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NONCONTACT ULTRASONIC CHECKING OF THE SURFACE DENSITY OF A LAYER OF A SOLID MEDIUM

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Consideration has been given to the field structure in ultrasonic monitoring of gas-liquid flows and technological parameters and to the basic characteristics of noncontact checking of the surface density of a layer moving in a field produced by an acoustic radiator in air.

High-quality products are manufactured by many industries with the use of ultrasonic automatic monitoring of technological processes; this monitoring is based on theoretical and experimental investigations of: the velocity and attenuation of ultrasound [1–6], the methods of echo ranging [7–10] and checking of the composition and properties of media [11–17], the velocity of gas-liquid flows and the rate of mass and heat transfer [6, 18–24], and other characteristics of media [25–27].

The informative parameters are the amplitude, phase, and frequency of vibrations in the ultrasonic field of an acoustic radiator in the medium checked. The field is described by a system consisting of the wave Helmholtz equation for pressure $\Delta P + k^2 P = 0$ and the wave equation of the potential of a point source $\Delta\psi - k^2\psi = 0$, where $k = 2\pi/\lambda$ and

$$\psi = r^{-1} \exp(-ikr) . \tag{1}$$

The finiteness and continuity of the functions P and ψ and their derivatives is assumed. The solution of the system of wave equations is found with the well-known integral theorem of Green, written for P and ψ in the form

$$\iint_{S_1} \left[\left(\psi \frac{\partial P}{\partial n} \right)_{S_1} - \left(P \frac{\partial \psi}{\partial n} \right)_{S_1} \right] dS_1 = 0 . \tag{2}$$

According to (1), the integrand experiences a discontinuity when $r = 0$, formally pointing mathematically to the presence of the "source" of vibrations with pressure P_q at this point. In this connection, we subdivide a closed integration surface S_1 into two surfaces: a surface S' (Fig. 1) in the form of a sphere with a radius $r' \to 0$ (the direction from the point Q from the "source" is opposite to the internal normal n' on the surface S') and a closed surface S (covering the sphere S') with radius vector r of the surface element dS and a normal n to dS. Expression (2) is transformed to the form

$$\iint_{S} \left[\psi \left(\frac{\partial P}{\partial n} \right)_S - P_S \left(\frac{\partial \psi}{\partial n} \right)_S \right] dS + J_{S'} = 0 , \tag{3}$$

where

$$J_{S'} = \lim_{r=0} \iint_{S'} \left[\psi' \left(\frac{\partial P}{\partial n} \right)_{S'} - P_{S'} \left(\frac{\partial \psi}{\partial n} \right)_{S'} \right] dS' .$$

Here the element dS' is equal to $(r')^2 d\Omega$; Ω is the solid angle changing from 0 to 4π;

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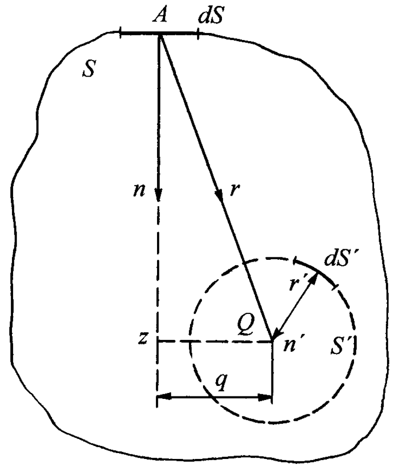

Fig. 1. Scheme of the field of an acoustic radiator.

$$\psi' = (r')^{-1} \exp(-ir'k)\ ;\quad \frac{\partial \psi'}{\partial n} = -\frac{\partial \psi'}{\partial r'} = [ik(r')^{-1} + (r')^{-2}] \exp(-ikr')\ .$$

With allowance for these values of dS', ψ', and $\partial\psi'/\partial n$, we have

$$J_{S'} = \int_0^{4\pi} \lim_{r'=0} \left\{ \left[r' \left(\frac{\partial P}{\partial n'} \right)_{S'} - P_{S'} (ikr' + 1) \right] \exp(-ikr') \right\} d\Omega\ .$$

Since $P_{S'} = P_q$ when $r' = 0$, we have

$$J_{S'} = -\int_0^{4\pi} P_q d\Omega = -4\pi P_q\ .$$

After substitution of the resulting expression into (3), we obtain

$$P_q = \frac{1}{4\pi} \iint_S \left(\psi \frac{\partial P_S}{\partial n} - P_S \frac{\partial \psi}{\partial n} \right) dS\ . \tag{4}$$

For short-wave acoustic radiators ($ka >> 1$) the pressure gradient on the internal normal (coincident in direction with the propagation of vibrations from dS) is $\partial P_S/\partial n = ikP_S$, as a consequence of which we have

$$\psi \frac{\partial P_S}{\partial n} = ik\psi P_S = -r^{-1} P_S \frac{\partial (\psi r)}{\partial r}\ .$$

The substitution of this value and $\frac{\partial \psi}{\partial n} = \frac{\partial r}{\partial n}\frac{\partial \psi}{\partial r} = zr^{-1}\frac{\partial \psi}{\partial r}$ into (4) yields the integral (given in [28])

$$P_q = -\frac{1}{4\pi} \iint_S P_S r^{-1} \frac{\partial}{\partial r} [(r + z)\, \psi]\, dS \tag{5}$$

for the pressure of the received wave at the point of the field located at a distance q from its axis and at a distance z from the plane of the acoustic radiator. Here the pressure is represented in the form of the set of actions of point monopole sources (term with a gradient of the function ψr) and dipole sources (term with the directivity z/r of a dipole) distributed over the surface S.

Considerable prospects for extending the fields of application of ultrasonic methods arose when it became possible to receive the wave and to informatively process it after its transmission in air by a solid layer of thickness h moving in the technological flow. Use is usually made of a short-wave acoustic radiator with a plane surface S; for this radiator we have $P_S = P_0 \exp(i\omega t)$, and it is excited by harmonic electric pulses that are long as compared to f^{-1}.

The solutions of the integral (5) yield [28] the expressions of the pressures on the axis of the acoustic radiator ($q = 0$)

$$P(z) = P_0 \left[1 - \frac{z + r_m}{2r_m} \exp(-i\varphi_0) \right] \exp i(\omega t - kz)$$

and on the acoustic cylinder ($q = a$) in the intermediate ($a^2/\lambda < z < 3.5a^2/\lambda$) and far ($z \geq 3.5a^2/\lambda$) zones

$$P_a = \frac{P_0}{2} \left[1 - \frac{z + r_0}{2r_0} J_0(\varepsilon) \exp(-i\varphi_P) \right] \exp i(\omega t - kz),$$

where the distances are $r_m = (r^2 + a^2)^{0.5}$ and $r_0 = (z^2 + 2a^2)^{0.5}$, the phases are $\varphi_0 = k(r_m - z)$ and $\varphi_P = k(r_0 - z) - ka^4 r^{-3/2}$, and $J_0(\varepsilon)$ is the Bessel function of zero order with an argument of $\varepsilon = ka^2/r$.

The coefficient of acoustic transparency of the solid layer in air, equal to the ratio of the amplitudes of pressures of the wave transmitted by the solid layer to the pressure of the radiated wave entering it from air with an acoustic impedance z_{air} (along the normal), is very small for the solid layer when $h >> \lambda_{long}$:

$$D = 4z_{air} z_{0long} (z_{air} + z_{0long})^{-2}.$$

In noncontact checking of the surface density of the solid layer, use is made of the effect of acoustic "bleaching" of the solid layer [29, 30], observed at $\lambda_{long} > 4h$.

In normal introduction of the wave from air into the solid layer, the transparency coefficient of the layer is

$$D_h = 2z_{air} z_{0long} [2z_{air} z_{0long} \cos\varphi_{0long} - i(z_{0long} + z_{air}) \sin\varphi_{0long}]^{-1}, \tag{6}$$

where $\varphi_{0long} = 2\pi h/\lambda_{long}$.

With allowance for the fifth order of smallness of the quantity z_{air}/z_{0long}, the transparency coefficient of the layer is

$$D_h = \left(\cos\varphi_{0long} - i \frac{z_{0long}}{2z_{air}} \sin\varphi_{0long} \right)^{-1}. \tag{7}$$

The module $\gamma_h = |D_h^{-1}|$ of the coefficient of attenuation of the wave propagating in air by the layer and its phase φ_h are determined by the expressions

$$\gamma_h = \left[\cos^2\varphi_{0long} + \left(\frac{z_{0long}}{2z_{air}} \sin\varphi_{0long} \right)^2 \right]^{0.5}, \quad \varphi_h = -\arctan\left(\frac{z_{0long}}{2z_{air}} \tan\varphi_{0long} \right). \tag{8}$$

Quite a linear dependence of γ_h on the surface density ρ_S (equal to ρh) occurs for $z_{0long} \sin\varphi_{0long} > 6z_{air}$ and $\varphi_{long} < 0.3$, when, with account for $z_{0long} = \rho c_{long}$, we have

$$\gamma_h = \frac{z_{0long}}{2z_{air}} \sin\varphi_{0long} = \frac{\rho c_{long}}{2z_{air}} \sin\frac{2\pi f h}{c_{long}} = \rho_S \pi f / z_{air}.$$

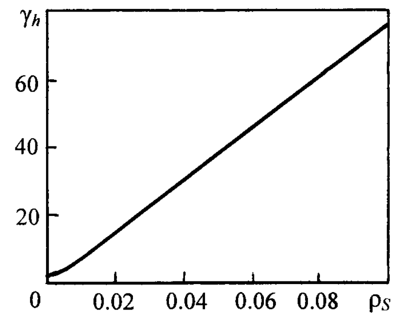

Fig. 2. Aeroacoustic attenuation γ_h of the wave by a thin solid layer vs. surface density ρ_S of the layer at a frequency of 100 kHz.

The dependence (calculated from expression (8)) of γ_h on ρ_S of the solid layer at a frequency of 100 kHz is given in Fig. 2. Attenuation of the ultrasonic wave by the layer in the initial part of the linear range of checking for densities from 0.005 to 0.1 kg/m^2 is in the range 3.9–75.7. This is equivalent to a decibel attenuation of 20 log γ_h in the range 11.9–37.5 dB. An attenuation of 37.5 dB, in particular, occurs at a frequency of 2.5 MHz for an acoustic radiator 20 mm in diameter for an echo from a reflector 3 mm in diameter at a depth of 180 mm of occurrence in steel. Such an attenuation in air at a frequency of 100 kHz is yielded by a layer of steel, aluminum, and polystyrene with a thickness h of 12.8, 37, and 95.2 μm respectively.

The power and stability of the level and frequency of radiation and minimization of the input electric noise of the detecting unit are ensured by the corresponding designs. Changes in the acoustic impedance of air can be corrected thermally by the temporal [2] and frequency-phase [4–6] methods.

NOTATION

A, point of radiation (emission) of vibrations; a, radius of the acoustic radiator, m; c_{long}, velocity of the longitudinal ultrasonic wave in the solid medium, m/sec; $\partial/\partial n$ and $\partial/\partial r$, symbols of the partial derivative with respect to the internal normal n and the distance r; dS, surface element of the acoustic radiator, m^2; dS_1, element of the surface of integration according to the Green theorem, m^2; D, coefficient of acoustic transparency of the solid layer; f, vibration frequency, Hz; h, thickness of the solid layer, m; i, imaginary unit; k, wave number, m^{-1}; ka, wave parameter of the acoustic radiator; J_0, Bessel function of zero order; n, normal; P, pressure, N/m^2; P_S, pressure on the acoustic-radiator surface, N/m^2; P_0, P_q, and P_{a}, pressure of the radiated wave, at the point of the field at a distance q from the acoustic-radiator axis, and on the acoustic cylinder, N/m^2; Q, point of detection of vibrations; r, distance between the points of radiation and detection of vibrations, m; r_{m}, distance from the point of detection of the pressure $P(z)$ on the axis to the edge of the acoustic radiator, m; r_0, conventional distance, m; S and S', radiation surfaces, m^2; S_1, surface of integration according to the Green theorem, m^2; t, time, sec; z, coordinate, projection of r onto the axis of the acoustic radiator, m; z_{air} and $z_{0\mathrm{long}}$, specific acoustic impedances of air and the solid layer, N·sec/m^3; ω, angular frequency, sec^{-1}; ε, argument of the Bessel function; γ_h, coefficient of attenuation of the wave by the solid layer; Δ, differential operator; λ and λ_{long}, wavelength in the radiation medium and length of the longitudinal wave in the layer material, m; ρ, bulk density of the layer material, kg/m^3; ρ_S, surface density of the solid layer, kg/m^2; φ_0 and φ_P, phase of the received wave on the acoustic-radiator axis and phase of the pressure P at a point of the field, rad; $\varphi_{0\mathrm{long}}$, phase incursion of the longitudinal wave in the solid layer, rad; ψ, potential of the point source, m^{-1}. Subscripts: a, acoustic cylinder; air, air; m, maximum; h, layer thickness; 0 and 1, figures (of numbering of: the distance r and the surface S); long, longitudinal.

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