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ULTRASONIC CONTROL OF THE FLUID-FLOW VELOCITY WITHOUT N. I. BRAZHNIKOV'S UNDOCKING OF A PIPELINE

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The functional diagram of a noncontact pulse control of fluid velocity without undocking of a pipeline and the main characteristics of the control with simultaneous counteremission of an ultrasound by superposed transducers with a decreased (by damping sound ducts) echo-pulse reverberation are considered.

In research work and in industry, ultrasonic control and regulation of technological processes have found widespread application. The general problems of the theory and metrology of this branch of technology were considered in [1–10]. In the metallurgical, thermal power engineering, rock, aviation, and other industries, an ultrasonic control is used: of the velocity of a stream of liquid and gaseous media by a phase method [11–13], a pulse-phase one [4, 14], a time-pulse one [15, 16], and by frequency-pulse [17–19] and frequency-phase ones [5, 20]; of mass and heat transfer, volumetric and mass flow rates of fluids according to [4, 21–25]; of concentration and density of pulps, binary and multicomponent solutions [3, 26–28]; of the level of various media according to [9, 29, 30] and of other technological parameters [31, 32].

A significant advancement in the development of the technique of controlling the parameters of media fluxes was the application of the method of exposure to an ultrasound of a solid layer in air with determination of its physical properties from the degree of acoustic transparency [33–36] and the method of a "ringing wall," according to which the wall of a hydraulic reservoir with excited antisymmetric normal [25, 37–41] and surface waves [42], of an obliquely propagating wave t of transverse vibrations [43] or a wave of echo-pulse reverberation [44] is an acoustic source of information on the fluid controlled — both methods being suggested for the first time by N. I. Brazhnikov.

In the practice of the use of automatic systems to control the technological processes of a number of industries, the basic and informatively needed parameter is the velocity of fluid flows. In many branches of industry, the medium controlled is chemically aggressive and is exposed to a high pressure, which excludes contact of acoustic transducers with it or introduction of an ultrasonic longitudinal wave l into a medium through "cut-in" sound ducts installed in the holes in the pipeline wall.

Figure 1 presents the functional diagram of a system of an automatic single-channel control of the velocity of fluid flow by ultrasonic pulses. It has been developed by N. I. Brazhnikov's method [4, 12, 15], which makes provision for the introduction of an ultrasound into a stream 1 from sound ducts 2 of superposed acoustic transducers T1 and T2 directly through the walls 3 of the pipeline at a supercritical angle of introduction, and was tested for the first time in 1958 on porcelain pipelines for chemically aggressive media of chlorine-cobalt production. The method allows one to make a noncontact control of the fluid-flow velocity not resorting to conventional undocking of the pipeline for imbedding a tubular velocity measuring insert. The operating principle of the system is as follows.

Electric high-frequency pulses 4 (as a packet of vibrations of length $10/f$) enter simultaneously, through separating blocks 5, piezoelements 6 in T1 and T2 from generator 7. The piezoelements are made in the form of disks of diameter $2a$ = 8 mm from piezoceramics of PZT-19 lead zirconate-titanate having a frequency of thickness resonance (frequency of free vibrations) f = 2.8 MHz. They transform electric pulses 4 into pulses of ultrasonic vibrations of the

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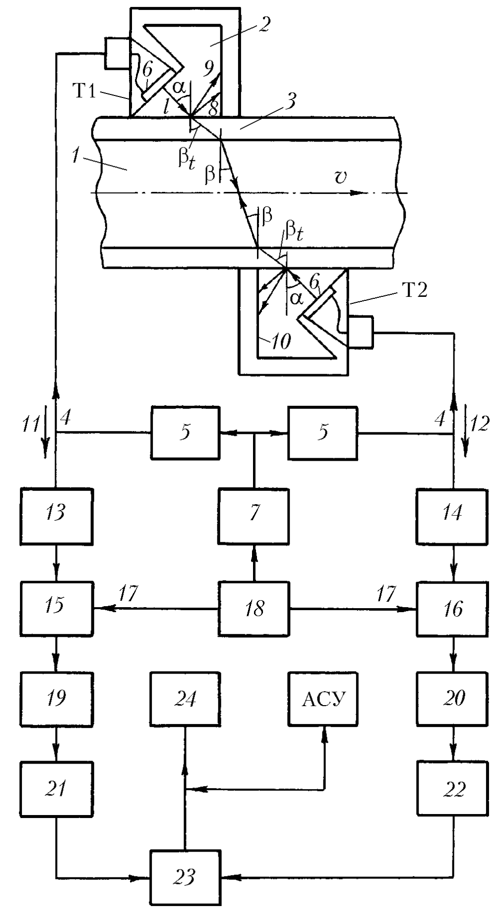

Fig. 1. Functional scheme of the system of automatic single-channel control of the fluid flow velocity.

indicated frequency that are simultaneously emitted into sound ducts 2 of transducers T1 and T2 in opposition at an angle $\alpha = 2\pi/9$ rad that exceeds the first critical one:

$$\alpha_{1\text{cr}} = \arcsin\,(c_{l\text{s}}/c_l)\,, \tag{1}$$

which is determined by the ratio of the speed of the ultrasound in the sound duct to the speed of longitudinal vibrations in the wall (3) of the pipeline. Here and below, the angles are reckoned from the normal to the media interface. The sound ducts of both transducers are made identically from polystyrene (moderately absorbing the ultrasound of the material), in which the speed of the longitudinal wave is less than that of the transverse one in the pipeline material.

The damping of the wave in the sound-duct material at a distance z is determined by the factor exp $(-\delta_{l\text{s}}z)$. The longitudinal ultrasonic vibrations of wave length $\lambda_{l\text{s}} = 0.85$ mm propagate in the sound ducts, and on the outer surface of the pipeline they transform into transverse vibrations with a wave length for steel of 1.15 mm propagating in the wall (3) at an angle determined from the expression

$$\sin\beta_t = c_t c_l^{-1} \sin\alpha\,. \tag{2}$$

The average time of propagation of a wave in sound duct is

$$\tau_\text{s} = l_\text{s}/c_{l\text{s}}\,. \tag{3}$$

The longitudinal wave in the wall material does not propagate because of the total internal reflection in the wall. (It is assumed that the pipeline wall thickness is much larger than the length of the transformed transverse wave.)

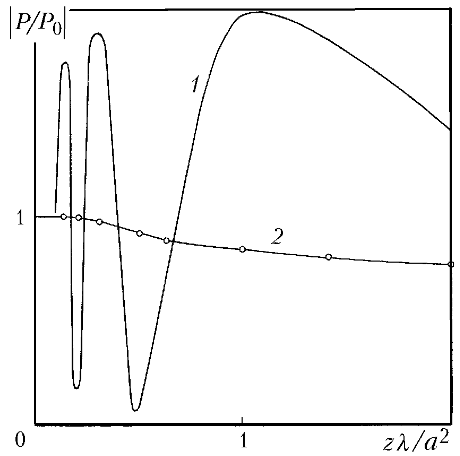

Fig. 2. Dependences of the ratios of axial pressure to emission pressure $|P(z)/P_0|$ (curve 1) and of the average pressure to emission pressure $|P_{av}/P_0|$ (curve 2) on the dimensionless distance $z\lambda/a^2$ for a transducer with the wave parameter ka = 30.

The propagation of an emitted wave in the sound duct occurs in the near zone, the extension of which is determined from the expression

$$z_n = a^2/\lambda_{ls} . \tag{4}$$

In this zone, in the "acoustic cylinder" of the emission of practically nondivergent ultrasonic rays, no less than 80% of the energy is concentrated.

For short-wave acoustic emitters that are employed for ultrasonic control and regulation of technological processes, the wave parameter of which $ka >> 1$ ($k = 2\pi/\lambda_{ls}$), the distribution of the ultrasonic pressure in the field of emission of harmonic vibrations and long pulses is described by the Helmholz–Brazhnikov integral [45, 46]:

$$P = -\frac{1}{4\pi}\iint_S P_0 r^{-1}\frac{\partial}{\partial r}[(r+z)\,\psi]\,dS , \tag{5}$$

where $\psi = r^{-1}\exp(-ikr)$ is the potential of the field for the point sources distributed over the emitting surface S. One of the basic characteristics of the field of emission are the distributions of the ultrasonic pressure obtainable by solving integral (5). The pressure on the Z axis of a transducer is calculated from Brazhnikov's formula [46]:

$$P(z) = P_0\left[1-\frac{1}{2}\left(1+\frac{z}{r_m}\right)\exp(-i\varphi_0)\right]\exp i(\omega\tau - kz) , \tag{6}$$

Here, $r_m = (z_2 + a^2)^{0.5}$; $\varphi_0 = k(r_m - z)$. The pressure on the "acoustic cylinder" of radius a is determined [47] from the computational relation

$$P_a = \frac{P_0}{2}\left[1-\frac{1}{2}\left(1+\frac{z}{r_0}\right)J_0(\varepsilon)\exp(-i\varphi_a)\right]\exp i(\omega\tau - kz) , \tag{7}$$

where $r_0 = (z^2 + 2a^2)^{0.5}$; $\varepsilon = ka^2/r_0$; $\varphi_a = k(r_0 - z) - ka^4r^{-3}/2$.

The dependences of these pressures on the generalized coordinate z/z_n, without allowing for damping in polystyrene selected as the material of sound ducts 2 (Fig. 1), calculated from Eqs. (6) and (7), are presented in Fig. 2. Here, according to Eq. (4), the near zone extends to z_n = 18.8 mm at a frequency of 2.8 MHz. Based on the minimum of damping, the length of the wave path in the sound duct is calculated to be many times smaller than z_n.

From the form of curve 1 in Fig. 2 for $P(z)/P_0$ constructed for the central ray, it follows that in the near zone the axial pressure is prone to substantial changes depending on the dimensionless distance $z\lambda/a^2$. However, measurements of the acoustic cylinder section-average pressure P_{av} performed for water with the aid of a piezoelement having ka = 30 show (Fig. 2, curve 2) that changes in $P(z)$ and P_a exert little influence on the average pressure in the near zone. Here, P_{av} has a weak dependence on the distance z with a certain "saddle" at z/z_n in the region of the minimum of $P(z)$. The coefficients of the attenuation of average pressure at the point where the central ray enters the wall 3 of the pipeline (l_s/z_n = 12/18.8) are equal to: 0.87 without allowance for attenuation in the sound duct and 0.67 with allowance for attenuation in polystyrene. The attenuation in the walls of the pipeline is small and may be neglected.

Under real conditions of functioning of the T1 and T2 transducers, measures should be taken to lessen noises to an acceptable minimum. These are a low-frequency noise caused by radial vibrations of a disk piezoelement on its pulse excitation and five high-frequency noises attributable to attenuating electric oscillations of the piezoelement on cessation of the oscillations of the electrical exciting pulse 4 (the rear front of the "initial" pulse) by oblique reflections by a longitudinal wave 8 at an angle α and a transverse one 9 at an angle $\alpha' = \arcsin (c_{ts}c_{ls}^{-1} \sin \alpha)$ in the sound duct from its contact working surface, by the reflection of a transverse wave at an angle β_t inside the wall 3 from its inner surface, and by reflection of a longitudinal wave from the piezoelement in a transducer on the opposite side of the pipeline. It should be noted that when these reflections directly arrive at the piezoelement, their amplitude is an order of magnitude higher than the informative pulse signal that arrives after passing through a fluid stream from the transducer on the opposite side of the pipeline.

The low-frequency noise was removed by optimal determination of the length of pulse 4, the piezoelement diameter-to-thickness ratio, and by the schematic electrofiltration. The length of the high-frequency initial pulse of the piezoelement and correspondingly the pulse amplitude by the time an information signal arrives from the opposite transducer are reduced by increasing the frequency f and decreasing the mechanical quality factor of the piezoelement by loading it on the sound duct without an intermediate layer.

Reflections 8 and 9 from the working surface of the sound duct at the designed parameters of a transducer were sent past the inclined plane where the piezoelement is installed (respectively, at angles $\pi/2 - \alpha$ and $\pi/2 - \alpha'$) to the side surface 10 of sound duct 2 covered by a weakly-reflecting sound-absorbing layer. The material of the layer (ED-5 polymerized epoxide resin with 50% finely dispersed powder of lead oxide) has the parameters ρ_{lr} = 1980 kg/m^3, c_{llr} = 1740 m/sec, δ_{llr} = 190 m^{-1} at f = 2.8 MHz. The closeness of its impedance $z_{llr} = \rho_{lr}c_{llr}$ = $3.4 \cdot 10^6$ N·sec/m^3 to the impedances of the sound duct $z_{ls} = \rho_s c_{ls}$ and $z_{ts} = \rho_s c_{ts}$ ensures a small reflection coefficient. The other two nonworking surfaces of the sound duct onto which reflections from surface 10 arrive also have such a coating. As a result of multiple reflections, the initially reflected pulses 8 and 9 arrive at the piezoelement attenuated to a level of the third order of smallness relative to the information signal. The reflections of the transverse wave from the pipeline wall that entered into the sound duct (transformed into longitudinal and transverse waves) at angles α and α_t' are attenuated similarly. They also bypass the piezoelement toward the side surface 10 covered by a sound-absorbing layer and subsequently are reflected to other damped nonworking surfaces of the sound duct.

In the majority of cases, industrial liquid flows are turbulent with a quasi-parabolic distribution of flow velocity over the pipeline cross section (with a maximum v_m on its axis substantially differing from the average velocity v). Near the inner surface the flow velocity is close to zero. The refracted wave (transformed from the transverse wave of the wall) enters into the stream of controlled liquid at an angle defined by the expression

$$\sin \beta = cc_t^{-1} \sin \beta_t = cc_{ls}^{-1} \sin \alpha . \tag{8}$$

The speed of the wave in the moving liquid $\mathbf{c}_v$ is equal to the vector sum of the velocities in a stagnant liquid $\mathbf{c}$ and of the stream $\mathbf{v}_\rho$ in a liquid layer of radius ρ relative to the pipeline axis, and its amplitude is defined by the expression

$$c_v = (c^2 + v_\rho^2 + 2cv_\rho \sin \beta)^{0.5} , \tag{9}$$

where, for the wave propagation along the flow (from T1), the velocity v_ρ is taken with a plus sign and opposite to the flow (from T2) — with a minus sign. Due to layer-by-layer refraction, the angle of propagation of a longitudinal wave in the liquid along the flow is increased smoothly from β at the inlet to the flow to a maximum on the pipeline axis and then is decreased to β on the opposite side of the inner surface. For acoustic beams propagating opposite to

TABLE 1. Interrelationship of Acoustic Parameters in the Flow Velocimeter

b_a	0	0.1	0.2	0.3	0.4	0.5
$(1-b_a)^{0.5}$	1.000	0.995	0.980	0.954	0.916	0.866
η_a	0.442	0.438	0.400	0.357	0.302	0.233

the stream, the angle that characterizes the direction of propagation relative to the normal to the pipeline axis attains a minimum on the axis and then is increased up to β on the opposite side of the inner surface of the pipeline.

The conclusion following from Eq. (9) on decrease in the time of propagation of the wave in the liquid along the flow and its increase opposite to the flow is erroneous. According to the theory set forth in [4, 7], the relative increase in the velocity c_v of the ultrasound as a result of layer-by-layer refraction leads to the same increase in the path of propagation of the wave in the liquid. When a wave propagates opposite to the flow, for the relative decrease in the ultrasound speed c_v there corresponds the same decrease in the path of propagation of the wave. Therefore, the time of its propagation in the liquid both along the flow and opposite to it is independent of the average flow velocity v and is defined by the expression

$$\tau_{\mathrm{fl}} = 2R_{\mathrm{p}}c^{-1}\cos\beta^{-1}\,. \tag{10}$$

The wave incident from the flow at an angle β onto the wall is transformed on its boundary into a transverse wave propagating in the wall (of the metal) at an angle equal to arcsin $(c_t c^{-1}\sin\beta)$ or, with account for Eq. (8), at an angle β_t (of the refractions of an emitted wave after its entry into the wall) defined by Eq. (2). On the boundary between the wall and the working surface of the sound duct of the opposite transducer, the transverse wave is transformed into a longitudinal one which propagates in the sound duct of this transducer at an angle arcsin $(c_{ls}c_t^{-1}\sin\beta_t)$ or, with allowance for Eq. (2), at an emission angle α. Not changing the time τ_{fl} of propagation of the longitudinal wave in the fluid, the flow causes geometrical "drift" of the wave due to the layer-by-layer refraction and corresponding change in the wave velocity c in the fluid according to (9). When the wave propagates along the flow (from T1), the "drift" decreases the average path in the receiving sound duct of T2 and the time of propagation in it. Against the flow (from T2), the "drift" increases the average path in the receiving sound duct of T1 and the time of wave propagation. The full times of propagation of an ultrasonic wave over the combined acoustic path of the system, with allowance for Eqs. (2) and (10), are defined by the following expressions:
along the flow

$$\tau_{+v} = 2l_{\mathrm{s}}c_{l\mathrm{s}}^{-1} + 2R_{\mathrm{p}}c^{-1}\cos^{-1}\beta - 2R_{\mathrm{p}}vc^{-2}B_{\mathrm{a-h}}\tan\beta\,, \tag{11}$$

opposite to the flow

$$\tau_{-v} = 2l_{\mathrm{s}}c_{l\mathrm{s}}^{-1} + 2R_{\mathrm{p}}c^{-1}\cos^{-1}\beta + 2R_{\mathrm{p}}vc^{-2}B_{\mathrm{a-h}}\tan\beta\,. \tag{12}$$

The acoustic-hydrodynamic coefficient of the beams of ultrasonic waves can be found from Brazhnikov's equation [7]:

$$B_{\mathrm{a-h}} = (1 - b_{\mathrm{a}}^2)^{0.5} + \eta_{\mathrm{a}}\theta_{\mathrm{p}}^{0.5}\,, \tag{13}$$

where $B_{\mathrm{a-h}}$ is the function of acoustic parameters $b_a = qR_{\mathrm{p}}^{-1}\tan\beta\tan^{-1}\alpha$, of the deviation $\Delta\alpha$ of the angle of emission from the reception angle, and of the pipeline resistance coefficient θ_{p}. The dependence of η_{a} on b_{a} is given in Table 1.

The longitudinal waves that entered the sound ducts with propagation times τ_{-v} in T1 and τ_{+v} in T2 are transformed by piezoelements 6 into electric high-frequency pulses 11 and 12 with a phase shift relative to one another, which, according to Eqs. (11) and (12), is described by the expression

$$\Delta\varphi = 2\pi f(\tau_{-v} - \tau_{+v}) = 8\pi fR_{\mathrm{p}}B_{\mathrm{a-h}}vc^{-1}\sin\alpha\,(c_{l\mathrm{s}}^2 - c^2\sin^2\alpha)^{-0.5} \tag{14}$$

TABLE 2. Experimental Data on Investigation of a System of Ultrasonic Control of the Flow Velocity of a Solution of Copper Sulfate

c, m/sec	λ_{fl}, mm	z_{fl}, 10^6 N·sec/m	δ_{fl}, m^{-1}	V_r, mW	τ_0, μsec
1519	0.54	1.60	0.1	37	52

and which is proportional to the average velocity v of the fluid flow controlled.

Pulses 11 and 12 of the informative acoustic signals (that passed opposite the flow and along it, respectively), together with the initial pulses of the piezoelement, enter, through the blocks of bipolar limitation 13 and 14, into selector amplifiers 15 and 16. The amplifiers are controlled by the selecting pulses 17 of a synchronizer 18 that also triggers a generator 7. Blocks 13 and 14 serve to prevent electrical breakdown of the amplifiers by high-frequency exciting pulses 4. Selecting pulses 17 block the initial pulses that are limited on both sides by amplitude, as well as ensure the passage of only informative signals to the outputs of the amplifiers.

Through phase-regulators 19 and 20 and amplitude stabilizers 21 and 22, the informative signals arrive at the pulse phase meter 23. The difference of the phases of informative signals in it is transformed into an output signal arriving at the recorder 24 of the flow velocity and at an automatic system of controlling (ASC) a technological process in an analog or digital form.

The stability of the automatic control of the flow velocity depends substantially on the amplitude V_r on the piezoelements in the transducers, the magnitude of the informative shift of phases $\Delta\varphi$, and the sensitivity of the phase meter. The experimental data obtained in the system investigated in controlling a flow of a hydrometallurgical solution of copper sulfate with a weight concentration of 5% in a pipeline of diameter $2R$ = 50 mm and wall thickness of 5 mm are presented in Table 2. For the flow velocity equal to 3 m/sec at $\theta_p = 0.03$ the phase shift measured was 1.14 rad. For the phase-meter sensitivity equal to 0.002 rad, the resolving power of the control of the flow velocity of the hydrometallurgical solution investigated was not worse than ±0.2%. The high level of the electrical signals of the transducers (tens of mW) do not pose special demands on electronic blocks.

Preliminary investigations confirmed the practical possibilities of noncontact ultrasonic control of the flow velocity of fluids.

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NOTATION

a, radius of a piezoelement and of an "acoustic" cylinder formed by the beams emitted by the piezoelement in the near zone, m; B_{a-h}, acoustic-hydrodynamic coefficient; b_a, acoustic parameter; $\mathbf{c}$ and $\mathbf{c}_v$, vectors of the velocity of propagation of a wave in a stagnant and a moving fluid, respectively, m/sec; c, c_v, c_{ls}, c_{llr}, and c_{lr}, velocities of propagation of a longitudinal wave in a stagnant and a moving fluid, a sound duct, a sound-absorbing layer, and in the pipeline wall, m/sec; c_t and c_{ts}, velocities of a transverse wave in the pipeline wall and in the sound duct, m/sec; dS, an element of the emission surface S, m^2; f, frequency of free vibrations of the piezoelement, Hz; i, imaginary unit; J_0, zero-order Bessel function; k, wave number, m^{-1}; ka, wave parameter; l, longitudinal wave; l_s, average length of the sound duct, m; P and $P(z)$, ultrasonic pressure in the field and on the axis of a transducer during emission, N/m^2; P_0 and P_a, ultrasonic pressure of emission and in the acoustic cylinder of radius a, N/m^2; P_{av}, average pressure of emission over the section of the acoustic cylinder, N/m^2; q, distance from the point of emission to the plane passing through the axes of the emitter and pipeline, m; r, distance between the points of emission and receipt, m; r_m, maximum distance from the reception point on the axes to the emitting surface, m; r_0, conventional distance, m; R_p, radius of the inner surface of the pipeline, m; S, area of the emission surface, m^2; t, transverse wave; v, maximum flow velocity (on the pipeline axis), m/sec; v, v_ρ, and $\mathbf{v}_\rho$, average flow velocity, flow velocity, and its vector in the flow layer of radius ρ, m/sec; V_r, electric voltage of the signal received, W; Z, transducer axis; z, coordinate, projection of r onto the transducer axis, m; z_n, extension of the near zone, m; z_{fl}, z_{ls}, and z_{llr}, specific acoustic impedances of the fluid, sound duct, and sound-absorbing layer for a longitudinal wave, H·sec/m^2; α_{1cr}, the first critical angle of introduction of a wave into the pipeline, rad; α, α', and α_t', angles of emission, reflection of the longitudinal and transverse waves in the sound duct reckoned relative to the normal to the pipeline axis, rad; $\Delta\alpha$, deviation of the receipt angle from the emission angle, rad; $\Delta\varphi$, phase shift, rad; β_l and β_t, refraction angles of the longitudinal and transverse waves in the pipeline wall relative to the normal to its axis, rad; β, angle of propagation of the wave in a fluid flow relative to the normal to its axis, rad; δ_{fl}, $\delta_{l\mathrm{s}}$, and $\delta_{l\mathrm{lr}}$, coefficients of damping of a longitudinal wave in a fluid, sound duct, and layer, m^{-1}; ε, argument of the Bessel function; η_{a}, acoustic parameter; θ_{p}, resistance coefficient of the pipeline; λ, λ_{fl}, and $\lambda_{l\mathrm{s}}$, length of the longitudinal wave in the medium of emission, the fluid, and the sound duct, m; ρ_{s} and ρ_{lr}, densities of the sound duct and layer, kg/m^3; τ, time, sec; τ_{+v} and τ_{-v}, full times of the propagation of a wave over the acoustic path along the flow ($+v$) and opposite it ($-v$), sec; τ_0, time of propagation of a wave over the acoustic path at $v = 0$, sec; τ_{s} and τ_{fl}, times of propagation of a wave in the sound duct and fluid; φ_0 and φ_a, phases of ultrasonic vibrations on the axis and acoustic cylinder (of radius a) of emission, rad; ψ, potential of a point source, m^{-1}; ω, circular frequency, Hz. Subscripts: a, acoustics; a-h, acoustic-hydrodynamic; av, average; m, maximum; r, receiver; lr, layer; p, pipeline; cr, critical; s, sound duct; n, near; fl, fluid.

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