Monitoring the Mechanical Vibration of In-Core Detector Tubes and Fuel Channels via ICFD Noise Analysis

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Introduction

Vibrations of core internals are regularly monitored in the CANDU nuclear generating stations of Ontario Power Generation (OPG) via the noise analysis of in-core flux detectors (ICFDs). Voltage signals of standard station instrumentation are recorded by portable multi-channel high-speed high-resolution data acquisition systems, then statistical parameters are derived from the multi-channel time series measurements.

Reactor noise analysis is a non-intrusive statistical technique regularly used in system surveillance, diagnostics and in actual operational I&C problems. It utilizes the dynamic information carried by the small fluctuations (noise) of station signals measured around their mean values during steady-state operation. The present paper discusses specific results related to the flow-induced mechanical vibrations of detector tubes and fuel channels.

1. Vibrations of Detector Tubes Detected by ICFD Noise Analysis

Evidence of flow-induced mechanical vibrations of both horizontal and vertical detector guide tubes has been found in the spectral functions of the noise signals of certain horizontal SDS2 and vertical SDS1/RRS in-core flux detectors.

A detector vibrating in an inhomogeneous static flux senses virtual flux fluctuations and it produces an oscillating current component at the vibration frequency via its prompt response channel. In this way, the movement of the detector in a non-zero flux gradient is directly mapped into detector current fluctuations. Increase in the vibration amplitude or possible impacting with surrounding structures can be detected indirectly by ICFD noise analysis.

The vibration of detector tubes, induced by the moderator flow, results in strong peaks in the spectra and coherence functions of noise signals of ICFDs in the frequency range of 2-5 Hz. Noise signals of detectors located in the same vibrating detector tube have high coherence and zero phase difference at the fundamental frequency of tube vibration. Depending on the locations of the ICFDs inside the guide tube, the detectors may have zero or 180 degree phase differences at the frequencies of the higher harmonics, with high coherence.

Noise signals from detectors located in different tubes have zero coherence at the vibration frequencies since the vibrations of different tubes are not correlated, even if they had the same vibration frequency.

Flow-induced vibrations of the long vertical detector guide tubes (VFD1 and VFD27), observed in all four Darlington units, were especially strong. Figure 1 shows a 40 sec portion of the time series signals of the three RRS Channel B ICFDs located in VFD27 of Unit 4 (12B, 13B and 14B) sampled at 200 Hz in 1996. A sample of a similar measurement of the same set of ICFDs in Unit 4 performed in 1999 can be seen in Figure 2. In both cases the ICFD signals exhibit a strong vibration effect. The rapid oscillations, superimposed on the normal slow flux fluctuations at steady state, are intermittent and correlated.

The corresponding frequency spectra (auto power spectral density functions, APSDs) of the ICFDs located in VFD27 in Unit 4 measured in 1996 and 1999 are shown in Figures 3 and 4, respectively. The fundamental vibration peak is followed by a series of relatively wide peaks (higher harmonics) at regular frequencies 2.7 Hz apart. The regular series of wide vibration peaks is an indication of detector tube impacting.

The frequency-dependent statistical coupling between detector noise signals is characterized by the coherence and phase-difference functions measured between two noise signals. The APSD spectra, coherence and phase functions measured between ICFDs 12B and 14B in 1996 are shown in Figure 5. Similar functions obtained in the same measurement between ICFDs 13B and 14B can be seen in Figure 6. At the vibration frequencies, the coherence and phase difference values of the two ICFDs depend on the vertical locations of the ICFDs and the static flux gradient at detector locations. Results from the repeated measurement of the same ICFD set in 1999 are shown in Figures 7 and 8. In both cases the patterns of coherence and phase functions are rather complex. The wide peaks in the APSD functions, the irregular phase functions, and the intermittent occurrence of vibrating signal components in the time series signals suggest that the vibration of detector tube VFD27 is not stationary.

A much simpler pattern can be seen in Figures 9 and 10, measured between ICFDs located in the same horizontal detector tube in Pickering-B Unit 5. Figure 9 shows the APSD, coherence and phase functions between the signal fluctuations of two Channel G ICFDs in HFD8 with a detector vibration frequency of 3.8 Hz. The same statistical functions of another pair of Channel G ICFDs located in HFD9 are shown in Figure 10, with a vibration frequency of 3.7 Hz.

In both cases, the strong and sharp vibration peak in the coherence function and the zero phase difference at the vibration frequency indicate that the oscillation is monochromatic and stationary, that is, the detectors in the horizontal tubes vibrate freely at a constant frequency.

By monitoring the trend of vibration peaks in the noise spectral functions of the measured ICFD signals, the mechanical condition of the detector tube can be assessed based on the following simple principles.

- Increase in the magnitude of the peak in the noise spectra of the ICFD indicates detector tube vibration with increasing amplitude.
- Shift in the frequency location of the spectral peak indicates changes in the mechanical conditions/support of the detector tube.
- Widening of the spectral peak and the occurrence of higher harmonics in the ICFD noise spectra indicate increasing impacting with the surrounding reactor internals [1].

The long-term trend monitoring of these vibration peaks is useful for early detection of mechanical damages in the reactor core caused by vibrations. Also, excessive detector tube vibration may lead to mechanical failures compromising the integrity of the ICFD signals (fatigue of lead cable and detector junction, loss of helium pressure).

2. Vibration of Fuel Channels Detected by ICFD Noise Analysis

Routinely performed ICFD noise measurements also detected the flow-induced vibration of fuel channels at frequencies around 4.5 - 6 Hz and at 15 Hz in the Darlington, Pickering-B and Bruce-B units. In-core flux detectors lined up along the same group of fuel channels showed common vibration peaks with high coherence. At these frequencies, the phase difference between the ICFD noise signals was either 0 or 180 degree, depending on whether the detectors were on the same side, or different sides of the vibrating fuel channel(s). In many cases, multiple vibration peaks at slightly different frequencies were seen in the coherence functions, indicating that there were several vibrating fuel channels among the common neighboring channels of the two in-core flux detectors. Similar noise measurements were performed in a CANDU-600 reactor, where evidence of fuel channel vibrations was found in the same frequency range [2].

A typical result of ICFD noise measurements performed in Darlington Unit 1 is shown in Figure 11. Two vibration peaks can be seen in the coherence and APSD functions at frequencies 4.6 Hz and 5.6 Hz. The two in-core flux detectors, VFD11-1E and VFD18-1E, have six common neighboring fuel channels, at locations rows H, J, K and columns 4 and 5. The double peak in the coherence function with zero phase shows that the signals of the two ICFDs are affected in the same way, by the vibration of at least two neighboring fuel channels.

The spectral functions of the same pair of in-core flux detectors in Darlington Unit 2 are shown in Figure 12. The same group of fuel channels is vibrating at frequencies slightly different from the previous case in Unit 1. There are five distinct in-phase vibration peaks in the coherence function over the frequency range of 4-6 Hz, indicating that five of the six neighboring fuel channels vibrate and affect the signals of the two ICFDs in phase. Figures 13 and 14 show the effect of fuel channel vibration of the same two ICFDs in Units 3 and 4. The collective motion of fuel channels merged into one wide peak at 5.5 Hz in Unit 3 shown in Figure 14.

Higher modes of fuel channel vibrations were also found in many cases. In Figures 15 and 16 the spectral functions of RRS-A in Zone 6 and Zone 8 ICFD noise signals are shown for Darlington Units 1 and 2, respectively. In both cases, strong and relatively wide (multiple) peaks were detected in the coherence functions centered at 15 Hz. The phase difference between the detectors at 15 Hz is 180 degree, which is typical for second mode vibrations. Similar results were obtained in routine ICFD noise measurements in the Pickering-B and Bruce-B reactor units as well.

Noise measurements clearly showed that ICFDs lined up along the same set of fuel channels, but separated by a relatively large distance, may exhibit in-phase coherence peaks at the above frequencies, due to the common effect of fuel channels vibrating nearby. Monitoring the vibration of fuel channels via ICFD noise analysis is done routinely as part of the regular noise-based ICFD surveillance. Changes in the above vibration patterns may indicate impacting or structural changes in the fuel channels.

Conclusion

CANDU noise measurements carried out over the past eight years have proved that fault detection and validation of process/instrumentation dynamics can be based on the existence of multi-channel complex patterns of statistical noise signatures. These signatures are obtained from the multi-channel time series measurements performed at steady-state operating conditions.

Monitoring the vibrations of detector tubes and fuel channels via ICFD noise analysis is done routinely as part of the regular noise-based ICFD surveillance. Changes in the above vibration patterns may indicate impacting or structural changes in core internals.

The technique is being successfully applied now in a wide variety of actual station problems as a powerful troubleshooting and diagnostic tool. CANDU reactors provide a unique opportunity, in that the amount of detailed information contained in their neutron spectra far surpasses that typically observed in light water reactors. There is significant potential to develop many more sophisticated and useful core surveillance tools by exploiting this information using noise analysis technology.

Acknowledgements

The noise measurements were performed in Pickering-B, Darlington and Bruce-B units with an active support of plant personnel. In particular the authors would like to acknowledge the contribution of A.V. Campbell, Sonya von Svoboda, M. Tulett, R. Vilkko, D. Williams, M. Woitzik of Pickering-B; F. Amantea, B. Cunningham, F. Dermarkar, D. Guernsey, E. Sadok, M. Ramphal, M. Wightman of Darlington; J. King, A. Kozak, H. Parsons, R. Quirk, J. Schut, P. Wright of Bruce-B.

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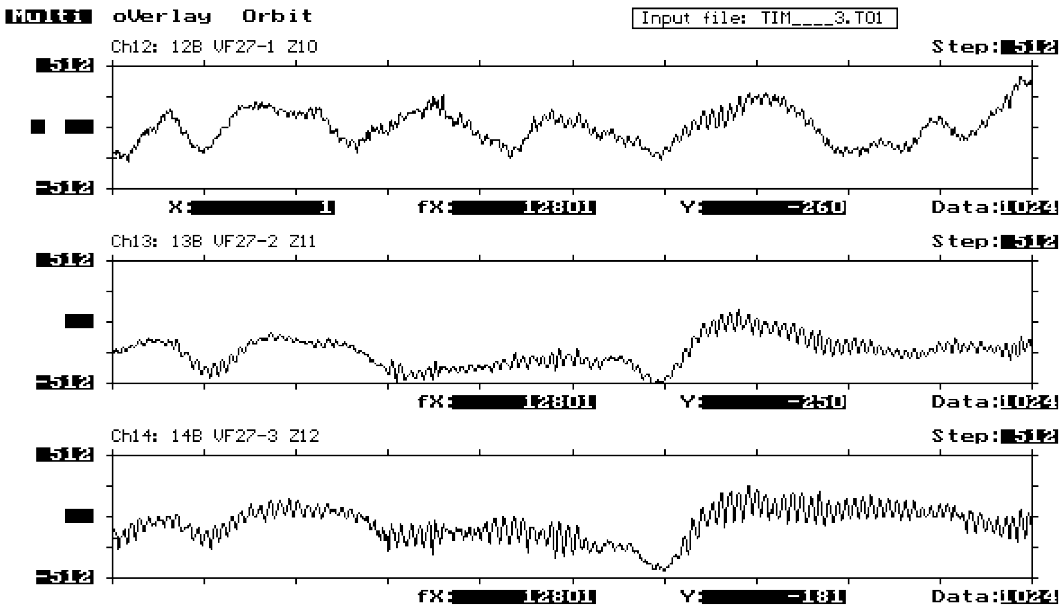

Figure 1. Portion of time series of RRS-B ICFD signals 12B, 13B and 14B in VFD27 in 1996.
Vertical amplitude scale: +\-31.25 mV around signal mean (DC) value
Horizontal time scale: 0 – 40.96 sec

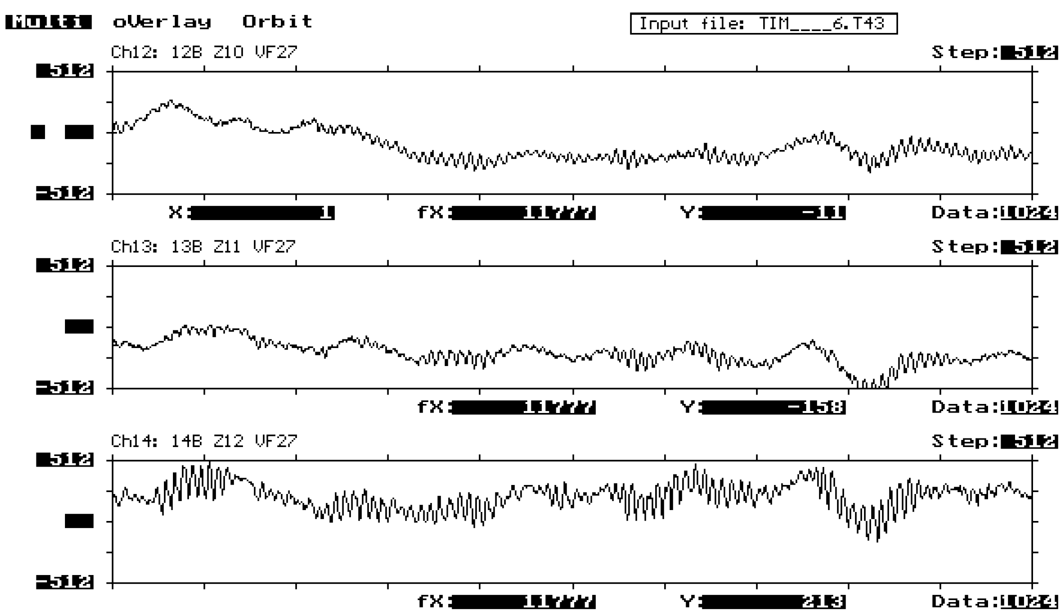

Figure 2. Portion of time series of RRS-B ICFD signals 12B, 13B and 14B in VFD27 in 1999.
Vertical amplitude scale: +\-31.25 mV around signal mean (DC) value
Horizontal time scale: 0 – 40.96 sec

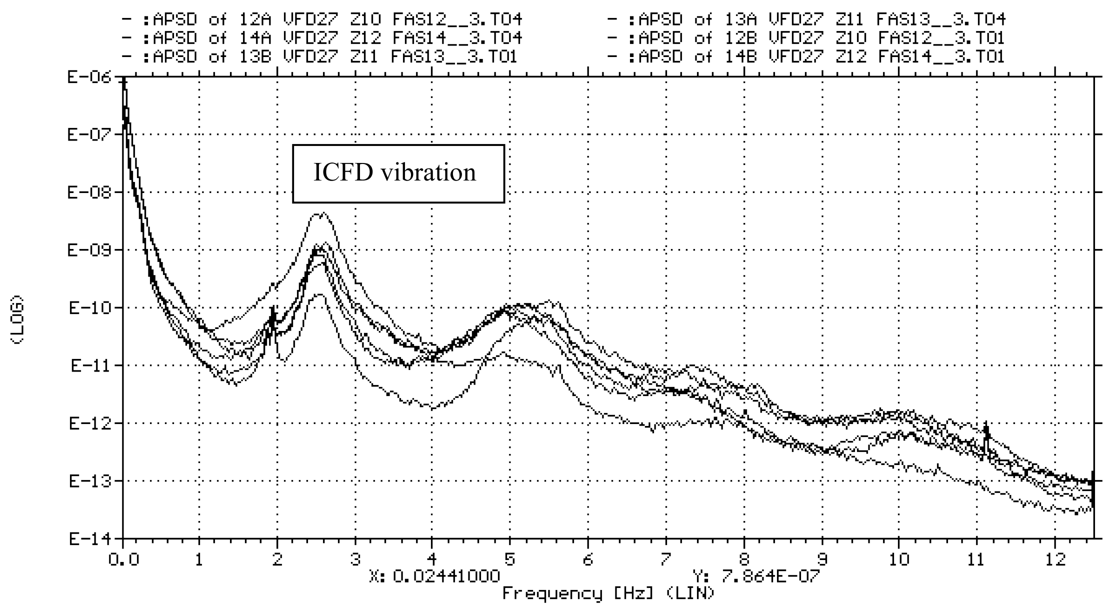

Figure 3. APSD spectra of ICFD signals in VFD27 measured in Unit 4 in 1996.

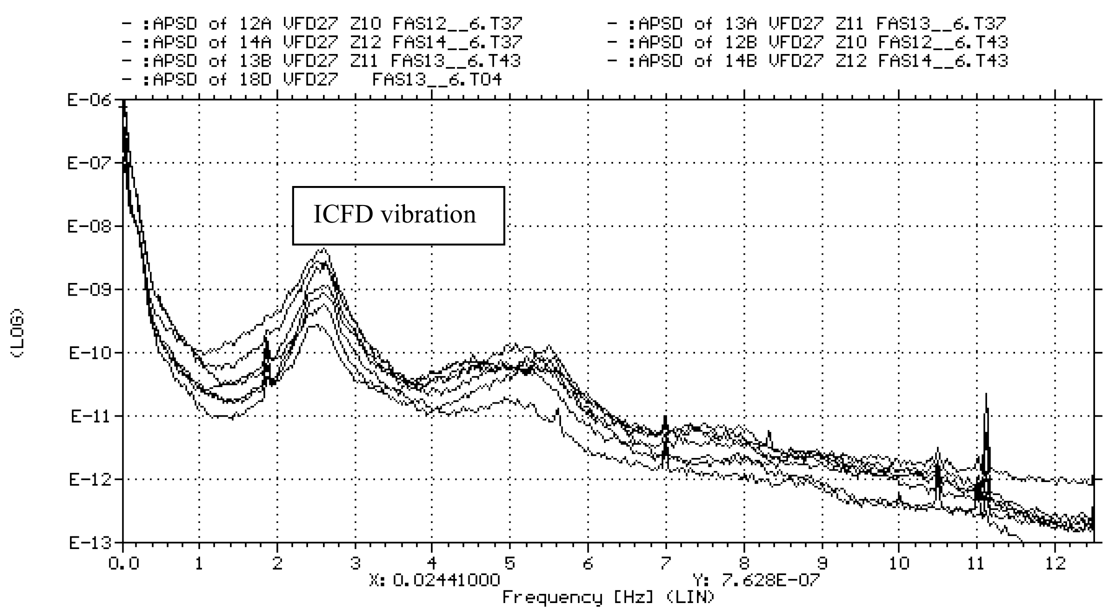

Figure 4. APSD spectra of ICFD signals in VFD27 measured in Unit 4 in 1999

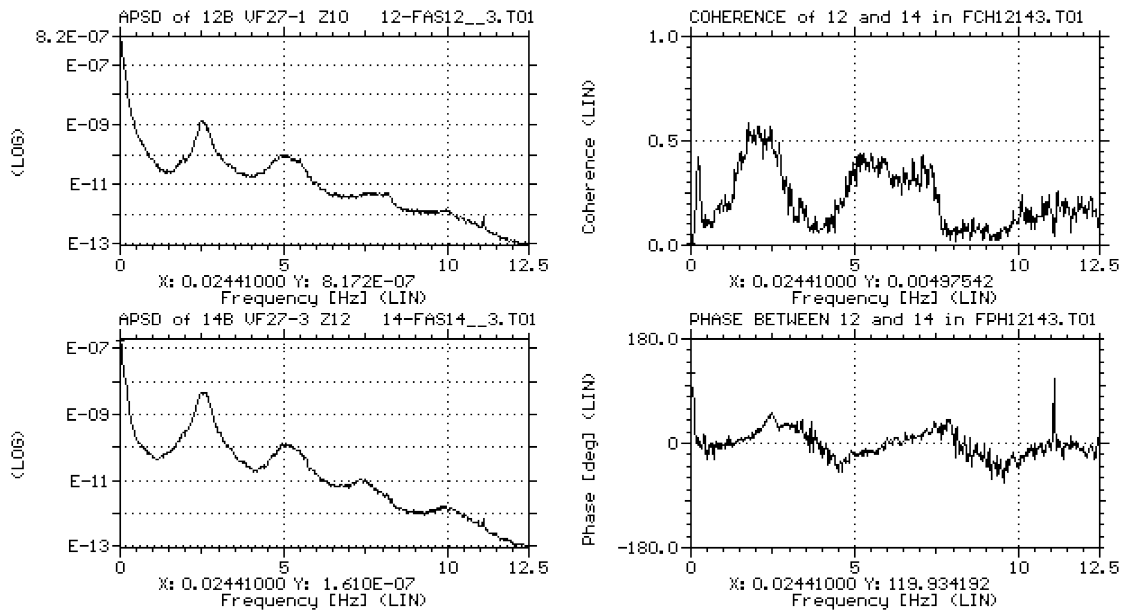

Figure 5. APSD spectra, Coherence and Phase functions of ICFD signals 12B and 14B in VFD27 measured in Unit 4 in 1996.

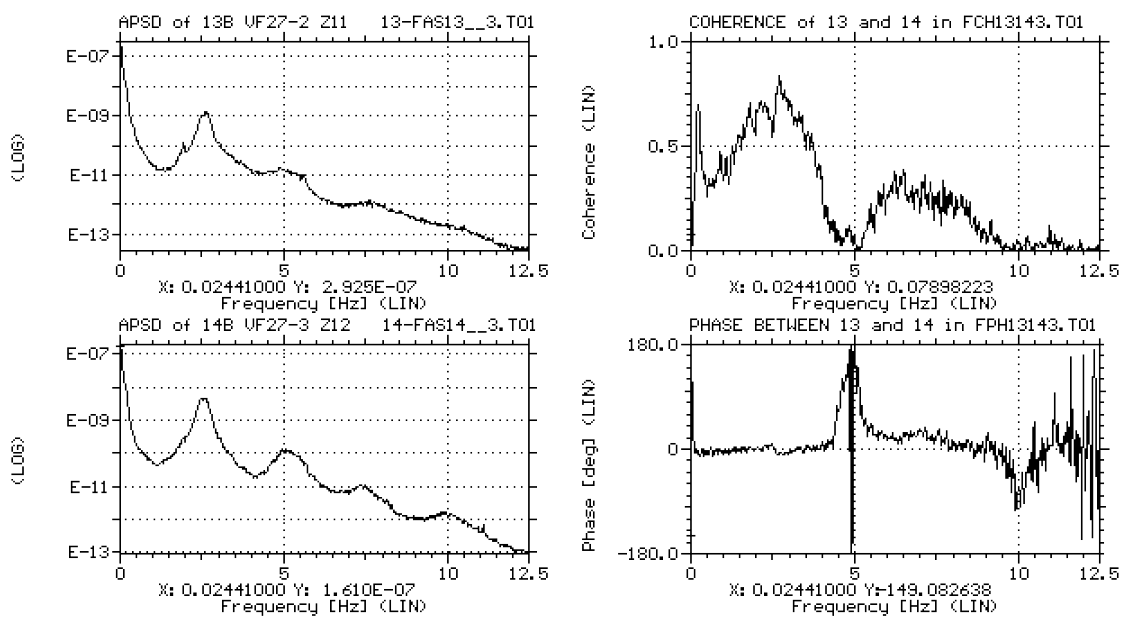

Figure 6. APSD spectra, Coherence and Phase functions of ICFD signals 13B and 14B in VFD27 measured in Unit 4 in 1996

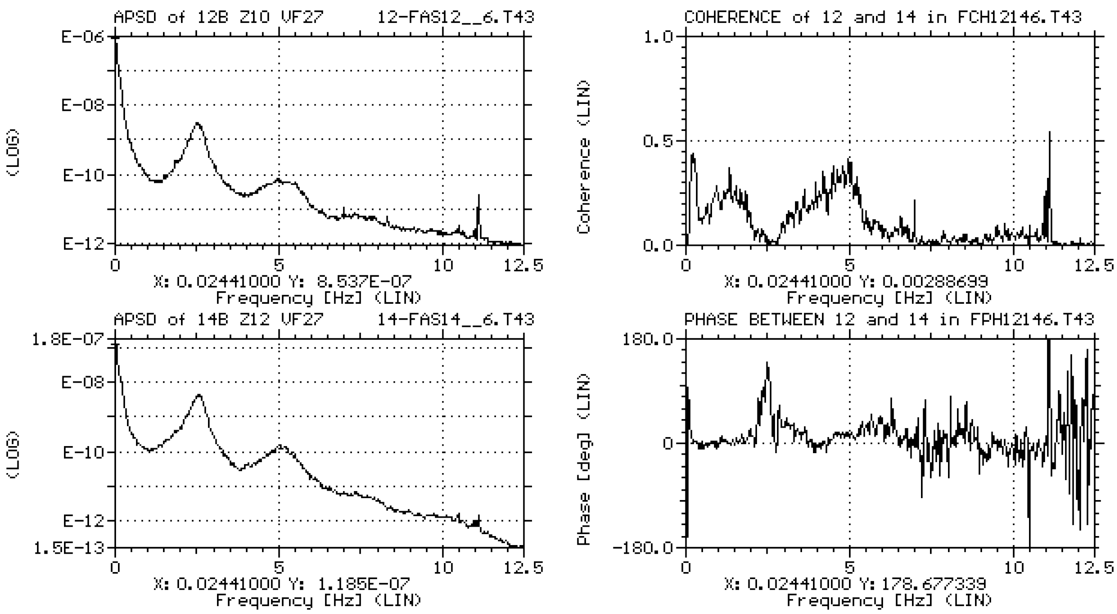

Figure 7. APSD spectra, Coherence and Phase functions of ICFD signals 12B and 14B in VFD27 measured in Unit 4 in 1999

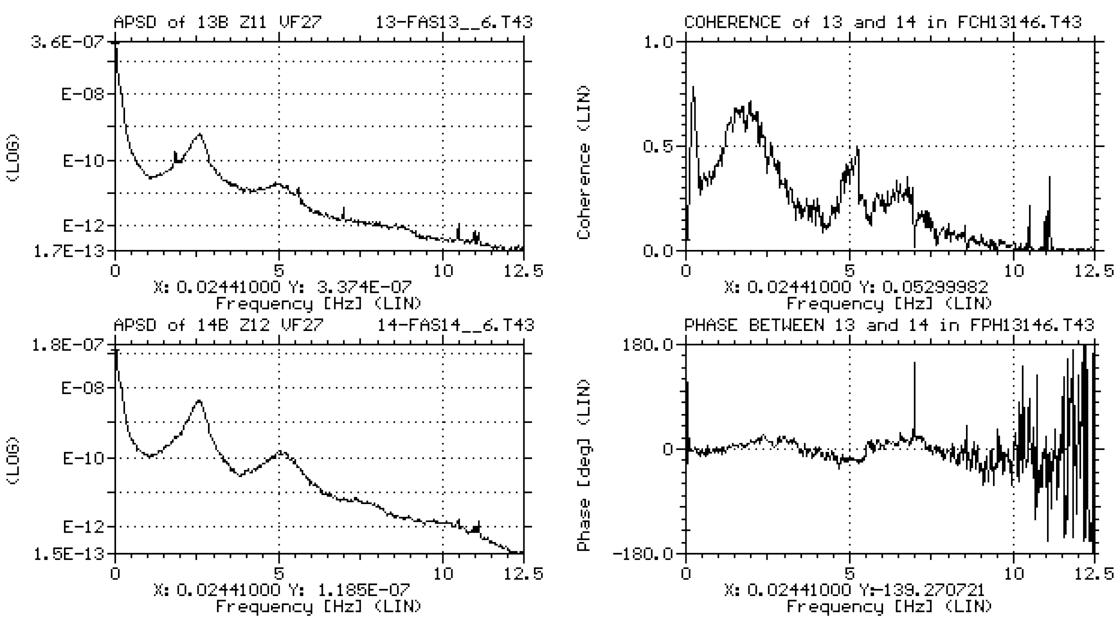

Figure 8. APSD spectra, Coherence and Phase functions of ICFD signals 13B and 14B in VFD27 measured in Unit 4 in 1999

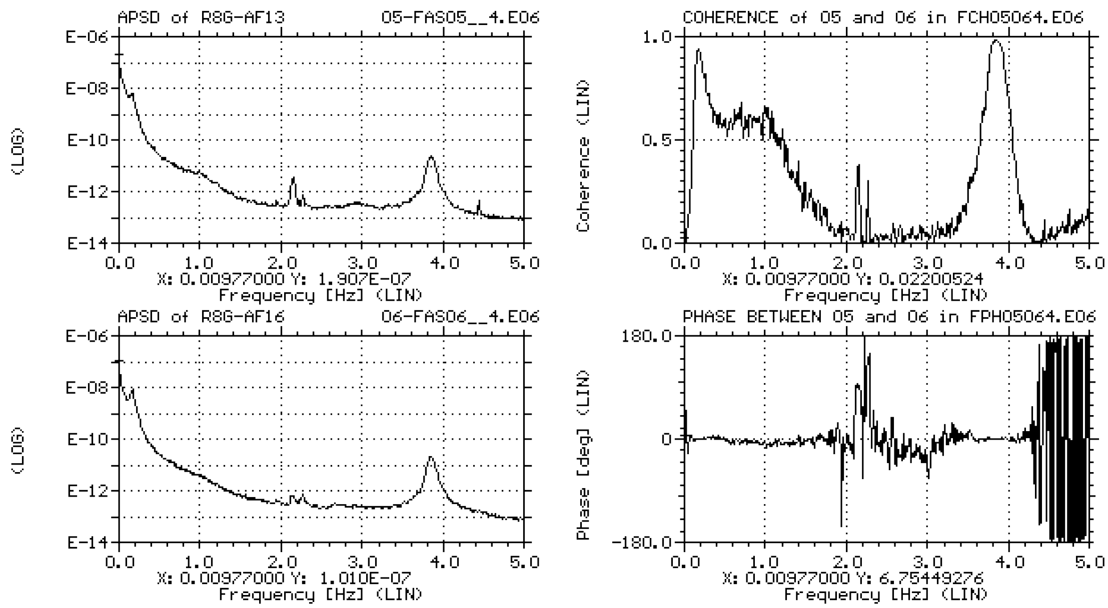

Figure 9. APSD spectra, Coherence and Phase functions of noise signals of two SDS2-G ICFDs located in the same horizontal detector tube, HFD8, measured in Pickering-B Unit 5.

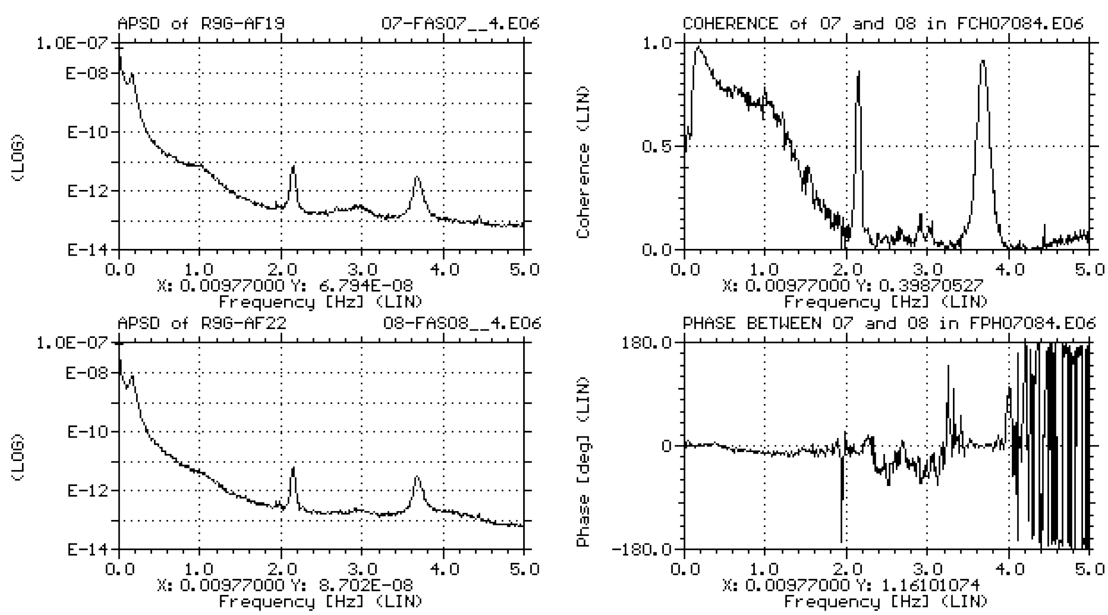

Figure 10. APSD spectra, Coherence and Phase functions of noise signals of two SDS2-G ICFDs located in the same horizontal detector tube, HFD9, measured in Pickering-B Unit 5.

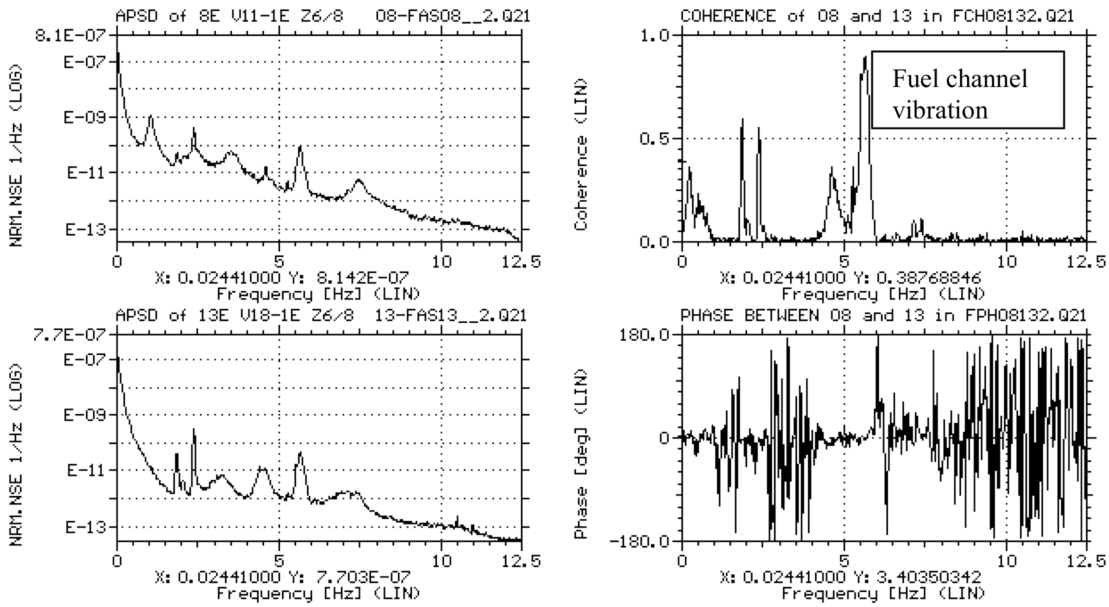

Figure 11. APSD spectra, Coherence and Phase functions of noise signals of two SDS1-E ICFDs VFD11-1E and VFD18-1E lined up along the same set of fuel channels in Zones 6 and 8 in Darlington **Unit 1.**

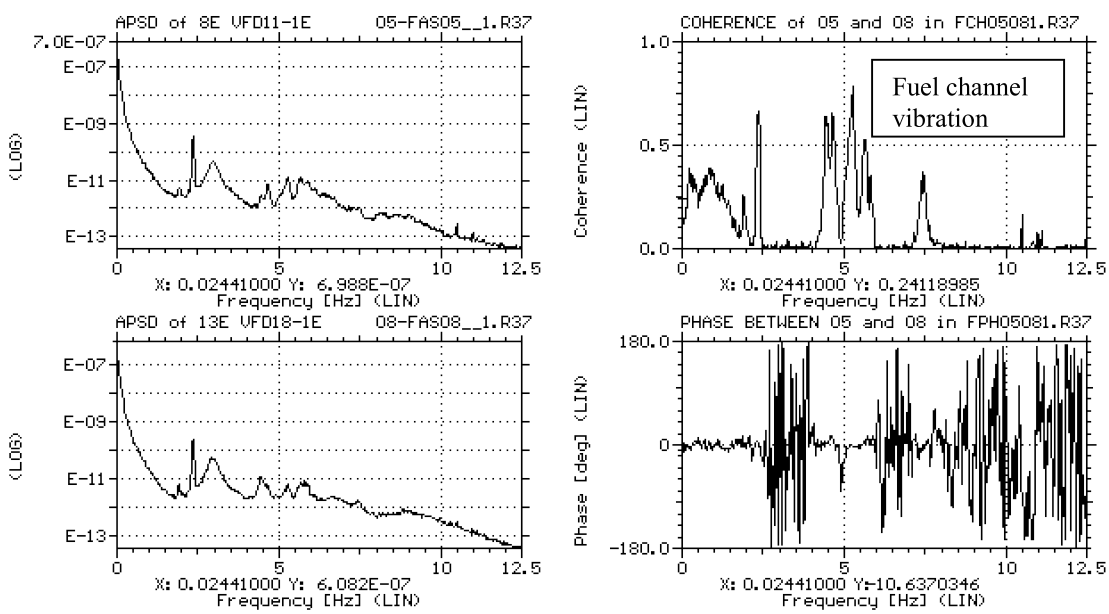

Figure 12. APSD spectra, Coherence and Phase functions of noise signals of two SDS1-E ICFDs VFD11-1E and VFD18-1E lined up along the same set of fuel channels in Zones 6 and 8 in Darlington **Unit 2.**

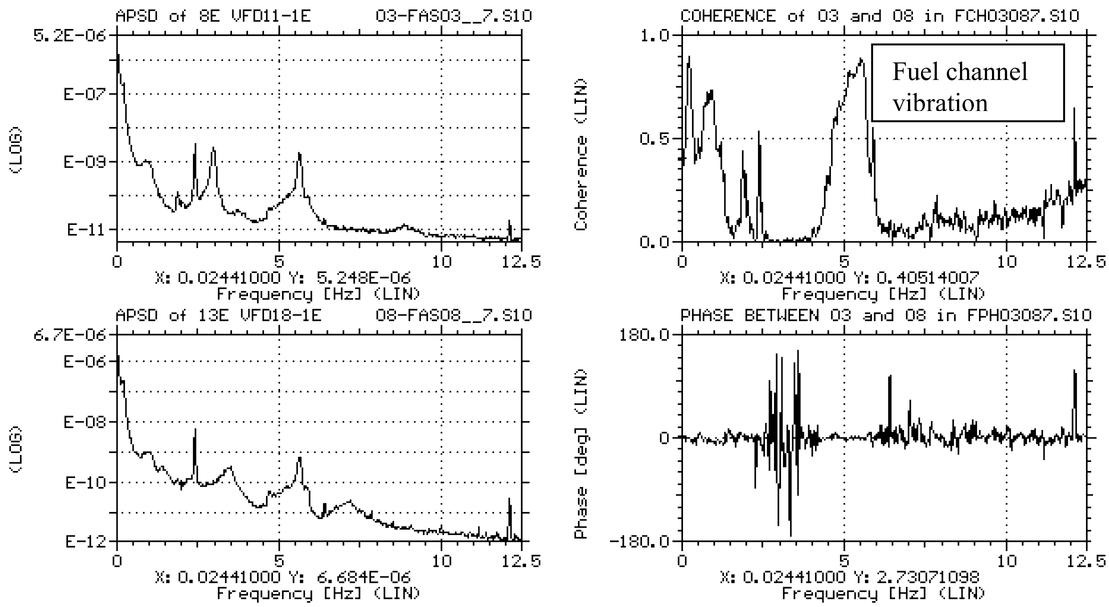

Figure 13. APSD spectra, Coherence and Phase functions of noise signals of two SDS1-E ICFDs VFD11-1E and VFD18-1E lined up along the same set of fuel channels in Zones 6 and 8 in Darlington **Unit 3.**

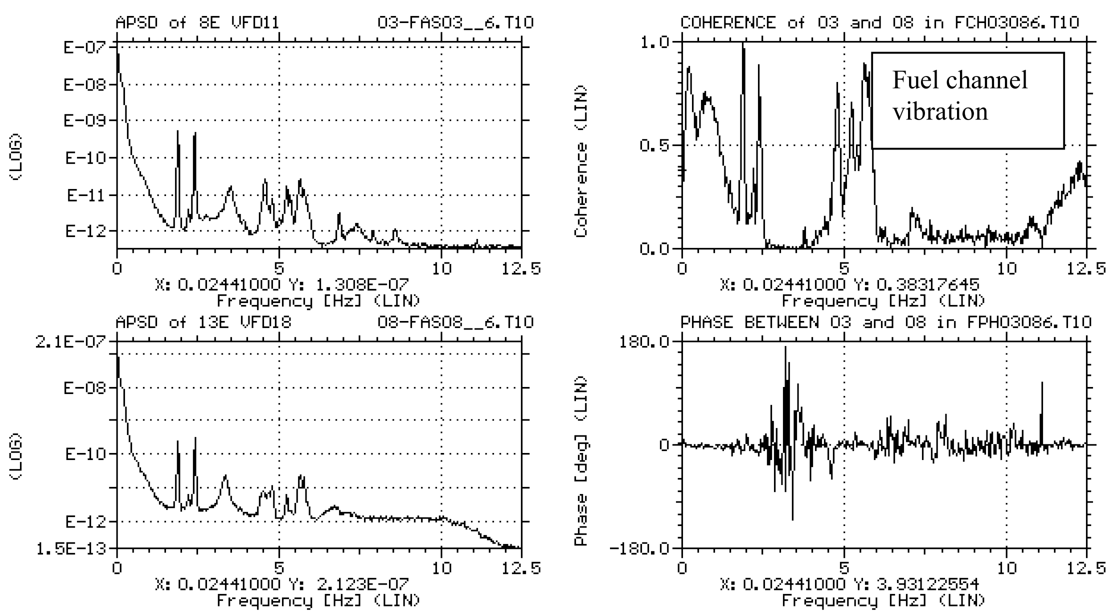

Figure 14. APSD spectra, Coherence and Phase functions of noise signals of two SDS1-E ICFDs VFD11-1E and VFD18-1E lined up along the same set of fuel channels in Zones 6 and 8 in Darlington **Unit 4.**

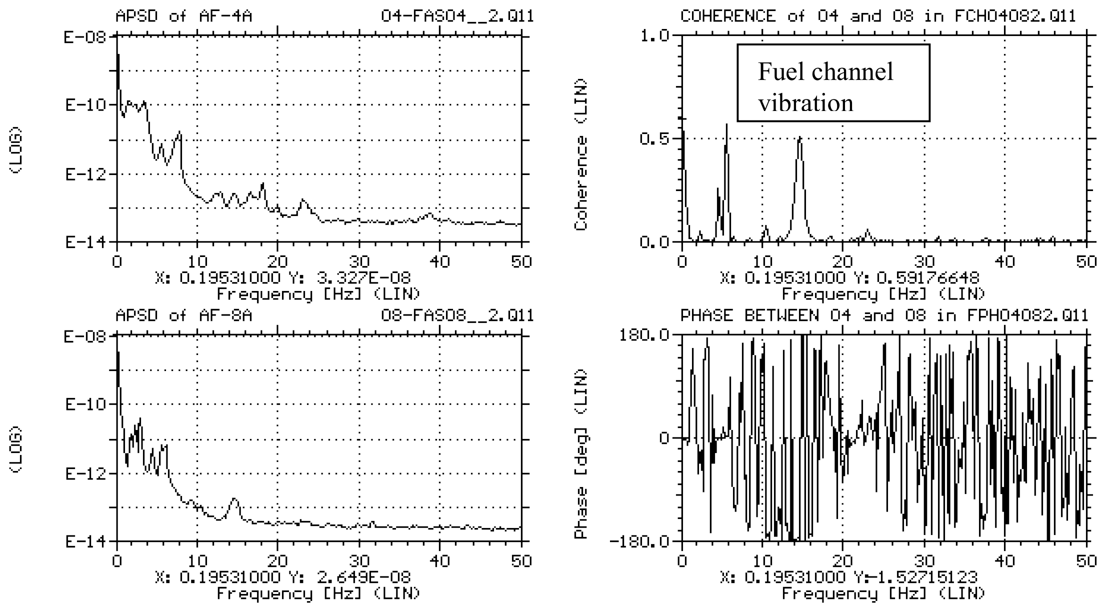

Figure 15. APSD spectra, Coherence and Phase functions of noise signals of RRS-A ICFDs in Zones 6 and 8, lined up along the same set of fuel channels in Darlington **Unit 1.**

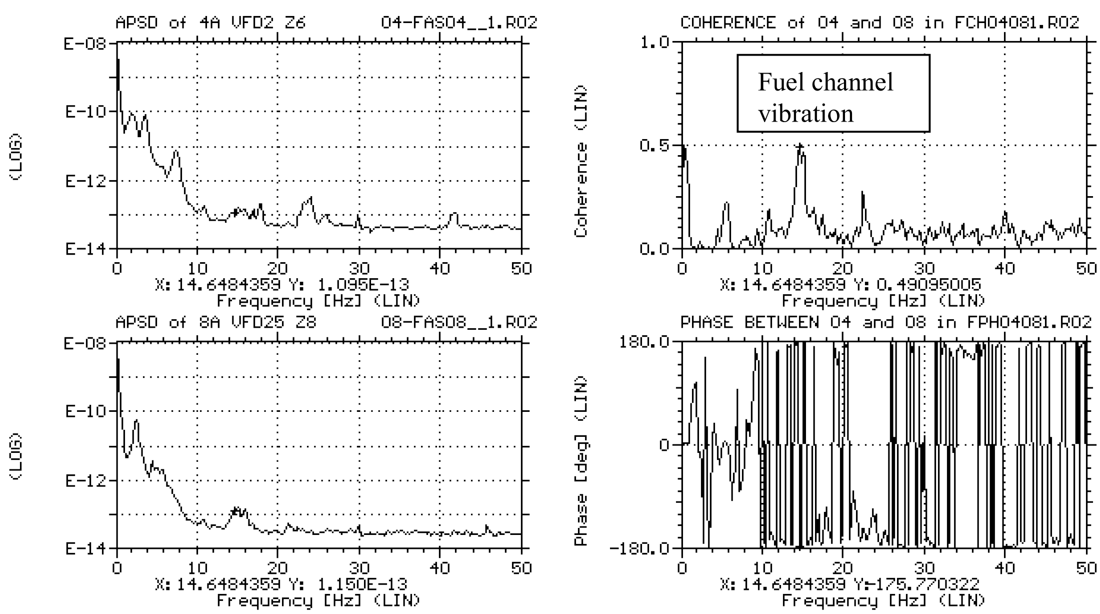

Figure 16. APSD spectra, Coherence and Phase functions of noise signals of RRS-A ICFDs in Zones 6 and 8, lined up along the same set of fuel channels in Darlington **Unit 2.**