the Baseline Data: N/A
[Step 5] Perform the Diagnostic Phase: N/A

The results found during Steps 1 to 3 are the baseline data acquired during startup of initial program fuel cycle by using the NIMS-IVMS. Therefore, the Steps 4 and 5 may be done later when the surveillance phase data show any abnormal characteristics.

2.5 Evaluation of CSB Shell Mode Vibration

[Step 1] Analysis of Phase Plots

Fig. 2 shows the IVMS historical analysis screen which presents 0^{o} phase shifts of acquired signals from between the ENFMS CH.1&4(G14) middle fission chambers in the frequency range of 13.5 to 14.5 Hz.

Fig. 3 also shows another case of the IVMS phase plots which present 0^{o} phase shifts of acquired signals from middle fission chambers of CH.2&3(G23) at the frequency range of 14.0 to 14.5 Hz.

Fig. 4 shows a special case of the IVMS phase plots which present 0^{o} phase shifts of acquired signals from lower fission chambers of CH.1&4(G14) at the frequency range of 25.0 to 50.0 Hz.

[Step 2] Analysis of Coherence Plots

As shown in Fig. 4&5, there are no noticeable coherence values in the frequency range of 13.5 to 14.5 Hz. However, Fig. 4 shows that two peaks of coherence values more than 0.3 are found at 25 and 50 Hz. The evaluation results are as follows:

- The noticeable peaks at 25 and 50 Hz on the coherence and NCPSD plots in Fig. 4 are caused by the coolant fluctuations by the reactor coolant pump (RCP) rotation speed. (The 1X and 2X frequencies of the BNPP RCPs are 25 and 50 Hz, respectively.)
- The IVMS analysis of coherence plots shows that significant CSB shell mode vibration is not found for the BNPP Unit 2.
- The beam mode vibration is a dominant vibration mechanism for the CSB of BNPP Unit 2.

It should be noted that ASME OM, Part 5 standard describes only CSB beam mode vibration, and it does not mention about CSB shell mode vibration [2].

[Step 3] to [Step 5]: Not Applicable (N/A)

2.6 Comparison with ASME OM, Part 5 Example Case

By comparing the APR1400 BNPP evaluation results with the representative example of ASME OM, Part 5 as shown in Fig. 6 [2], we can see the following:

- APR1400 BNPP shows the CSB beam mode vibration in the frequency range of 9.0 to 9.5 Hz with coherence of more than 0.75 and NCPSD of more than 10^{-8}.
- ASME OM, Part 5 example shows the CSB beam mode vibration at frequency of around 7.0 to 7.5 Hz with coherence of 0.8 and NCPSD of less than 10^{-7}.
- BNPP IVMS shows the CSB shell mode vibration in the frequency range of 13.5 to 14.5 Hz with coherence of less than 0.05.
- A representative example in ASME OM, Part 5, Fig B1 shows two CSB shell mode vibrations as follows:
  - 1^{st}: in the frequency range of 13.5 to 14.5 Hz with coherence of 0.4 and NCPSD of less than 10^{-9}.
  - 2^{nd}: in the frequency range of 13.0 to 15.0 Hz with coherence of approximately 0.4, and NCPSD of more than 10^{-10}.
  - 3^{rd}: in the frequency ranges of 19.5 to 20.0 Hz with coherence of more than 0.5, and NCPSD of 10^{-11}. It can be the result of the coolant vibrations caused by the RCP with 1200 rpm speed.

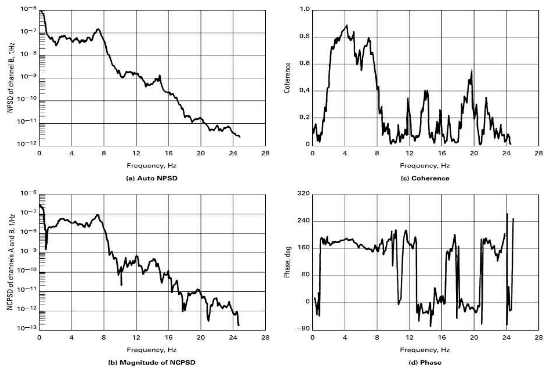

Fig. 6. Example of ASME OM, Part 5, App. Fig B-1

2.7 Consideration of Low Frequency Neutronic Effects

Per ASME OM, Part 5, experiences have shown that the neutronic effects can be of the same magnitude as the vibration effects, which can lead to misinterpretations of the data. Furthermore, the baseline NRMS (Normalized Root Mean Square) values in the low frequency range can increase with changes in core parameters such as core burnup and boron concentration because of low frequency neutronic effects [2]. The increase of NRMS value with changes in boron concentration may be associated with the broadening of

CSB motion-related peak, but it is not directly related with the beam mode vibration of the CSB which is clamped with an appropriate axial preload. Therefore, it is recommended that the lower frequency range of 0 to 5 Hz are excluded as the CSB beam mode frequency.

We should note that the NIMS-IVMS of APR1400 has a compensation function to the boron dilution of the plant. It is recommended that the changes of baseline NCPSD magnitude in the low frequency range of 0 to 5 Hz with the application of boron dilution compensation function should be reviewed and verified later.

2.8 Comparison of Evaluation Results between APR1400 IVMS and OPR1000 IVMS Data

The NIMS-IVMS historical data were reviewed by the KAERI, and the KAERI's research results shows that the CSB beam mode (BM) and shell mode (SM) frequencies of the OPR1000 (including Hanbit 3&4 and Hanul 1&3) has been commonly found at 8 Hz and 14.5 Hz, respectively [5]-[7].

Table 1 summarizes the previous research results for OPR1000 (including Hanbit 3&4 and Hanul 1,2&3) by KAERI/KINS and current joint research results for APR1400 (i.e., BNPP 2) by KEPCO-E&C and KHNP:

Table 1: Summary of OPR1000/APR1400 CSB Beam & Shell Mode Frequencies identified by using the NIMS-IVMS data

	CSB BM Freq.	CSB SM Freq.
Hanbit 3&4	8.0 Hz [5]	14.5 Hz [5]
Hanul 3	8.0 Hz [6]	14.5 Hz [6]
Hanul 1&2	8.0 Hz [8][9]	The SM vibration at 20 Hz caused by RCP 1X speed [9].
BNPP 2	9.0 – 9.5 Hz	No significant SM vibration is found.

Based on the contents of Table 1, it is recommended that the filter frequency ranges for the BNPP IVMS for the beam mode and shell mode vibration monitoring, respectively, are recommended as follows:

- Filter for Beam Mode: 7 to 11 Hz
- Filter for Shell Mode: 12 to 16 Hz

3. Conclusions

For the evaluation of CSB beam and shell modes of vibration, practical five steps for the IVMS evaluation and diagnosis are developed and explained in this paper based on the KEPCO-E&C's engineering experiences, KHNP's site data/experiences, and the guidelines of ASME OM, Part 5 standard. The five steps for the NIMS-IVMS evaluation and diagnosis were practically applied for the BNPP Unit 2. As a result, the CSB beam mode vibrations are clearly found in the frequency range of 9.0 to 9.5 Hz based on 180° phase shift, high coherence value ($\geq$ 0.75), and a peak ($\geq 10^{-8}$) on NCPSD plot. However, no significant CSB shell mode vibration evidences are found based on the Phase, Coherence, and NCPSD plots. It should be noted that the BNPP Unit 2 is one of the APR1400 plants, and it is just in the stage of initial program fuel cycle. Therefore, the results of IVMS data and plots shown in this paper are classified as parts of the baseline data of the BNPP Unit 2, and the studies in this paper should be updated throughout the fuel cycles. The results of in this paper need to be further supplemented after the similar researches are done for other APR1400 plants.

REFERENCES

[1] Yang Gyun Oh, Scott R. Galin, and Sang Jeong Lee, An Advanced NSSS Integrity Monitoring System for Shin-Kori Nuclear Units 3 and 4, IEEE Transactions on Nuclear Science, Vol. 57, No. 6, page 3661-3665, December 2010.

[2] ASME OM-2020, Division 2, Part 5, Inservice Monitoring of Core Support Barrel Axial Preload in Pressurized Water Reactor Power Plants, The American Society of Mechanical Engineers, June 30, 2020.

[3] J. S. Bendat, A. G. Piersol, Random Data, Wiley-Interscience, 1986.

[4] https://en.wikipedia.ord/w/index.php?title=Coherence (signal_processing)&oldid=1104626489

[5] Jinho Park, et al., Reactor Noise Analyses in Yonggwang 3&4 Nuclear Power Plants, 한국소음진동공학회 창립 10 주년기념 소음진동학술대회논문집 pp. 679-696, 2000.

[6] Jinho Park, Jeong Han Lee, and Bong Soo Kim, Vibration Mode Identification in Ulchin 3 Reactor Internals through Reactor Noise Analysis, KNS 2002 추계학술발표회 논문집.

[7] Jinho Park, et al., Identification of Reactor Internals' Vibration Modes of a Korean Standard PWR Using Structural Modeling and Neutron Noise Analysis, Progress in Nuclear Energy, Vol. 43, No. 1-4, pp. 177-186, 2003.

[8] Won Young Yun, Byung Jun Koh, In Yong Park, and Hee Cheon No, Neutron Noise Analysis for PWR Core Motion Monitoring, Journal of the Korean Nuclear Society Vol. 20, No. 4, December, 1988.

[9] KAERI/RR-1908/98, Development of Fault Diagnostic Technique using Reactor Noise Analysis, KAERI, April 1999.