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**MODELING AND DIAGNOSTIC TECHNIQUES APPLICABLE TO THE
ANALYSIS OF PRESSURE NOISE IN PRESSURIZED WATER REACTORS AND PRESSURE-SENSING SYSTEMS**

J. A. Mullens,* J. A. Thie**

*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831 USA¹

**Analysis & Measurement Services, Inc., Knoxville, Tennessee 37919

ABSTRACT

Pressure noise data from a PWR are interpreted by means of a computer-implemented model. The model's parameters, namely hydraulic impedances and noise sources, are either calculated or deduced from fits to data. Its accuracy is encouraging and raises the possibility of diagnostic assistance for nuclear plant monitoring. A number of specific applications of pressure noise in the primary system of a PWR and in a pressure sensing system are suggested.

KEYWORDS

Pressure noise; noise modeling; LOFT reactor; pressure-sensing systems; diagnostic application; acoustic impedances; standing waves; pressure resonances

INTRODUCTION

The purpose of this study is to use a combination of theory and experiment to better understand pressure noise in PWRs. Research by Posse (1973) and by Bauernfeind (1974) a decade ago pointed out the information content of pressure fluctuations. This research has been renewed recently by Grundwald (1981, 1984) and by the authors (Thie, 1982; Mullens, 1983).

The investigation conducted by ORNL has made use of data from (a) the Loss-of-Fluid Test Facility (LOFT) at Idaho National Engineering Laboratory, Idaho, USA; (b) a few commercial PWRs, and (c) a small laboratory loop at ORNL. A more extensive report detailing these investigations is being written for the U.S. Nuclear Regulatory Commission (Mullens, 1984).

The main subject of the study is far-field noise, treated in one dimension by theoretical models; near-field noise and local turbulences have not been emphasized. The frequency band investigated ranges from the neighborhood of 0.1 Hz (above the frequencies dominated by control systems) to the neighborhood of 10 to 100 Hz, depending on the phenomena and the transducer response. Modeling is limited to the use of sources and passive linearized elements.

MODEL

The model developed for this study is a lumped-parameter model. It is a low-frequency (<10 Hz) case of the distributed parameter model, and its implementation is convenient for geometrically complex systems. Its relationship to distributed parameter models is detailed in a more extensive report (Mullens, 1984).

The forms of the momentum conservation, continuity, and state equations applicable to a region of fluid are:

$$A^2 \frac{dM}{dt} = \rho(u_1 - u_0) \quad (1)$$

$$M \frac{du}{dt} = p_1 - p_0 - Ru \quad (2)$$

$$dp/dt = 1/C (A^2/\rho) dM/dt \quad (3)$$

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¹Research sponsored by the U.S. Nuclear Regulatory Commission under Interagency Agreement No. 40-551-75 and performed at Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

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A small-perturbation, linearized approach is used here. Subscripts i and o refer to the inlet and outlet of the volume, u is volumetric flow, ρ is density, and A is flow cross section. The impedance (inertance), resistance, and capacitance are conceptually convenient combinations of system properties:

$$M = \rho L/A \quad (4)$$

$$R = \rho L F/A \quad (5)$$

$$C = LA/B \quad (6)$$

where L is the region length, F is the flow friction factor, and B is the fluid bulk modulus.

The equations may be Laplace transformed and solved for the general control volume of Fig. 1 to give

$$\left(C s + \frac{1}{\bar{X}_i} + \frac{1}{\bar{X}_o} \right) p = C s p_s + \frac{1}{2} p_d \left(\frac{1}{\bar{X}_o} - \frac{1}{\bar{X}_i} \right) + \frac{1}{\bar{X}_i} \left[\frac{\sum_j \frac{p_j + \frac{1}{2} p_d}{X_j}}{\sum_j \frac{1}{X_j}} \right] + \frac{1}{\bar{X}_o} \left[\frac{\sum_k \frac{p_k + \frac{1}{2} p_d}{X_k}}{\sum_k \frac{1}{X_k}} \right] \quad (7)$$

where

$$\bar{X}_i = X_i + 1/\sum_j \frac{1}{X_j}, \quad (8)$$

$$\bar{X}_o = X_o + 1/\sum_j \frac{1}{X_j}, \quad (9)$$

with each impedance X being $M s + R$, and subscripts j and k referring to connected regions upstream and downstream respectively. Both absolute (p_s) and differential (p_d) pressure noise sources are postulated. The signs of the latter depend on defined positive flow directions in their control volumes.

The equation can be solved to calculate pressure noise, given the sources (Mullens, 1984). It is desirable to fit measured data for sources (which are given a magnitude and a frequency dependence) and selected system dynamics parameters not known well a priori. The best fit minimizes the difference between model and measured spectra, weighted by measurement precision.

ORNL-DWG 84-11151

Fig. 1. The electrical analog of the general control volume equations.

SOURCES

A variety of independent physical phenomena in the primary system of a PWR provide pressure noise sources: main coolant pumps; turbulence; controllers; pressurizer level sloshing (Mullens, 1984); charging pumps; mechanical vibrations transmitted to the fluid; boiling/condensation in the core and pressurizer; and nonboiling heat transfer variations in the core and steam generator.

In addition, pseudo-pressure noise sources must be added to compare the model to measurements that have effects of electronic noise and mechanical excitation of transducers.

A significant pressure noise source in the core and steam generator is heat transfer fluctuation. The simplified conservation of energy equation is:

$$d/dt(\rho A h) = u_i \rho_i h_i - u_o \rho_o h_o + H(T_s - T) \quad (10)$$

where h is the enthalpy per unit mass, h_i and h_o are the enthalpies at inlet and outlet, H is the heat transfer rate per unit temperature, T is the temperature of coolant, and T_s is the temperature of the heat source or sink.

Also, density changes are related to inlet and outlet densities:

$$d\rho/dt = 1/(A l) \delta u(\rho_i - \rho_o) \quad (11)$$

The solution of Eqs. (10) and (11) for small pressure variations leads to the result that the thermally-induced pressure noise is driven by three other fluctuations: inlet enthalpy, flow, and heat source/sink temperature.

MODEL APPLICATIONS

The generalized lumped-parameter model can be applied to many systems. The LOFT reactor is discussed below. Applications to sensing lines and a benchtop flow loop are discussed by Mullens (1984) and Machado (1983).

LOFT

The highly instrumented LOFT reactor provided a realistic set of primary pressure noise signals. Though only a 50-MW thermal reactor at full power, its piping and core geometry are sized and its operating conditions selected so as to give hydraulic and thermodynamic conditions similar to commercial PWRs. Figure 2 shows the system and the model control volumes.

The five signals selected for model fitting were the hot and cold leg absolute pressures and the differential pressures (dp) from the pump pair, reactor vessel, and steam generator. A frequency range of 0.5 Hz to 8 Hz was used. From noise data at five conditions--0%, 25%, 50%, 75%, and 100% power--175 spectra [power spectral densities (PSDs), transfer functions, phases, and coherences] were selected for these five fits. Typical data and fits are shown in Figs. 3a through 3e.

In applying the model, a priori values of control volume parameters were used whenever possible. The remaining fitted parameters are listed in Table 1. Sources not likely to be white were allowed a shape, as follows: the pump dp PSD noise source was given the form $A/(1+f/f_b)^{2r}$, where the fitting parameters are amplitude A , break frequency f_b , and roll-off rate r ; the pressurizer PSD noise source was taken to be the tail of low-frequency excitation, A/f^{2r} . Fitted signal gains allow for calibration error and for an actual tap position differing slightly from the control volume position.

Only two impedance parameters were selected for fitting: surge line resistance and pressurizer capacitance. Two locations for thermal sources of pressure noise were included, the steam generator and the core. Their shapes were derived and their amplitudes fitted to a dimensionless heating parameter: pressure noise units per unit of flow pressure drop. With flow-fluctuation thermal-to-pressure effect being dominant over surface temperature and inlet enthalpy fluctuations, it was possible to use this simple formulation for the amplitude of this effect.

From inspection of the fits and the various features of Table 1, it was possible to conclude that the model was reasonable for LOFT. The following features support this conclusion:

- A complete set of 35 functions $\times$ 32 measured points per function at one condition, full power, are fitted reasonably by only 21 empirically determined parameters.
- Gains are not too far from the idealized value of 1.0.

Fig. 2. Control volumes used in the LOFT reactor.

- The fitted surge line resistance is larger when there is higher viscosity when cold, and when there is more surge flow at high power.
- The fitted resistance of the surge line is corroborated by a measurement of the damping of the Helmholtz resonance obtained from transient data.
- The heating parameters, which describe the core and steam generator thermally induced pressure noise sources, increase with power as expected and are close to a priori estimates for the full-power fit.
- At higher power, where there is more pressurizer pressure controller action, the pressurizer noise source increases as expected.

Despite the encouraging results, the model is not complete, and there is a $\pm 9\%$ error in the spectral measurement itself. Hence it is not surprising that some features in Table 1 are not perfectly understood. For example, at 25% power, while the dominating noise source is correctly the pumps' dp, the distribution of the minor sources differs from that of the other cases.

SURVEILLANCE AND DIAGNOSTIC OPPORTUNITIES

Having an interpretive model for pressure noise measurements, it is reasonable to speculate on monitoring applications. The applications are summarized here from a more thorough treatment (Mullens, 1984).

- Standing waves in primary piping are a universal phenomenon in FWRs. If an observed standing wave frequency and known wavelength are used, an experimental velocity of sound (c) in the primary piping is deduced. With c being a function of temperature, this is a redundant indication of temperature (and hence subcooling). Also, minor steam and gas bubble content can be detected by their significant influence on c .
- An oscillation of flow between the primary loop and the pressurizer is also a universal FWR phenomenon (see Fig. 3 at 1 Hz.) Changes in its frequency reflect changes in levels in the

Fig. 3. Typical measurement and model for LOFT reactor at 100% power.

TABLE 1 Fitted LOFT model parameters

Parameter	Power level and temperature ^a				
	0% 197°C	25% 281°C	50% 286°C	75% 294°C	100% 295°C
Pressure noise sources (in Pa ² /Hz for A) ^b					
Pump dp A	27.0E6	26.5E6	26.0E6	23.0E6	24.6E6
Pump dp f _b in Hz	31.1	56.9	53.5	60.8	58.7
Pump dp r	5.56	9.28	9.36	9.98	9.96
Core dp A	0.55E6	0	0.48E6	0.55E6	0.57E6
Pressurizer A	0.18E6	0	0.34E6	0.44E6	5.41E6
Pressurizer r	0.399	0.287	0.602	0.514	1.01
Hot leg inlet local A	0	0.071E6	0	0	0
Pump inlet local A	0.319E6	0.212E6	0.390E6	0.378E6	0.345E6
Pump outlet local A	0	0.16E6	0	0	0
Signal noise sources (in Pa ² /Hz for A)					
Cold leg absolute A	0.38E6	0.016E6	0.048E6	0.048E6	0.033E6
Pump differential A	0.856E6	0.964E6	0.838E6	0.825E6	0.806E6
Steam generator differential A	0.520E6	0.606E6	0.620E6	0.591E6	0.545E6
Reactor vessel differential A	0	0.099E6	0.029E6	0.012E6	0.014E6
System parameters					
Surge resistance in kg/m ⁴ /s	1.49E6	0.482E6	0.854E6	1.23E6	1.54E6
Pressurizer capacitance in s ² m ⁴ /kg	0.200E-6	0.0174E-6	0.0115E-6	0.0108E-6	0.0111E-6
Core heating (dimensionless)	0.0216	0.0245	0.774	2.92	7.37
Steam generator heating (dimensionless)	0.0000	0.0000	0.0005	0.299	0.927
Signal gains (dimensionless)					
Hot leg absolute	1.13	1.11	1.27	1.22	1.15
Pump differential	1.24	1.19	1.22	1.24	1.22
Steam generator differential	0.980	0.913	0.941	0.949	0.930
Reactor vessel differential	0.946	0.904	0.920	0.925	0.934

^aExcept at 0% power, where the hot leg pressure was 5.6 MPa (812 psig), the reactor operated at 14.1 MPa (2050 psig).

^bLegend:

- A - amplitude
- dp - differential pressure
- f_b - break frequency
- r - roll-off rate

pressurizer and reactor vessel (i.e., head bubble). The frequency is particularly sensitive to a nearly solid pressurizer.

- Analysis (Mullens, 1983, 1984) of 653 failures in sensing systems has indicated the value of using pressure noise for detection and possibly diagnosis. In addition to permitting earlier detection of the majority of failures, these modeling techniques also make it possible to quantify during the initial detection the one in seven failures caused by sensing line problems.
- A host of primary system components/conditions having anomaly potential, in addition to these already indicated, can be addressed via their influence on the model parameters.

This last, somewhat general application deserves further discussion. In the LOFT data, five pressure signals were used, taking only 8 Hz of their available bandwidth. The model describing their PSD/CPSDs showed 21 fitted parameters in Table 1 in addition to the 43 impedance parameters calculated *a priori*. Each of these 64 parameters is dependent on more basic system properties, which anomalies can influence.

Some of these parameters are listed in Table 2, which shows their influence on the spectra. Parameters in the final fitted model were changed to see their effect on model-predicted signals. The figure of merit (FM) tabulated is proportional to the amount of data needed to detect a parameter change. The small FMs indicate the most sensitive monitoring configurations. Only the most sensitive detector(s) and frequencies are listed in Table 2.

One observation from Table 2 is that the hot leg pressure sensor is the single most useful sensor. Also, pump discharge is the optimal sensor for use in combination with other sensors.

CONCLUSIONS

An understanding of pressure noise is possible using a quantitative model whose parameters pervade the entire primary system. The model's adequacy is sufficient for diagnosing a number of specific anomalies. These capabilities show that there is merit in using noise analysis for making more effective use of installed pressure sensors--and possibly adding others. Also, there are ample research opportunities to seek benefits from a better understanding of pressure noise, particularly for extensions to phenomena below 0.5 Hz and above 20 Hz.

TABLE 2 Detectability of changes for LOFT at 100% power
(The signals and frequencies shown here provide the best sensitivity for a given system parameter.)

System parameter	Signal*	Power spectrum frequency (Hz)	Figure of Merit**	Signals	Transfer function frequency (Hz)	Figure of Merit
Capacitance (entire system)	HLA	0.9	0.26	HLA/PD	1.2	0.44
	CLA	1.2	0.80	HLA/RVD	1.2	0.52
Pressurizer capacitance	HLA	0.9	0.83	CLA/HLA	0.9	4.8
				CLA/RVD	1.2	5.4
Upper plenum capacitance	HLA	1.4	15	CLA/HLA	1.4	26
Resistance (entire system)	HLA	1.2	5.4	CLA/HLA	1.2	7.6
Inductance (entire system)	HLA	1.2	0.27	HLA/PD	1.2	0.40
	CLA	0.9	0.32	HLA/SGD	1.2	0.48
Core heat transfer coefficient	HLA	1.2	0.81	CLA/PD	1.4	1.3
				CLA/RVD	1.2	1.6
Steam generator heat transfer coefficient	HLA	1.4	3.3	CLA/PD	1.4	3.6
				CLA/SGD	1.2	4.3
Absolute pressure noise source (pressurizer) amplitude	HLA	0.7	3.1	HLA/PD	0.5	12
				HLA/RVD	0.5	13

*Signals: CLA = cold leg absolute at reactor vessel inlet,
HLA = hot leg absolute at reactor vessel outlet,
PD = pump differential pressure,
SGD = steam generator differential pressure, and
RVD = reactor vessel differential pressure.

**Frequencies above 0.5 Hz and below 8 Hz.

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