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TEMPERATURE OSCILLATIONS AND THEIR INTERACTIONS WITH OSCILLATIONS OF A DIFFERENT PHYSICAL NATURE

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Interactions between temperature oscillations and other kinds of oscillations occurring simultaneously in a heated system are considered. It is shown that in the case of a corresponding relationship between the frequencies of these oscillations the interaction acquires a parametric character, as a result of which these oscillations amplify each other. The process of mutual amplification terminates in the establishment of combined self-oscillations.

It is known that no free temperature fluctuations (oscillations) exist, but nevertheless, different kinds of thermal oscillations frequently occur in technology and nature. It is thought that temperature oscillations appear in bodies due to periodic thermal effects (a change in the thermal head, etc.). However, very often the reason for the appearance of thermal oscillations can be traced to various recurring nonthermal processes that occur in systems whose temperature is noticeably different from that of the surrounding medium [1] (such oscillatory systems will be called heated systems).

An essential point here is that between excited thermal oscillations and the oscillations of a different physical nature that generated them certain interactions appear that affect the behavior of both periodic processes and, under certain conditions, lead to the formation of complex oscillations.

Recently, we carried out a number of theoretical and experimental investigations of the physical mechanisms underlying the indicated interactions and their effects. First of all, it was found that heated oscillating systems have a kind of "parametric character," i.e., if such a system develops nonthermal oscillations that satisfy the conditions considered below, they are capable of exciting temperature oscillations and, conversely, temperature oscillations existing in a system can excite corresponding nonthermal oscillations. Or, more generally, if any nonthermal oscillations (mechanical, electrical, magnetic, acoustic, optical, etc.) and simultaneous temperature oscillations occur in a heated system, then, provided the above-mentioned conditions are satisfied, the interactions existing between these oscillations lead to mutual parametric amplification of both types of oscillations and to the establishment of combined self-oscillations in the system.

As is known, parametric excitation or amplification of oscillations results from a periodic change in the magnitude of any of the reactive parameters of the vibrational system (i.e., quantities on whose values the intensity of the oscillations depends) [2].

Examples of reactive parameters are: in the case of elastic oscillations of a string the tension σ and the linear density ρ of the string, for an oscillating gravitational pendulum its length l, and in the case of electrical oscillations in a circuit the inductance L and the capacitance C.

A natural question arises: changes in which physical quantities affect the intensity of temperature oscillations, i.e., represent their reactive parameters?

It is not difficult to show that since changes in the coefficients of heat transfer α and heat conduction k influence the rapidity of changes in the temperature of a heater, i.e., the intensity of thermal oscillations, then the quantities α and k are reactive parameters of temperature oscillations.

Thus, we come to the conclusion that for parametric excitation or amplification of temperature oscillations it is necessary to produce periodic changes in the coefficients of heat transfer α or heat conduction k, i.e., to modulate them.

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An analysis of a number of experiments [3-7] on investigation of the mechanism of such modulations and general concepts of heat transfer theory [8] allow one to assert that the heat transfer coefficient α depends directly on the velocity of motion v of the heater with respect to the surrounding medium, namely:

$$\alpha = \alpha_0 + h\sqrt{v}, \tag{1}$$

where α_0 is the heat transfer coefficient of the motionless body; h is a constant that depends on the geometry and thermophysical properties of the moving heater.

Using the indicated property, D. I. Penner and co-workers [9, 10] suggested that the heat transfer coefficient α in the case of transverse oscillations of a heated stretched wire whose displacement velocity changes periodically must suffer periodic modulations. If the frequency of elastic oscillations of the hot string is equal to ω_0, then the frequency of the modulations turns out to be $2\omega_0$, and the depth of these modulations naturally depends on the span of the mechanical oscillations of the wire.

As indicated in [1], modulation of the coefficient α parametrically generates synchronous (i.e., with a frequency $2\omega_0$) temperature oscillations, which are more substantial, the thinner the heater. As for the phase of these oscillations, according to [1], it usually lags behind the modulations $\Delta\alpha(t)$ by approximately the angle $\varphi = \pi/2$.

Turning now to the question of modulations of the heat conduction coefficient k, we note at once that they always appear in the case of electrical oscillations accompanied by periodic changes in the electrical conductivity λ. Actually, according to the Wildemann–Franz law, for metals the ratio k/λ at a constant temperature is constant. Consequently, if in the case of electrical oscillations the value of λ begins to change periodically, this induces simultaneous periodic modulations of the coefficient k in the system.

We produced and investigated experimentally the indicated modulations of the coefficients α and k [11-16], and this made it possible to conclude that if mechanical or electrical oscillations occur in a heated oscillatory system, they modulate the temperature reactive parameters α and k.

The inverse relationship is also valid: if there are temperature oscillations in an oscillatory system, they generate modulations of reactive parameters: mechanical (tension σ and linear density ρ) or electrical (inductance L and capacitance C).

When the modulations formed satisfy the necessary conditions of parametric resonance (PR), nonthermal oscillations generate temperature oscillations, and temperature oscillations excite mechanical or electrical oscillations in the system.

It remains to be learned when modulations generated by coexisting temperature and nonthermal oscillations satisfy the necessary conditions of parametric resonance and parametric interactions appear in the system.

According to the classical theory of oscillations [2, 17], the basic condition for parametric excitation and amplification of oscillations is approximate equality of the ratio ω/ω_0 (ω is the frequency of the modulations, ω_0 is the frequency of natural oscillations) to the quantity $2/n$, i.e.,

$$\omega = \frac{2\omega_0}{n} \quad (n = 1, 2, 3, \ldots). \tag{2}$$

Investigations of parametric interactions between temperature and other oscillations carried out in [1, 18] showed that condition (2) must be refined. But since in the interactions considered here, just as in ordinary PR, this process develops most easily and the arising oscillations turn out to be most intense when

$$\omega = 2\omega_0, \tag{3}$$

and, as proved by investigations, equality (3) is usually satisfied in the case of the phenomena described, we will use this equality in what follows.

The situation concerning the relationship between the phases of the basic oscillations and the modulations of the reactive parameter needed for the onset of PR is more complicated. The classical theory assumes that under actual conditions the necessary phase condition is satisfied by itself, i.e., automatically. However, it was noted already in [1] that in the case, say, of thermomechanical oscillations the phases of temperature oscillations generated by mechanical vibrations were closely linked and could not be established arbitrarily. Therefore, according to [1], the necessary phase condition is reduced to the requirement that the modulations lag in phase behind the square of basic mechanical oscillations $U^2(t)$ by the angle $\varphi = \pi/2$; in the case of thermoelectrical oscillations, conversely, the phase of the modulations must be ahead of the square of the function $q^2(t)$ by the angle $\varphi = \pi/2$.

It is significant that when these two conditions are satisfied and the intensities of modulation of the corresponding parameter are not very small, parametric interaction of temperature and nonthermal oscillations in the system gives rise to the process of mutual amplification of both.

We arrived at this conclusion having analyzed the results of a number of experiments, a typical example of which is the following experiment [19].

An alternating current $I = I_0 \sin \omega_0 t$ flows through a thin horizontally stretched wire (string) whose natural frequency of transverse oscillations is equal to ω_0. Since the Joule heat experiences periodic pulsations with a frequency of $2\omega_0$, at each point of the string there were temperature oscillations $\Theta(t)$ of the same frequency. These oscillations generated synchronous modulations of the tension $\Delta\sigma(t)$. Since the modulation frequency satisfies condition (3), and the necessary phase relationship between the independent mechanical oscillations of the string and the pulsations of the intensity of the current flowing through it can be established by itself, the indicated modulations parametrically excited transverse oscillations of the string $U(t)$ at its natural frequency ω_0.

Consequently, in our system we had three types of oscillations: electrical $I(t)$, temperature $\Theta(t)$, and mechanical $U(t)$. It is easy to see that there are parametric interactions between the temperature and mechanical oscillations. In fact, the thermal oscillations $\Theta(t)$ modulate the reactive parameter of the mechanical oscillations, i.e., the tension σ, while the mechanical oscillations of the wire $U(t)$ (because of periodic changes in the velocity of the wire) modulate the magnitude of the heat transfer coefficient of the heated string α, which plays the role of the reactive parameter of the thermal oscillations. It is important that the process of parametric interaction is not terminated by the generation of transverse oscillations of the string: the temperature oscillations $\Theta(t)$ occurring in the wire continue steadily to parametrically amplify the mechanical vibrations of the string $U(t)$, and, as this takes place, the mechanical vibrations intensify the temperature oscillations.

A physical analysis of the processes occurring in the experiment under consideration makes it possible to conclude that the energy that provided the monotonic parametric increase in the intensity of the temperature and mechanical oscillations was supplied by the alternating-current generator that heated the string: with increase in the span of the mechanical vibrations of the string and the resulting increase in the heat transfer coefficient α, the temperature of the wire and its electrical resistance decrease, thus leading to an increase in the current intensity I and the Joule heat released inside the wire.

It is understood that the indicated mutual amplification of the thermal and mechanical oscillations cannot continue indefinitely: when the rapidly increasing dissipative losses become commensurable with the inflow of oscillatory energy into the system, intensification of both oscillations ceases and distinctive electrothermo-mechanical self-oscillations are established in the system heated by the alternating current [20].

Similar complex parametric interactions occur in various other high-temperature oscillatory systems.

In conclusion we note that the phenomenon of parametric interaction of temperature and nonthermal oscillations can be used to solve many technical problems, for example, remote and rapid increase of the heat transfer coefficient α upon a sudden sharp increase in the temperature of heated elements of heat-engineering devices, shedding of glazed frost from electric-power lines and prevention thereby of onset of the dangerous process of "line-wire dancing," etc.

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