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IDENTIFICATION OF THE EXCITATION SOURCE OF THE PRESSURE VESSEL VIBRATION IN A SOVIET BUILT WWER PWR WITH SIGNAL TRANSMISSION PATH ANALYSIS

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Abstract - Signal Transmission Path Analysis via Multivariate Auto-Regressive modelling was applied at signals recorded at a WWER power reactor. The analysis suggests that the source of excitation of all signals at 25 Hz is due to main coolant pump vibration.

1. INTRODUCTION

Signal Transmission Path (STP) analysis (Oguma (1981), Oguma and Turkcan (1985)) based on Multivariate Auto-Regressive (MAR) modelling can, in theory, identify open loop transfer functions and sources of excitation of signals (Oguma and Turkcan (1985), Antonopoulos-Domis et all (1994)). The present work is an application of these techniques on actual measurements made on a WWER 440 MWe Unit of Paks NPP (Hungary).

The core is equipped with strings of Self Powered Neutron Detectors (SPND's). Each string has seven SPND's. Signals were recorded from twelve SPND's, four from each of the strings named A, C and E, on elevations 1, 3, 5 and 7; the numbering of the elevations starts from the bottom of the core. The signals of the following sensors were also recorded: six out-of-core ionization chambers, coolant inlet and outlet pressure, pressures of primary coolant loops 4 and 6, pressurizer pressure difference, and vibration sensors of three, out of six, Main Coolant Pumps (MCP's). The signals were high pass filtered with cut-off at 0.03 Hz and low pass-filtered with cut-off at 25 Hz.

In section 2 definitions of MAR and STP analysis are given. In section 3 the results of this analysis are presented.

2. DEFINITIONS

This work was presented at SMORN-VII , June 1995 Avignon France.

The MAR(p) model of the vector $\mathbf{x}(t) = \left[x_1(t)\ x_2(t) \ldots\ldots x_m(t)\right]^T$ of jointly wide-sense stationary processes is

$$\mathbf{x}[n] = \sum_{i=1}^{p} \mathbf{A}[i] \cdot \mathbf{x}[n-i] + \mathbf{e}[n] \tag{1}$$

where $\mathbf{x}[n]$ is the digital signal vector $\mathbf{x}[n] = \mathbf{x}(n \cdot \Delta t)$ sampled at time $t = n \cdot \Delta t$, $\mathbf{A}[i]$ $i = 1 \ldots p$ are the $m \times m$ autoregressive coefficient matrices, Δt is the sampling time and $\mathbf{e}[n]$ is a multivariate white noise process with covariance matrix $\boldsymbol{\Sigma}$. The residuals, elements of vector $\mathbf{e}[n]$, are considered as the driving noise sources acting on the signals $x_i[n]$. From equation (1) through Fourier transform we have

$$\mathbf{H}(f) \cdot \mathbf{X}(f) = \mathbf{E}(f) \tag{2}$$

where $\mathbf{X}(f)$ and $\mathbf{E}(f)$ are the Fourier transforms of $\mathbf{x}[n]$ and $\mathbf{e}[n]$ respectively, f is frequency in Hz and,

$$\mathbf{H}(f) = \mathbf{I}_m - \sum_{i=1}^{p} \mathbf{A}[i] \cdot \exp(-j2\pi i f \Delta t) \tag{3}$$

The closed loop transfer function from $x_j[n]$ to $x_i[n]$ is defined as the element $H_{ij}(f)$ in row i and column j of matrix $\mathbf{H}(f)$. The $m \times m$ power spectral matrix derived from MAR model (1) is

$$\mathbf{S}_{xx}(f) = \mathbf{H}(f)^{-1} \cdot \boldsymbol{\Sigma} \cdot \mathbf{H}^{*}(f)^{-1} \cdot \Delta t \qquad |f| \le \frac{1}{2\Delta t} \tag{4}$$

where * indicates complex conjugate transpose. The diagonal elements $S_{ii}(f)$, of power spectral matrix are the Auto Power Spectral Densities (APSD) of the signals $x_i(t)$ $i = 1 \ldots m$ and the off- diagonal elements $S_{ij}(f)$ are the Cross Power Spectral Densities (CPSD) of signals $x_i(t)$ and $x_j(t)$. The contribution to the APSD of signal $x_i(t)$ from driving noise source $e_j(t)$ through all possible paths is the ordinary noise contribution ratio NCR_{ij} and is defined by

$$\mathrm{NCR}_{ij} = \frac{\left|\left\{\mathbf{H}^{-1}(f)\right\}_{ij}\right|^2 \cdot \sigma_{jj} \cdot \Delta t}{S_{ii}(f)} \tag{5}$$

where σ_{jj} is the variance of noise source j. From equation (2) it can be readily found that,

$$\mathbf{X}(f) = \mathbf{G}(f) \cdot \mathbf{X}(f) + \mathbf{N}(f) \tag{6}$$

where the element $G_{ij}(f)$ of matrix $\mathbf{G}(f)$, is the open loop transfer function from signal j to i, that is:

$$G_{ij}(f) = -\frac{H_{ij}(f)}{H_{ii}(f)}, \qquad G_{ii}(f) = 0, \qquad N_i(f) = \frac{E_i(f)}{H_{ii}(f)} \tag{7}$$

The inherent noise PSD (Auto or Cross) of $\mathbf{N}(f)$ is defined by

$$Q_{ij}(f) = \frac{\sigma_{ij} \cdot \Delta t}{\left\{\mathbf{H}(f)\right\}_{ii} \cdot \left\{\mathbf{H}(f)\right\}_{jj}^{*}} \tag{8}$$

Neglecting effects in signals *i* and *j* from the *m* -2 remaining signals in MAR model (1) then we have

$$\begin{bmatrix} 1 & -G_{ij}(f) \\ -G_{ji}(f) & 1 \end{bmatrix} \cdot \begin{bmatrix} X_i(f) \\ X_j(f) \end{bmatrix} = \begin{bmatrix} N_i(f) \\ N_j(f) \end{bmatrix} \tag{9}$$

The partial coherence of signals *i* and *j* is (Oguma and Turkcan (1985), Antonopoulos-Domis et all (1994))

$$(\mathrm{PCOH})_{ij} = \frac{\left| G_{ji}^{*}Q_{ii} + G_{ij}Q_{jj} + G_{ij}G_{ji}^{*}Q_{ji} + Q_{ij} \right|^{2}}{\left[Q_{ii} + \left| G_{ij} \right|^{2} Q_{jj} + 2\,\mathrm{Re}(G_{ij}Q_{ij}^{*}) \right] \left[Q_{jj} + \left| G_{ji} \right|^{2} Q_{ii} + 2\,\mathrm{Re}(G_{ji}Q_{ji}^{*}) \right]} \tag{10}$$

The partial noise contribution ratio of the driving noise source *j* to signal *i* is

$$(\mathrm{PNCR})_{ij} = \frac{\left| G_{ij} \right|^{2} Q_{jj}(f)}{Q_{ii}(f) + \left| G_{ij}(f) \right|^{2} Q_{jj}(f) + 2\,\mathrm{Re}\left[G_{ij}(f) \cdot Q_{ij}^{*}(f) \right]} \tag{11}$$

Comparison of partial coherence and partial noise contribution ratios between channels *j* and *i*, reveals the existence, or otherwise, of the causal relationship between the two signals. That is, if for a particular frequency PCOH$_{ij}$ coincides with PNCR$_{ij}$, while PNCR$_{ji}$ is zero, then the excitation source of signal *i* in that frequency is the noise source *j*, provided that the covariance between noise sources *j* and *i* is zero

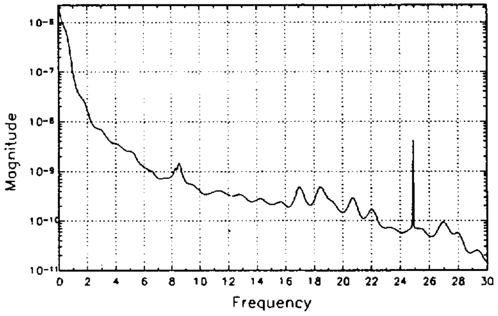

Fig. 1. APSD of in-core neutron detector on the seventh elevation of string A

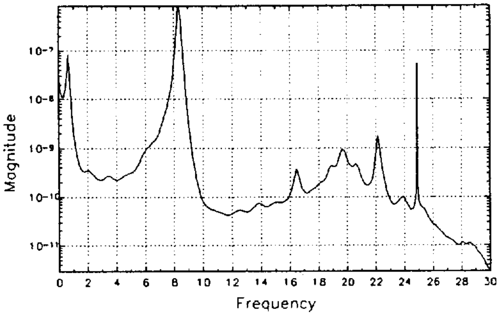

Fig. 2. APSD of outlet coolant pressure

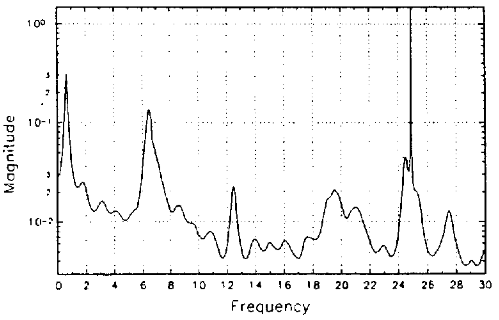

Fig. 3. APSD of pressure of loop 6 (cold leg)

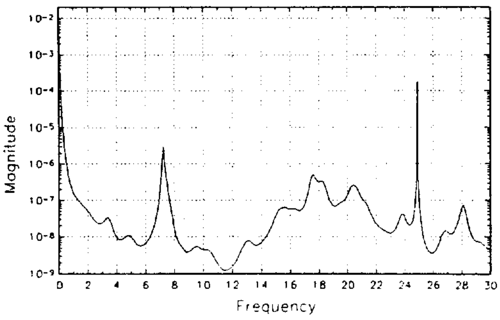

Fig. 4. APSD of vibrations on MCP of loop 1

3. RESULTS AND DISCUSSION

Figure 1 presents the APSD of in-core neutron detector on the seventh elevation of string A. It can be seen that there is a strong peak at 25 Hz. Such a strong peak at 25 Hz is present in the APSD's of all recorded signals. Typical examples are presented in figure 2 (APSD of coolant outlet pressure), figure 3 (APSD of pressure of cold leg of loop 6) and figure 4 (APSD of vibration of MCP of loop 1).

A smaller peak at 8.5 Hz can be seen in figure 1. Such a peak is present in the APSD's of in-core

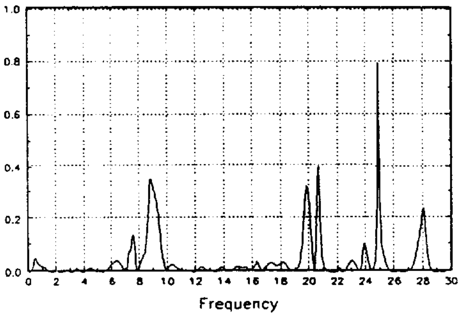

Fig. 5.a. Partial Coherence between outlet pressure and vibrations on MCP of loop 1.

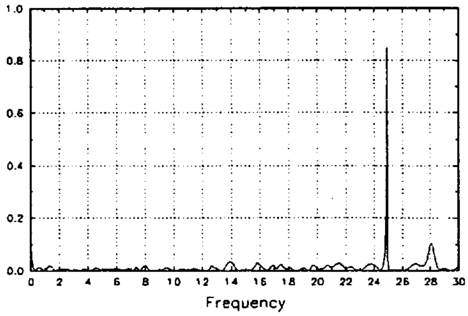

Fig. 6.a. Partial Coherence between neutron detector on the seventh elevation of string A and vibrations on MCP of loop 5.

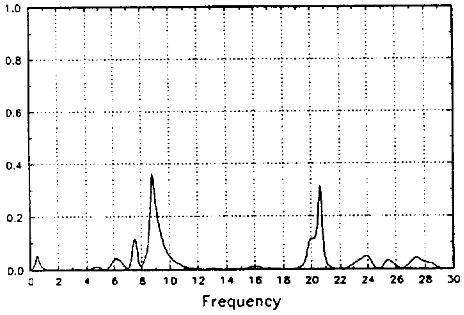

Fig. 5.b. Partial Noise Contribution Ratio from outlet pressure to vibrations on MCP of loop 1.

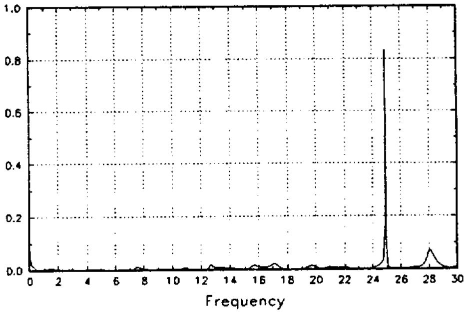

Fig. 6.b. Partial Noise Contribution Ratio from vibrations on MCP of loop 5 to neutron detector on the seventh elevation of string A.

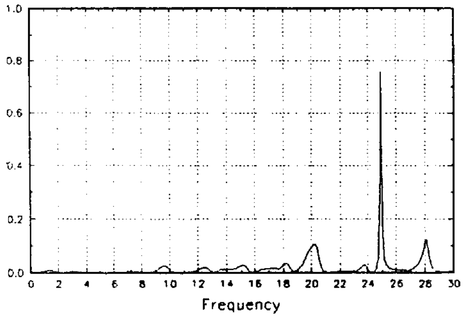

Fig. 5.c. Partial Noise Contribution Ratio from vibrations on MCP of loop 1 to outlet pressure

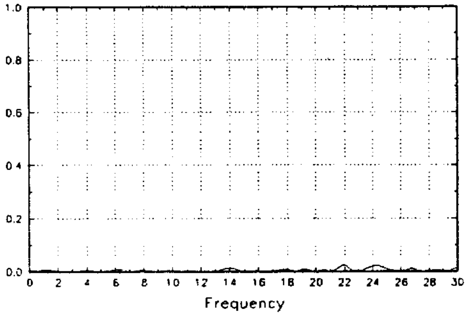

Fig. 6.c. Partial Noise Contribution Ratio from neutron detector on the seventh elevation of string A to vibrations on MCP of loop 5.

neutron detectors near the top (fifth and seventh elevations) of the core.

Figure 2 presents the APSD of coolant outlet pressure. It can be seen that a strong peak is present at 8.5 Hz. A similar peak at 8.5 Hz is also present in the APSD of coolant inlet pressure.

Figure 5.a presents the partial coherence between outlet pressure and vibrations of MCP of the first loop, whilst figure 5.b and figure 5.c present the corresponding partial noise contribution ratios. It can be seen that at 25 Hz the value of the partial coherence is 0.8 and the value of the partial noise contribution ratio from MCP vibrations to outlet pressure is very near to the value of the partial coherence. On the other hand the partial noise contribution ratio from outlet pressure to MCP vibrations is almost zero at 25 Hz. It is clear that there is a strong direct path from MCP vibration of the first loop to coolant outlet pressure at this frequency.

Similarly it can be seen in figure 6 that there is a strong direct path from vibration of MCP of loop 5 to neutron detector on the seventh elevation of string A. In fact any pair of anyone of the MCP's and any other signal presents a similar picture to that of figures 5 and 6, from which it is concluded that there are strong direct paths from each one of the MCP's to all of the signals. On the other hand any combination of signals not including a MCP presents a high ordinary coherence and practically zero values of partial coherence and partial noise contribution ratios at 25 Hz.

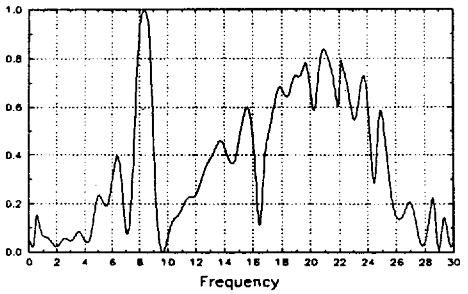

Fig. 8.a. Partial Coherence between outlet and inlet pressure.

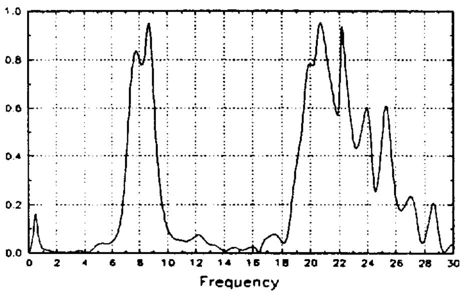

Fig. 8.b. Partial Noise Contribution Ratio from outlet pressure to inlet pressure.

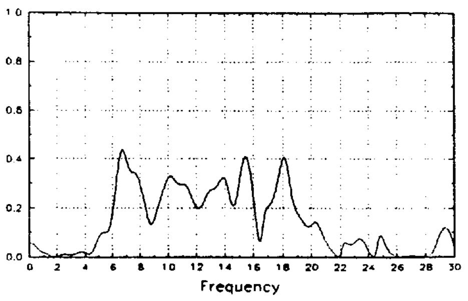

Fig. 8.c. Partial Noise Contribution Ratio from inlet pressure to outlet pressure.

A typical example is presented in figures 9.a and 9.b. In 9.a the ordinary coherence between outlet coolant pressure and in-core neutron detector on the seventh elevation of string A is presented, whilst in figure 9.b the corresponding partial coherence is presented. It can be seen that while ordinary coherence has a high value at 25 Hz (about 0.8), partial coherence is almost zero at this frequency. It is clearly concluded that the source of excitation for all signals at 25 Hz is the vibration of MCP's of all loops. It was reported earlier (J. Valko et all (1985), G. Por et all (1985)) that the 25 Hz peak might be due to a bearing problem in MCP's. The present STP analysis clearly confirms that the origin of excitation at 25 Hz is at the MCP's.

Partial coherence and partial noise contribution ratios between coolant outlet and inlet pressures, suggest that there is a direct path from coolant outlet pressure to coolant inlet pressure at about 8.5 Hz as can be seen in figure 8. There is a strong peak at this frequency in the APSD's of coolant outlet and inlet pressure (see figure 2). Direct path at this frequency is also suggested by STP analysis from coolant outlet pressure to the signals of in-core neutron detectors located at the upper part of the core (fifth and seventh elevations) as can be seen for example from figures 9.b, 9.c and 9.d. On the other hand the spectra of all other primary coolant pressure signals do not present a peak at 8.5 Hz; see for example figure 3. Moreover STP analysis does not indicate paths from outlet pressure to other primary coolant pressure signals. It has been suggested (J. Valko et all (1985)) that the peak at 8.5 Hz in the spectrum of outlet pressure is related to standing waves. Figures 8.a and 8.c suggest the existence of direct path from inlet to outlet pressure at 6.5 Hz. On the other hand there is no peak at the APSD of outlet pressure (figure 2)

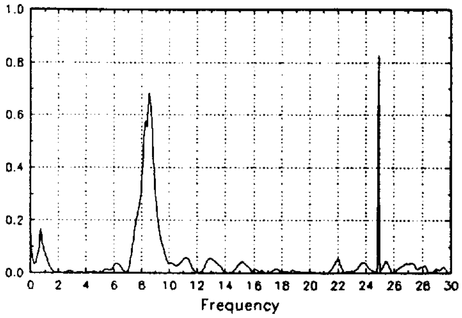

Fig. 9.a. Ordinary Coherence between outlet pressure and neutron detector on the seventh elevation of sting A

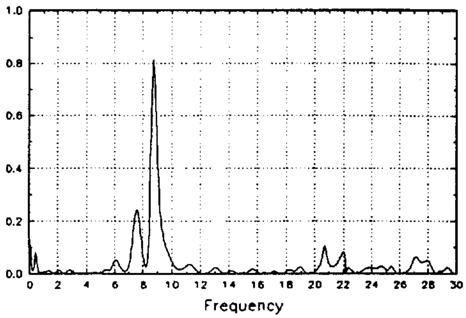

Fig. 9.b. Partial Coherence between outlet pressure and neutron detector on the seventh elevation of sting A.

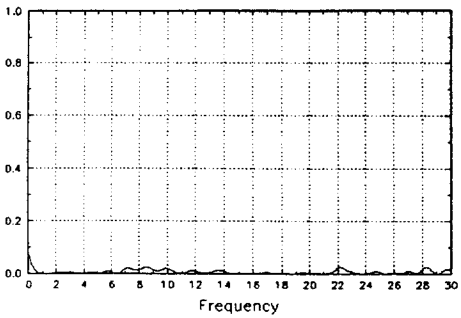

Fig. 9.c. Partial Noise Contribution Ratio from neutron detector on the seventh elevation of string A to outlet pressure.

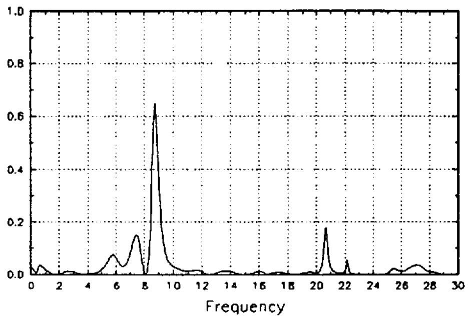

Fig. 9.d. Partial Noise Contribution Ratio from outlet pressure to neutron detector on the seventh elevation of string A.

whilst there is a small peak at 6.5 Hz at the APSD (not shown here) of inlet pressure. Such a peak is present at the APSD's of pressures of loops 4 and 6 (figure 3), but STP analysis does not suggest direct paths from inlet pressure to pressures of loops 4 and 6; in fact both ordinary and partial coherence between inlet pressure and pressures of loops 4 and 6 are practically zero.

For the rest of the peaks appearing in the spectra, STP analysis does not provide any interesting suggestions.

4. CONCLUSIONS

Signal Transmission Path analysis was applied on noise signals of a WWER power reactor. It suggests clearly that there are strong direct paths from main coolant pumps to all signals at 25 Hz. It was confirmed that there is vibration of main coolant pumps at this frequency due to a bearing problem. Signal Transmission Path analysis also suggests direct paths from outlet coolant to inlet coolant pressure and in-core neutron detectors at the upper part of the core.

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REFERENCES

Antonopoulos-Domis M., Mourtzanos K., Por G. (1994), *Annals of Nuclear Energy* **21**, 667
Oguma R. (1981), *J. Nucl. Sci. Technol.* **18**, 835.
Oguma R. and Turkcan E. (1985), *Progress in Nuclear Energy* **15**, 863.
Por G., Lux I., Mesko L.(1985), *Progress in Nuclear Energy* **15**, 897.
Valko J., Por G., Czibok T., Tzsak E., Hollo E., Siklossy P.(1985), *Progress in Nuclear Energy* **15**, 403.