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INVESTIGATION OF THE DYNAMIC CHARACTERISTICS OF HEAT EXCHANGERS BY CORRELATION ANALYSIS

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Frequency characteristics obtained from experimental correlation functions are presented for a steam superheater channel. The results permit the use of the random function method in the investigation of hydrodynamic stability problems of steam generation.

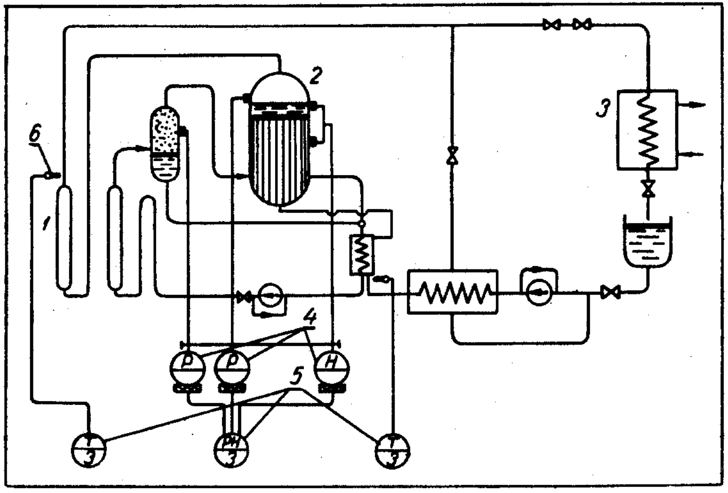

Fig. 1. Flow diagram: 1) steam superheater channel; 2) evaporator; 3) condenser throttle valve; 4) pressure and level sensor with electric readout; 5) secondary instruments; 6) temperature sensor.

There are at present two methods for the experimental investigation of the dynamic properties of industrial and semi-industrial equipment. One method is based on the artificial excitation of the system by continuous aperiodic and periodic signals [1-3], while the other does not require artificial excitation, but uses natural fluctuations of the input and output values during normal operation.

This paper, which is a logical continuation of [3], examines the use of the second method in determining some of the dynamic characteristics of a process model of the Beloyarsk Kurchatov Atomic Power Plant from experimental data.

In recording the dynamic characteristics of the installation (Fig. 1), it was noticed that, for a definite relationship of the process parameters, their values displayed a tendency to increased fluctuation, although the intrinsic noise level was generally comparatively low. This hindered full use of the artificial excitation method because the amplitude of the output signal – the response to an external perturbation – is commensurate with the noise level.

Under certain conditions, connected with a reduced steam volume in the evaporators, increased fluctuations were noticed in the temperature of the superheated steam at the outlet from the superheat channel, while the variation of pressure with time recorded in the steam space of the evaporators also became random in nature (Fig. 2).

The physical explanation of the observed phenomenon is as follows.

At normal values of the level in the evaporators, hydrodynamic instability of steam generation causes pressure oscillations in the evaporator proper. However, the appreciable steam volume due to steam compressibility damps the pressure oscillations at the inlet to the steam superheat channel (the steam volume of the evaporator greatly exceeds that of the steam superheat loop).

At higher evaporator levels, the steam space is reduced and the steam generation fluctuations react on the pressure oscillations with practically no lag. It should be noted that the pressure oscillations ahead of the condenser throttle valve are identical with those in the body of the evaporator owing to the absence of additional external disturbances and the small volume of the steam superheat loop.

Special precautions resulted in almost complete freedom from voltage fluctuations in the electrical circuit and enabled the heat flux in the steam superheat channel to be stabilized, i. e., excluded all secondary external perturbations.

It is not impossible for superheat temperature oscillations to be caused by drops of unseparated water being thrown into the steam superheat channel.

However, the presence of pressure oscillations in steam generators is evidence that this is not the main source of steam temperature fluctuations, although it evidently has some effect on these fluctuations.

This random behavior of the temperature at the outlet of the superheat channel, and also of the pressure in the evaporators, allows the statistical method to be used, so that the dynamic characteristics can be determined from correlation functions based on the normal operating data.

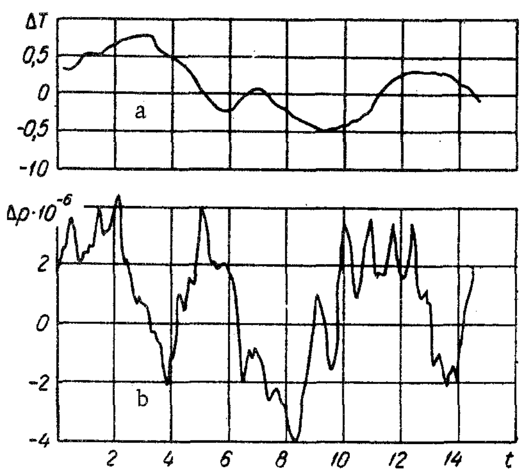

Fig. 2. Fluctuations of (a) superheated steam temperature and (b) pressure in the evaporators.

The physical significance and the sequence of occurrence of the perturbation signal may be represented by a very simple block diagram (Fig. 3).

Pressure oscillation causes oscillation of the steam flow rate and, at constant heat load, the latter acts on the change in superheat temperature. The pressure change, in turn, causes a direct change in superheated steam temperature. However, since the volume of the steam superheater channel and the pressure deviations from the mean are small the functions $\Phi_1(i\omega)$ and $\Phi_3(i\omega)$ may confidently be replaced with zero-inertia elements with gains k_1 and k_3, respectively, where $\Phi_1(i\omega)$ and $\Phi_3(i\omega)$ are the superheated steam flow rate and temperature transfer functions for pressure perturbations. It should be added that the system examined has no transport delay and is also stable in the small, as is clear from physical considerations.

The equation relating the correlation functions and impulse-forced responses, which form the starting points in obtaining the characteristics of plants with one input and output by the statistical method, may be written as follows:

$$R_x(\tau) = \int_0^\infty R_x(\tau - \nu)\, k(\nu)\, d\nu,$$

where (1)

$$R_x(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t+\tau)\, x(t)\, dt$$

is the correlation function of the process x(t), x(t) being an ergodic stationary random input signal,

$$R_{yx}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T y(t+\tau)\, x(t)\, dt$$

is the cross-correlation function of the process x(t) and y(t), y(t) being an ergodic stationary random output process. The unknown impulse-forced response k(t) must satisfy the condition of physical realizability

$$k(t) = 0 \quad \text{at} \quad t < 0.$$

Using a Fourier transformation, we can find a solution in the frequency domain. In other words, we can go from the given frequency characteristics of the plant to the impulse-forced responses or transfer functions.

The solution of Eq. (1) is found by division of the spectral densities

$$\Phi(i\omega) = \frac{S_{yx}(\omega)}{S_x(\omega)}, \tag{2}$$

where $\Phi(i\omega)$ is the transfer function of the plant, and

$$S_{yx}(\omega) = \int_{-\infty}^{+\infty} R_{yx}(\tau) \times \exp(-i\omega\tau)\, d\tau, \quad S_x(\omega) = \int_{-\infty}^{+\infty} R_x(\tau) \exp(-i\omega\tau)\, d\tau -$$

are the input and output spectral densities, respectively.

From random values of the evaporator drum pressure and superheated steam temperature the correlograms of Fig. 4 were constructed, respectively, for the correlation function $R_{\Delta p}(\tau)$ and the cross-correlation function $R_{\Delta T,\,\Delta p}(\tau)$, using a graphoanalytical method [4] with period T = 60 sec.

The frequency characteristic of the steam superheat channel was found from relation (2) and compared with the theoretical value (Fig. 5).

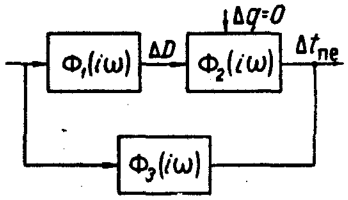

Fig. 3. Block diagram of steam superheater channel.

The mathematical model of the steam superheater channel is based on the balance equation for the flow rate of superheated steam

$$\frac{\partial i(x,\tau)}{\partial \tau}+\omega(\tau)\frac{\partial i(x,\tau)}{\partial x}=$$

$$=\frac{p}{\gamma S}d(\tau)\left[t_{\text{ht}}.(x,\tau)-t(x,\tau)\right],$$

the heat conduction equation for the tubular heat-transfer element of the channel

$$\frac{\partial t_{\text{ht}}}{\partial \tau}=a\Delta t_{\text{ht}}+\frac{q_v}{c\gamma}$$

with boundary conditions

$$\lambda\frac{\partial t_{\text{ht}}}{\partial n}=-(t_{\text{ht}}\cdot|_{d_{\text{вн}}}-t);$$

$$\left.\frac{\partial t_{\text{ht}}}{\partial n}\right|_{d_{\text{out}}}=0,$$

and the equation of motion written in integral form:

$$p_1-p_2=k_1\frac{\omega^2(\tau)\gamma}{2g}+k_2\frac{d\omega(\tau)}{d\tau}.$$

The normalized correlogram $R_{\Delta p}(\tau)/R_{\Delta p}(0)$ was approximated by the sum of components of the form

$$\frac{R(\tau)}{R(0)}=\exp(-\alpha|\tau|)\cos\beta\tau.$$

From an examination of the approximate function

$$R_{\Delta p}(\tau)/R_{\Delta p}(0)=\exp(-0.04|\tau|)\,[0.125\cos 0.419\tau+0.25\cos 0.628\tau+$$
$$+0.5\cos 1.25\tau+0.125\cos 2.51\tau+0.32\cos 6.28\tau]\cdot 0.759 \tag{3}$$

it is clear that components with frequency $\omega = 1.25$ and $\omega = 6.28$ make the greatest contribution.

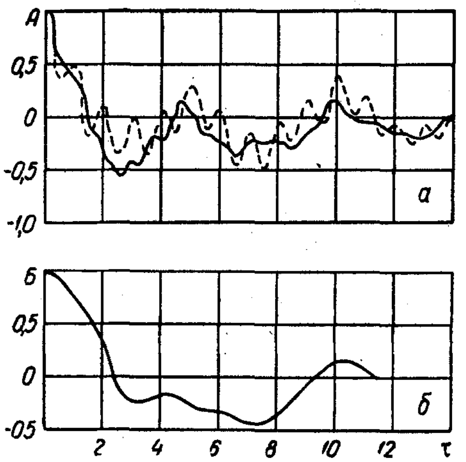

Fig. 4. Autocorrelation (a) and cross-correlation (b) functions ($A\equiv R_{\Delta p}(\tau)/R_{\Delta p}(0)$; $B\equiv R_{\Delta p\Delta T}(\tau)/R_{\Delta p\Delta T}(0)$) broken line – approximation; solid line – according to (3).

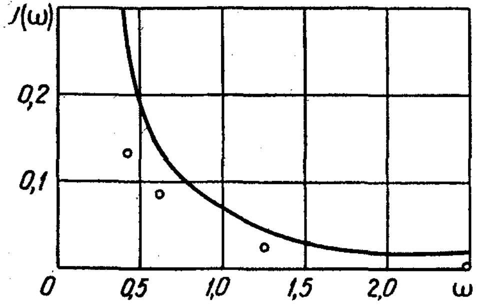

Fig. 5. Theoretical and experimental characteristics of steam superheater channel.

The first component is physically attributable to harmonic oscillations of the piston feed pump. The second higher-frequency component, in terms of the ratio of the time constant of heat transfer from the heated wall to the boiling medium to the life-time of a vapor bubble in the boiling volume, is in all probability attributable to hydrodynamic instability of steam generation.

These investigations, in which the superheated steam temperature was affected by numerous different factors, indicate that it is indeed possible to apply correlation analysis to the study of complex problems of hydrodynamic instability in steam generation.

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