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Research Article

Analysis of acoustic leak signals for enhancing sensitivity of control due to the creation of effective diagnostic indicators*

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Abstract

Acoustic leak control systems (for instance, SAKT) are used at present for controlling leak tightness of equipment and pipelines, as well as for detecting in timely manner coolant leaks from the primary cooling circuit of nuclear reactor installations (NRI) during operation of power unit on different power levels in the modes of normal operation and during disturbances of normal operation. Time averaged dispersion of acoustic signal is used as the main diagnostic indicator for detecting leaks in these systems. Sensitivity of this indicator is determined by the exceedance by the signal of the preset threshold value which is defined in accordance with the background. Here, background values of acoustic signal depend on the operational modes of the equipment and do not allow in many cases determining coolant leak during early stages of leak development.

New approach to the formation of diagnostic indicators for detecting loss of sealing in the circuit during early stage of development of coolant leak is suggested.

Methodology for obtaining diagnostic indicators is based on the processing in different frequency bands of acoustic signal accompanying coolant leakage from the pipeline using the method of principal components.

Efficiency of the developed methodology of coolant leak detection is illustrated by processing acoustic signals for experimental facility modeling coolant leakage in case of loss of sealing of the circuit.

Even in the presence of significant acoustic background sensitivity of the method allows detecting leaks with significantly lower flow rates (up to five times smaller) than the conventional processing of acoustic signals.

Implementation of the developed methodology will not require significant expenditures for upgrading already existing leak control systems operated at present on different NPPs.

Keywords

control of leak tightness of equipment; dispersion of acoustic signal; modeling coolant leaks; method of principal components; additional diagnostic indicators; pattern identification

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Introduction

Acoustic leak control systems (SAKT in Russian abbreviation) are used at present for controlling leak tightness of equipment and pipelines, as well as for detecting in timely manner coolant leaks from the primary cooling circuit of nuclear reactor installations (NRI) during operation of power unit on different power levels in the modes of normal operation and during disturbances of normal operation (Arkadov et al. 2010, Weiss et al. 1988, Basseville 1988, Herbert 1984). Time averaged dispersion of acoustic signal is used as the main diagnostic indicator for detecting leaks in this system. Sensitivity of the above indicator is determined by the exceedance by the signal of the preset threshold value which, in turn, is determined by the background. Here, background values of acoustic signal depend on the operational modes of the equipment and do not allow in many cases determining coolant leak during early stages of leak development.

Additional diagnostic indicators and methods for their identification allowing more reliably determining presence of leakages in the case of small coolant leakage flow rates are examined in the present paper. Pattern identification theory (Abagyan et al. 1987, Tu and Gonsales 1978, Fukunaga 1972, Classification and clustering (1980), Tao Gu and Tou 1982) successfully applied in different studies on the diagnostics of NRI equipment (Leskin et al. 2016, Leskin et al. 2017, Ujita Hiroshi 1986, Fault diagnosis in dynamic systems 1989, Willsky 1976, Iserman 1984, Frank 1990, Reisen and Marshall 1988, Abagyan et al. 1987, Herbert 1984, Pavelko 1990, Urig Robert 1991, Leskin 1997) constitutes the basis for formation of additional diagnostic indicators.

Experimental facility

Measurements were conducted on the experimental stand imitating circulation loop at the INPE NRNU MEPhI designed for implementation of studies of acoustic noises and hydraulic characteristics of circulating coolants.

The experimental facility consists of the device for imitation of leak with compressed air and the simulator of heat exchange pipe intended for investigation of the nature of propagation of surface waves inside steel pipe. The simulator represents a pipe made of stainless steel 1X18H10T with length equal to 5000 mm and diameter equal to 45×3.5 mm. Acoustic emission sensor GT301 is fixed on one of the pipe's ends.

Nozzle with calibrated aperture arranged on the pipe as part of the special tool acts as the transmitter of stress waves (leak imitator). Noise emitted during gas discharge from the nozzle imitates the noise of water leakage. Gas supply system consists of pressurized gas cylinder, gas pressure regulator, measuring volume, pressure gauge measuring gas pressure inside the measuring volume and the system of valves and nozzle.

Procedure for calibration of gas flow channel consists of the measurement of the value of gas pressure imitating the working medium.

Measuring volume V from which gas is bled through the nozzle is filled from the pressurized gas cylinder. Ultrasonic oscillations exciting Rayleigh surface waves are generated in the process of gas bleeding. Average gas flow rate is calculated according to the following formula:

$$G = -VM_{\mathrm{N}}(V_{\mu}P_0)^{-1}\times dP/dt, \qquad (1)$$

where G is the gas flow rate, kg/s; M_{N} is the molecular mass of the gas, kg; V_{μ} is equal to $22{,}4\times10^{-3}$ m^3; P_0 is the value of atmospheric pressure, MPa; dP/dt is the rate of pressure reduction, MPa/s.

Let us note that the above formula is valid only for the subcritical gas discharge i.e. for the value $P \leq 2$ atmospheres. Above this value pressure changes linearly while the flow rate remains constant. Nevertheless, formula (1) determines gas flow rate specifically in the area of small values which allows testing sensitivity of the automated measurement system with regard to small leaks.

Dependences of the value of pressure in the measuring volume and gas flow rate on the time of gas discharge are presented in Figure 1. Gas discharge in the present experiment begins from 12-th second. Value of gas flow rate has physical meaning from approximately 100-th second.

Traditional approach

Two integral statistical characteristics – acoustic wave spectrum power and average frequency of the spectrum – are usually applied for the detection of leaks during diagnostics of pipelines by acoustic method.

Spectrum power is equal to:

$$M = \sum_{i=1}^{N} S(F_i),$$

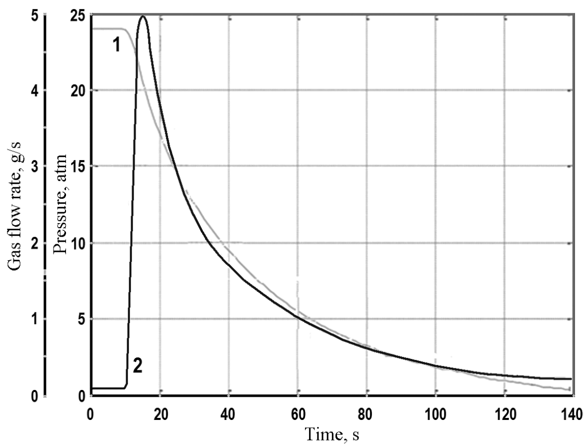

Figure 1. Time dependences of pressure and gas flow rate during gas discharge: 1 – pressure; 2 – flow rate.

where $S(F_i)$ is the spectral power density (SPD) on a frequency F_i proportional to the area under the SPD curve and determined by the dispersion of the measured acoustic signal.

Average spectral frequency F_R (Reiss frequency)

$$F_R = \sum_{i=1}^{N} F_i \cdot S(F_i) \Big/ \sum_{i=1}^{N} S(F_i)$$

is determined by the shape of frequency spectrum of the measured acoustic signal.

Application of the above diagnostic indicators is predetermined by the following facts:

– Acoustic spectrum power increases with growing leakage;
– Shape of acoustic spectrum changes when the leak emerges as compared with the background value (sharp shifting of the center of mass of the acoustic spectrum in the area of low frequencies takes place during the initial phase of leak initiation);
– Implementation of estimation of the value and tentative location of the leakage source is possible using the correlation between quantitative characteristics, i.e. the diagnostic indicators, characterizing variation of power and shapes of spectra for sensors installed in different points.

Dispersions and average frequencies of acoustic signal of the sensor are presented in Figure 2. It is evident that beginning from 500-th second with gas flow rate equal to about 0.04 g/s these diagnostic indicators practically fail to identify the leak.

Ratio of signal energies on different parts of the power spectrum, as well as the ratio of current average frequency to the average background frequency were selected as the diagnostic indicators in the suggested approach. Since signal within different frequency bands is attenuated differently, assumption was made that ratios of energies of signals within different frequency bands will be more informative diagnostic indicators than the total dispersion.

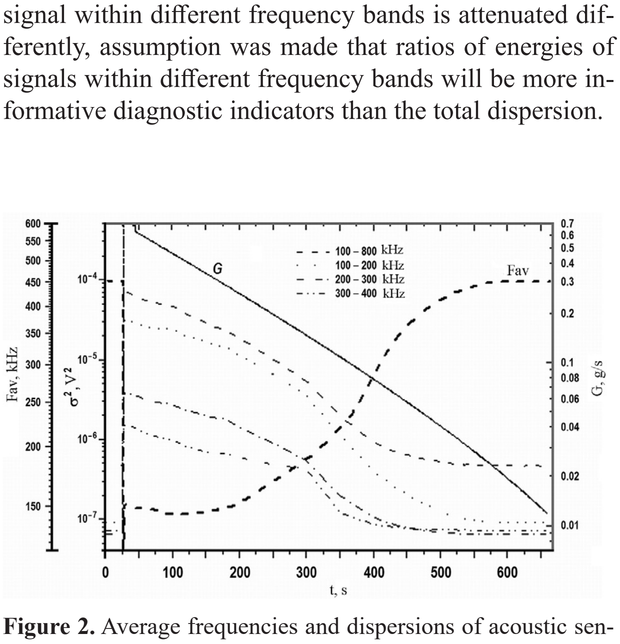

Figure 2. Average frequencies and dispersions of acoustic sensor signal within the frequency range from 100 kHz to 800 kHz.

Signal energies within the frequency band from 100 kHz to 200 kHz (E_1), from 200 kHz to 300 kHz (E_2), from 300 kHz to 400 kHz (E_3) and over the whole spectrum from 0 to 800 kHz (E_4), as well as the average frequency of the spectrum F_R were calculated. The above values were calculated by averaging the signal over the time interval equal to one second. Measurement discretization frequency F_s = 2 MHz. Diagnostic indicators were constructed based on these values as follows: different ratios $P_i = E_{i_1}/E_{i_2}$ for $i = 1 - 8$ (i_1 and i_2 are the different combinations of partial energies) were taken, as well as $P_9 = F_R/F_{bgr}$.

It was necessary to normalize all indicators according to the same scale for the purpose of performing their analysis and to construct covariance matrix. In order to achieve the above the following formula was applied to each of the indicators:

$$P^* = (P - \mu)/\sigma, \tag{2}$$

where dispersion σ and mathematical expectation μ are calculated for the current time window.

Scaled indicators are shown in Figure 3. Their difference from the background values is significantly better pronounced in such representation. They practically coincide with background only by the 640-th second of the leakage.

Let us construct covariance matrix for the indicators at i-th time moment

$$C_{ij} = \sum_{j=1}^{N} P^*_{ij} \times P^{*T}_{ij} - M_i \times M^T_i, \tag{3}$$

And, following this, calculate its eigenvalues which are, essentially, the dispersions of the indicators in the new space:

$$\Lambda Q = \mathbf{C} Q, \tag{4}$$

where $\Lambda = \mathrm{diag}(\lambda_1, \lambda_2, ..., \lambda_N)$ are the eigenvalues of the covariance matrix; $Q = (q_1, ..., q_N)$ are the respective eigenvectors of the covariance matrix.

For calculating covariance matrix all indicators P_i were averaged within the frame of the current time window

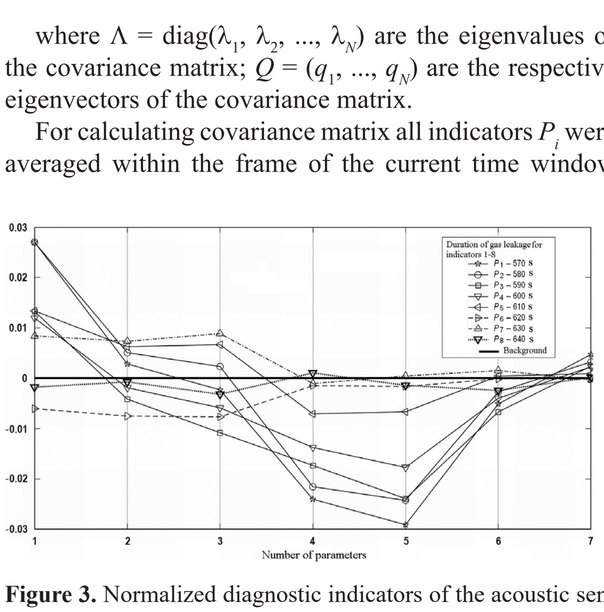

Figure 3. Normalized diagnostic indicators of the acoustic sensor at different time moments.

which was equal to 10 seconds, i.e. indicators P_{ij} were taken at each time moment for the last 10 s, where i is the number of the indicator, and j is its time stamp within the limits of the current time window. It is specifically averaging over the time window which is meant by the summation in Formula (3).

Comparison of variation of the largest eigenvalue of the covariance matrix (Fukunaga 1972) (LEVCM) with time with signal dispersions, as well as leakage flow rate in g/s is shown in Figure 4. It is evident from the figure that application of LEVCM as the indicator for leak control is found to be more sensitive than the signal dispersion or the average spectrum frequency. Indication of the leak when LEVCM is applied occurs at flow rate ~ 0.015 g/s, while when indication of leak is made using signal dispersion it is achieved at flow rate ~ 0.04 g/s.

Thus, indication of leak using LEVCM allows enhancing sensitivity of leak detection by more than two times. Results of leak indication are presented in Figure 5 in the representation of principal components of the covariance matrix.

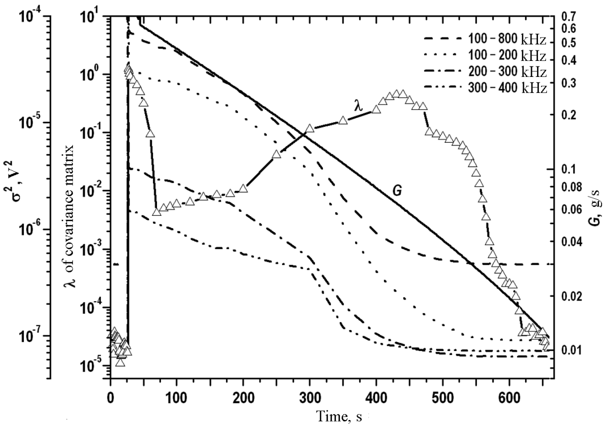

Figure 4. Comparison of variation of the largest eigenvalue of covariance matrix (LEVCM) in time with signal dispersions (Fukunaga 1972).

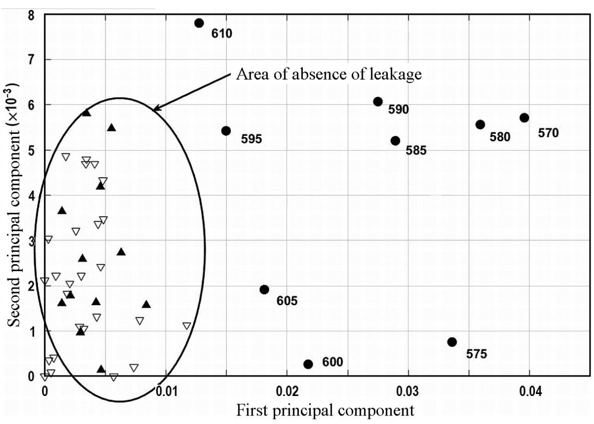

Figure 5. Tome evolution of the leak in the representation of principal components of the covariance matrix: triangles – conditions with absence of leak (vertex down – before initiation of the leak, vertex up – after leak attenuation); solid circles – conditions of leak at respective time moments.

The fact is of interest that LEVCM has sufficiently high value in the area of coolant flow rate where traditional diagnostic indicators (dispersion and average spectral frequency) already begin to attenuate exponentially. Therefore, it can be expected that in the presence of external noises (interferences) the method implying the use of LEVCM will demonstrate much higher sensitivity of leak detection than the conventional diagnostic indicators.

The following test problem was solved for confirming this fact. White noise signal with dispersion equal to 1×10^{-2} V^2 was added to the signal imitating the leak.

Comparison of variation of the largest eigenvalue of covariance matrix (LEVCM) with time with dispersions of signals and average spectral frequency is shown in Figs. 6 and 7. It is clear from the figure that application of LEVCM as the indicator significantly improves sensitivity of leak detection as compared with the use of dispersion of signal or average spectral frequency. Leak detection occurs in the case of application of LEVCM at the low value of rate equal to ~ 0.02 g/s, while in the case of leak detection using signal dispersion of average spectral frequency

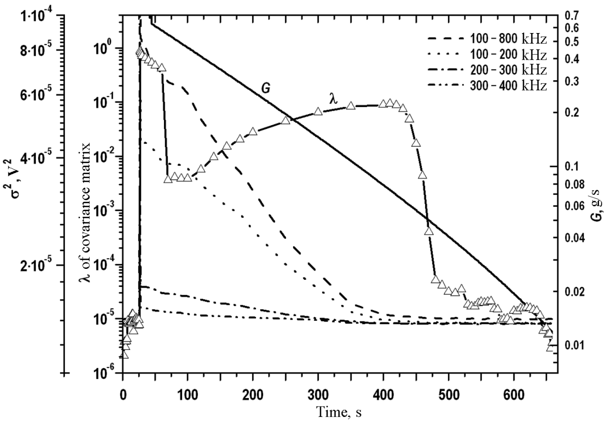

Figure 6. Comparison of time variation of LEVCM with signal dispersions for the case when white noise signal is superimposed.

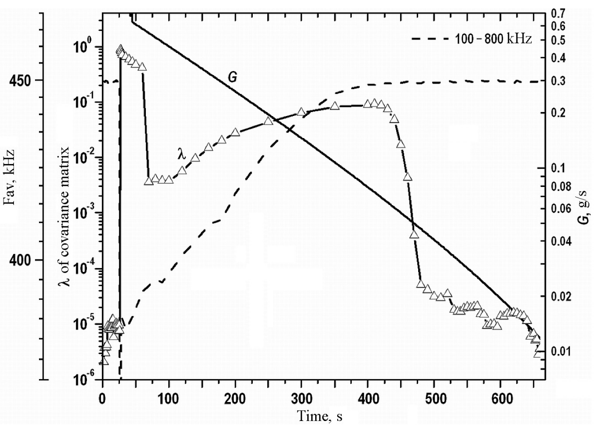

Figure 7. Comparison of time variation of LEVCM with average signal frequencies.

occurs at ~ 0.1 g/s. That means that when LEVCM is used sensitivity increases by approximately five times.

Practical application of the suggested approach in operable leak control systems can be implemented with employment of broadband acoustic sensors.

Conclusion

The suggested new approach allows enhancing sensitivity of leak control systems with regard to low-volume leaks although it requires experimental investigation of the case of real leaks of heated coolant.

In the case of presence of background noises sensitivity of the suggested method with respect to small leaks increases by up to five times as compared with conventional approach.

Implementation of the suggested approach will not require significant expenditures for upgrading existing leak control systems operated at present on different NPPs.

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