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PHYSICAL FOUNDATIONS OF TECHNICAL ACOUSTICS

Thermal Interference When Recording Turbulent Pressure Fluctuations on the Surface of a Floating Device

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Abstract—Thermal interference is studied when recording turbulent pressure fluctuations on the surface of a floating device at specified experimental parameters of temperature stratification of an aquatic medium. The effect of distortion of the spectral levels of pressure fluctuations recorded by a sound receiver in the field of temperature inhomogeneities is studied using the example of measurements of turbulent pressure fluctuations in the boundary layer during the vertical ascent of a device from a specified depth. At moderate flow velocities exceeding 1–2 m/s, the temperature susceptibility of a piezoceramic receiver is shown to be decisively determined by its characteristic "thermal" frequency. The parameters of the threshold critical frequency, below which the temperature signal (thermal interference) prevails over the useful signal generated by pressure fluctuations, are determined. With respect to the receivers used in experiments on a floating device [7], the values of the threshold critical frequency are 130 and 215 Hz.

Keywords: turbulent pressure fluctuations, temperature inhomogeneity of the medium, thermal interference
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INTRODUCTION

The field of turbulent pressures on a flow surface usually includes a significant long-wavelength component formed by the acoustic field in the flow zone [1–4]. In laboratory studies, this component, associated with the operation of equipment and other third-party sources, is considered as acoustic interference, the elimination or suppression of which is one of the important problems of carrying out correct measurements [5]. With respect to the aquatic medium, this problem is solved by using floating devices equipped with an autonomous measuring system. The floating device is an elongated body of rotation, which when submerged has excessive Archimedean buoyancy and for this reason is capable of independently floating up from the deep-sea parts of the sea. The principles implemented when creating a floating device make it possible to study acoustic-hydrodynamic processes in a turbulent boundary layer at high Reynolds numbers (up to 10^8) while the measurement data is practically not distorted by extraneous acoustic noise because the movement of the device is caused exclusively by the gradient of the hydrostatic pressure field.

The results of experimental studies of flow noise using a setup of this type are presented in [6]. In Russia, a floating device was developed at the Krylov Central Research Institute (Krylov Scientific Center). Its detailed description is given in [7]. For further consideration, it is essential that near-wall turbulent pressures are measured at various points of the measuring section using two types of piezoceramic pressure transducers: rod (tubular) with a depth of ~15 mm and a receiving surface with a diameter of 1.3 mm and plate receivers with a thickness of ~1 mm and a receiving surface with a diameter of 20 mm; in this case, the flow velocities were 8–22 m/s.

Since the piezoceramics used in receivers also has pyroelectric properties when the device ascends in a temperature-stratified environment, an additional "temperature" signal is generated at the output of the pressure fluctuation transducers, which is considered as thermal interference.

In this study, specific estimates of the parameters of thermal interference are carried out with respect to a floating device [7] under conditions of temperature inhomogeneity of the environment, presented in the book [8] based on the results of research [9]. The estimates are based on the general approach proposed in [10]; some results were previously discussed by the authors in a report at the XVII Brekhovskikh School-Seminar "Ocean Acoustics" [11].

PIEZOCERAMIC PRESSURE RECEIVER IN A TEMPERATURE-INHOMOGENEOUS TURBULENT FLOW

According to available data [10, 12, 13], the relation between the sensitivity of receivers to temperature (γ_T, V/K) and pressure (γ_p, V/Pa) can be estimated as $\Gamma_{Tp} = 2 \times 10^6$ Pa/K, which approximately corresponds to the product of the linear coefficient thermal expansion and the Young's modulus of piezoceramics. This value corresponds to complete heating of the receiver, which is never achieved under conditions of measuring turbulent fluctuations in a temperature-inhomogeneous environment. At the same time, in order to determine the real influence of the temperature factor on operation of the receiver of near-wall turbulent pressures, it is necessary, first of all, to evaluate to what extent temperature fluctuations heat the body of the piezoelement.

According to the model developed in [10], a receiver in direct contact with the flowing medium characterized by boundary temperature field $T_0(\boldsymbol{\kappa}, \omega)$ ($\boldsymbol{\kappa}$ is the two-dimensional wave vector, ω is the angular frequency) generates an electrical signal with amplitude $e_T(\boldsymbol{\kappa},\omega)$ due to the pyroelectric effect. The root-mean-square value of this signal for a receiver built into a streamlined body is determined by the equality

$$\left|\overline{e_T(\boldsymbol{\kappa},\omega)}\right| = \gamma_T^2 \frac{1 - 2e^{-\alpha}\cos\beta + e^{-2\alpha}}{R}\left|\overline{T_0^2(\boldsymbol{\kappa},\omega)}\right|, \quad (1)$$

in which

$$R = h^2\sqrt{\kappa^4 + (\omega/\chi)^2}, \quad \varphi = \arctan\left(\frac{\omega}{\chi\kappa^2}\right),$$
$$\alpha = \sqrt{R}\cos\left(\frac{\varphi}{2}\right), \quad \beta = \sqrt{R}\sin\left(\frac{\varphi}{2}\right), \quad (2)$$

and parameters χ and h represent, respectively, the thermal diffusivity and the extent of the receiver in the direction normal to the wall. With respect to the effect of a random homogeneous stationary temperature field, relation (1) is represented as

$$\Phi_{\mathrm{SS}}^T(\omega) = \gamma_T^2 \int\limits_{\infty} S_T(\kappa,\omega)E_{\mathrm{TT}}(\kappa,\omega)d\kappa. \quad (3)$$

Here, $\Phi_{\mathrm{SS}}^T(\omega)$ is the frequency spectrum of the temperature signal, $E_{\mathrm{TT}}(\kappa,\omega)$ is the frequency-wave spectrum of near-wall temperature fluctuations, and $S_T(\kappa,\omega)$ is the wave temperature characteristic of the receiver that, in view of (1), is determined by the equality:

$$S_T(\kappa,\omega) = \frac{1 - 2e^{-\alpha}\cos\beta + e^{-2\alpha}}{R}. \quad (4)$$

Next, we consider the effect of temperature inhomogeneities of the medium using a specific example of studying flow noise produced by turbulent pressure fluctuations in the boundary layer on the body of a floating device.

In the "frozenness" model, the spectral frequency-wave spectrum and temperature unevenness of the medium are related by the simple relation

$$E_{\mathrm{TT}}(\boldsymbol{\kappa},\omega) = \frac{1}{U}P_{\mathrm{TT}}(\kappa)\delta\left(\kappa - \frac{\omega}{U}\right), \quad (5)$$

where $P_{\mathrm{TT}}(\kappa)$ is the spectrum of vertical temperature inhomogeneity in the zone of the floating device. Accordingly, expression (3) for the frequency spectrum of the temperature signal takes the form:

$$\Phi_{\mathrm{SS}}^T(\omega) = \gamma_T^2 \frac{1}{U} S_T\left(\frac{\omega}{U},\omega\right) P_{\mathrm{TT}}\left(\frac{\omega}{U}\right). \quad (6)$$

Calculations show (Fig. 1) that at moderate flow velocities exceeding 1–2 m/s, the frequency dependence of the temperature characteristic is determined only by the characteristic "thermal" frequency

$$\Omega_\chi = \frac{\chi}{h^2} \quad (7)$$

of the pressure fluctuation receiver. Accordingly, the wave characteristic practically ceases to depend on speed and so

$$S_T \approx \frac{\Omega_\chi}{\omega}. \quad (8)$$

The Ω_χ "thermal" frequency parameter is practically determined only by the geometry of the used pressure transducer; the Ω_χ parameter value can vary within sufficiently wide limits. In particular, for the two types of receivers used on the floating device [7], the parameter Ω_χ is estimated as 0.073 and 0.55 s^{-1}. In this case, due to design features, the thermal diffusivity of the rod receiver that is determined by the thermal properties of the steel body is characterized by a value of 16.4×10^{-6} m^2/s while the corresponding value for the plate receiver is set to a value typical for ceramics of 5.5×10^{-7} m^2/s.

The degree of the effect of the temperature signal is determined by the ratio

$$\frac{\Phi_{\mathrm{SS}}^T(\omega)}{\Phi_{\mathrm{SS}}^p(\omega)} = \Gamma_{\mathrm{Tp}}^2 \frac{S_T(\omega/U,\omega)P_{\mathrm{TT}}(\omega/U)}{\Phi_{\mathrm{pp}}(\omega)U} \quad (9)$$

of temperature characteristic (6) to frequency spectrum $\Phi_{\mathrm{SS}}^p(\omega)$ of the useful signal caused by wall pressure fluctuations with the spectrum $\Phi_{\mathrm{pp}}(\omega)$.

ESTIMATES OF THE EFFECT OF THE TEMPERATURE SIGNAL FOR A FLOATING DEVICE

For specific estimates, we use the data [9], presented in [8], on the spectral density of temperature

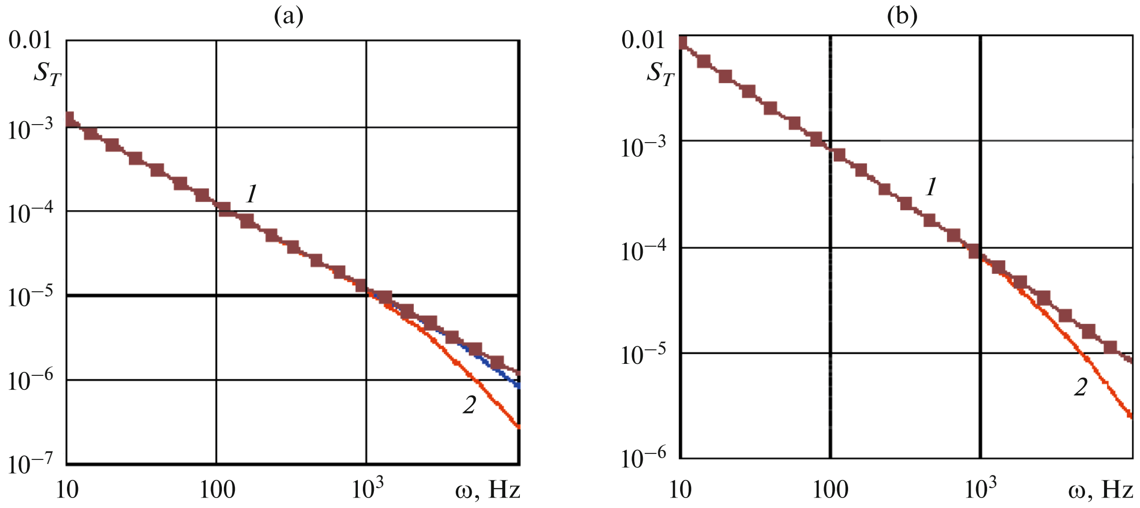


Fig. 1. Temperature transfer characteristic $S_T(\omega/U, \omega)$, formula (4). Receivers: (a) rod, U = (1) 1–10 and (2) 0.5 m/s; (b) plate, U = (1) 1–10 and (2) 0.1 m/s. ■■■■■, approximation (8).

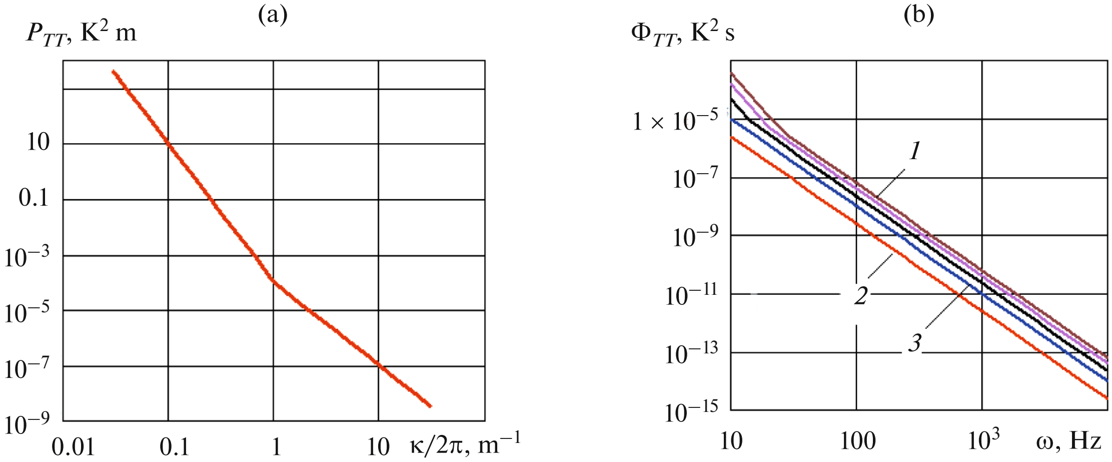


Fig. 2. Wave and frequency spectra of temperature on flow surface. (a) Wave spectrum $P_{\rm TT}(\kappa)$ (10), and (b) corresponding frequency spectra $\Phi_{\rm TT}(\omega) = \frac{1}{U} P_{\rm TT}(\omega/U)$, U = (*1*) 1, (*2*) 5, and (*3*) 10 m/s.

inhomogeneity in the Baltic Sea. In accordance with these data (Fig. 2), the model dependence of the spectral temperature density, K^2 m, on the wavenumber κ, m^{-1}, can be approximately represented as follows:

$$P_{\rm TT}(\kappa) = \begin{cases} 10^{-4}\left(\kappa/2\pi\right)^{-5} \text{at } \kappa/2\pi \le 1 \text{ m}^{-1}, \\ 10^{-4}\left(\kappa/2\pi\right)^{-3} \text{at } \kappa/2\pi > 1 \text{ m}^{-1}. \end{cases} \tag{10}$$

The frequency spectrum of turbulent pressures is estimated by the widely accepted [3] empirical Goody model [14]. According to Goody's model,

$$\Phi_{\rm pp}(\omega) = \frac{(\rho U_\tau^2)^2\delta}{U} \times \frac{3\left(\omega\delta/U\right)^2}{\left[\left(\omega\delta/U\right)^{0.75} + 0.5\right]^{3.7} + \left[(1.1R_T^{-0.57})\,\omega\delta/U\right]^7}, \tag{11}$$

where $R_T = \dfrac{U_T^2}{U}\dfrac{\delta}{\nu}$; ρ and ν are the density and kinematic viscosity of the flowing fluid, respectively; δ is the thickness of the boundary layer; $U_\tau = \sqrt{\tau/\rho}$, and τ is the tangential stress on the wall. In this study, the

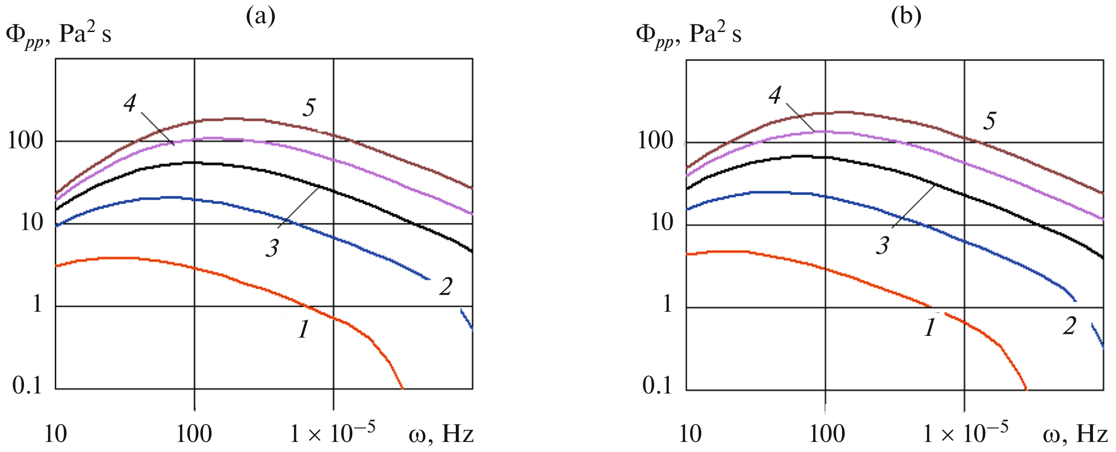
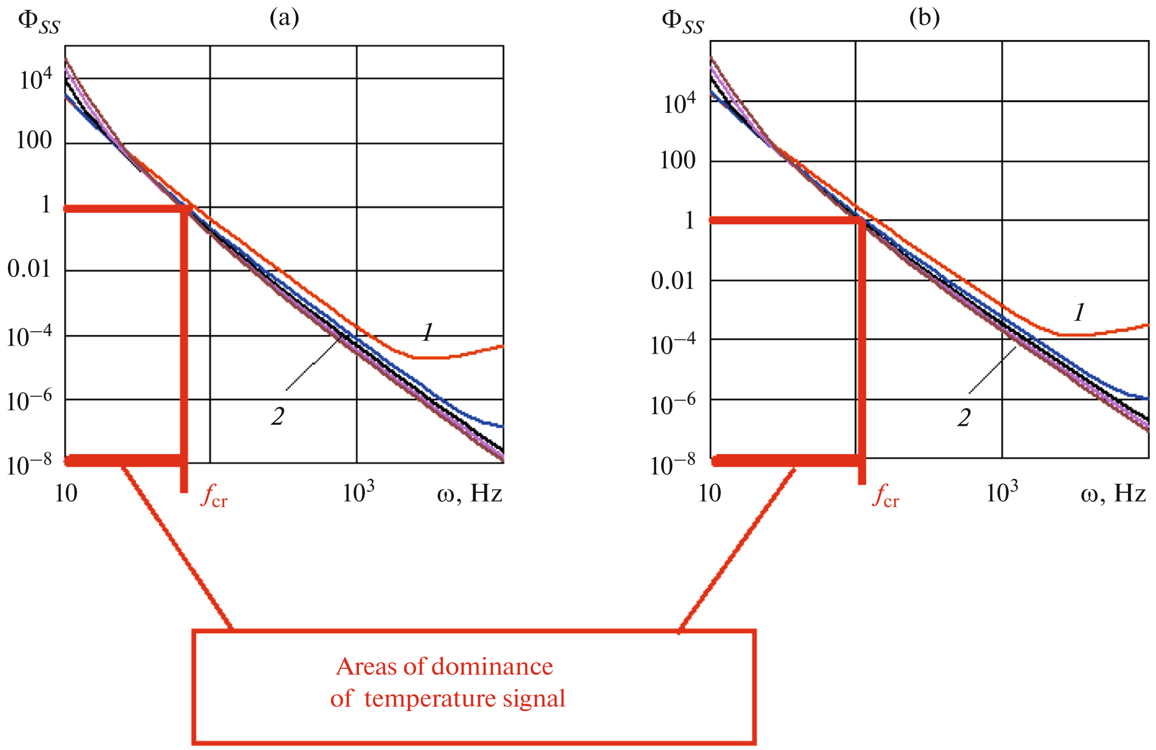


Fig. 3. Frequency spectrum of pressure fluctuations on surface of floating device in areas, where receivers are located. Calculation using formula (11). (a) Front zone, (b) rear zone. U = (*1*) 5, (*2*) 10, (3) 15, (*4*) 20, and (*5*) 25 m/s.



Areas of dominance
of temperature signal

Fig. 4. Ratio of spectral components of temperature and dynamic signals on piezoceramic receivers of floating device [7]. Calculation using relation (9), rear zone of receivers. Receivers: (a) rod, (b) plate. U = (*1*) 5 and (*2*) 10–25 m/s.

frequency spectrum of pressure fluctuations was estimated with respect to the surface of the measuring section of the device [7] in the range of ascent velocities of 5–25 m/s (the corresponding U_τ values in the areas where the receivers were located ranged from 0.17 to 0.79 m/s, while the thickness δ of the boundary layer ranged from 35 to 68 mm).

Model representations (10) and (11), which specify the shape of the spectral characteristics included in relation (9), make it possible to determine the relative contribution of temperature fluctuations to the formation of the turbulent pressure receiver signal at a specified flow mode around the floating device.

The calculation results (Fig. 4) show that in the zone of significant influence of temperature inhomogeneity, the value of ratio (9) quickly decreases with increasing frequency while the dependence itself is decisively determined by "thermal" frequency $\Omega\chi$ of

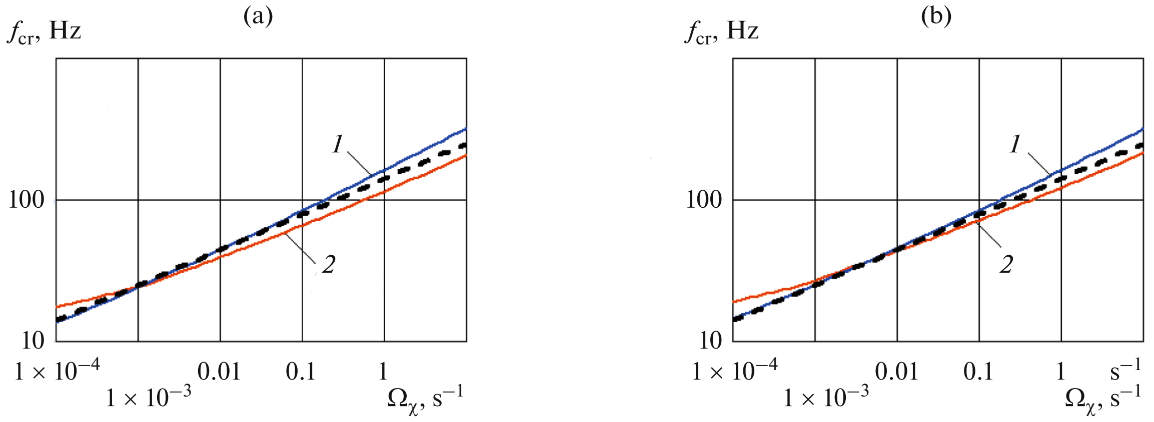


Fig. 5. Critical frequencies of exposure to temperature interference. Comparison of calculated data with approximating formula (12) (dashed curve). Receivers: (a) rod, (b) plate. U = (*1*) 5 and (*2*) 25 m/s.

the receiver. In particular, the flow parameters and the dimensions of the receiver have virtually no effect on the values of threshold critical frequency f_{cr}, at which ratio (9) becomes equal to unity. Accordingly, below this frequency determined by the $\Omega\chi$ value, the temperature signal becomes higher than the useful one.

The obtained calculated $f_{cr}(\Omega_\chi)$ dependences (Fig. 5) in a wide range of "thermal" frequency values from 10^{-4} to 10 s^{-1} can be approximated by a single formula:

$$\frac{f_{cr}}{f_0} \approx 250\left(\frac{\Omega_\chi}{\Omega_0}\right)^{0.25}, \quad f_0 = 1\ \text{Hz},\ \ \Omega_0 = 10\ \text{s}^{-1}, \qquad (12)$$

which is substantiated to characteristic (10) of temperature inhomogeneity based on specific data [8, 9]. By definition (7), the last equality means that the critical frequency is inversely proportional to square root of the length of the receiver in the direction normal to the wall:

$$f_{cr} \sim 1/\sqrt{h}.$$

Application of dependence (12) to the evaluation of measurements on a floating device [7] shows that, under the considered conditions, temperature inhomogeneity has a significant effect on the signals of the two used types of turbulent pressure receivers at frequencies below 130 and 215 Hz.

Note that a close estimate of the frequency limit of the influence of temperature interference was obtained based on a qualitative analysis in [15].

CONCLUSIONS

We have presented estimates of the frequency characteristics of thermal interference when recording turbulent pressure fluctuations on the surface of a floating measuring device for specific experimental parameters of the temperature stratification of the aquatic medium.

At moderate flow velocities exceeding 1–2 m/s, the temperature susceptibility of a piezoceramic pressure receiver is shown to be decisively determined by its characteristic "thermal" frequency Ω_χ (7).

The parameters of the threshold critical frequency, below which the temperature noise signal prevails over the useful signal generated by pressure fluctuations, are determined. The performed studies showed that the flow parameters and the dimensions of the sensitive surface of the pressure fluctuation receiver have virtually no effect on the values of the threshold critical frequency while its values for the studied temperature field are proportional to $\sqrt[4]{\Omega_\chi}$. In particular, with respect to the receivers used in experiments on a floating device [7], the values of the threshold critical frequency are 130 and 215 Hz.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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