Peculiliarities of the Through Transmission Method

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Abstract. Some problems of the through transmission method (TTM) based on ultrasonic arrangement and used for flaw detection and structure measurement are discussed. Using the "liquid modeling" method, we have found optimal conditions, at which the TTM sensitivity is maximum, and have made recommendations on optimal construction of ultrasonic arrangement employed for flaw detection and structure control in solids. If an object to be tested is not magnetic, we suggest to use ponderomotive forces of a magnetic system to move a pair of ultrasonic probes used for testing sheet materials, including bimetals.

Introduction and problem analysis

In making ultrasonic control of the structure of metals and in revealing their flaws, various regimes of sonic tests are used: echo method, through transmission method, mirror-through transmission method and their modifications [1]. Despite the fact that the through transmission method is rather simple and high-efficient [2], however there are a number of restrictions on its use that are connected with the conditions of its functioning during automated, mechanized and manual control. In particular, when a rate of ultrasonic scanning of objects is increased, the shift (parallel) of the axes of probes can be disturbed and angle deviations can appear due to elastic deformation of fastening (holder) under the action of inertia and hydrodynamic forces of an immersion medium and also of friction forces.

When the discontinuity is present in the sounding zone of material, a resultant field in the receiving region can be presented as a sum of fields: field of transmitting probe (Φ_E) and the so-called "effective field of flaw" (Φ_d) [1]. In this case, the wave amplitude P_A on the receiving probe with an area S_{re} and an arrival time of signal τ are of the form:

$$P_A \sim \iint_{S_{res}} [\Phi_E(R_r,\theta_r) + \Phi_d(R'_r,\theta'_r)]dS_{re}\,;\ \tau = f(\tau_1, \tau_{def}); \qquad (1)$$

where $\vec{R}_r$ and $\vec{R}'_r$ are the radius-vectors from the center of the transmitter (z=0) and the flaw coordinate to the element of the surface dS of the receiving probe; θ_r and θ'_r are the inclination angles of the corresponding radius-vectors.

Analysis of expression (1) shows that the quantity P_A depends not only on the flaw transverse size d of the probe shift δ, but also on the probe aperture characterized by radii R_{tr} (transmitting probe) and R_{re} (receiving probe), elastic wave length in fluid λ, acoustic base L. Further, for convenience, the above geometrical parameters will be used in dimensionless form:

$$R_{tr}' = R_{tr}/\lambda;\ \ R_{re}' = R_{re}/\lambda;\ \ \delta' = \delta/R_{tr};\ \ L' = L/N;\ \ d' = d/R_{tr};\ \ \rho' = \rho/R_{tr};\ \ \varepsilon_R = R_{re}/R_{tr} \qquad (2)$$

where $N=R^2/\lambda$, and $L'<1$.

A knowledge of regular changes in P_A depending on the above-mentioned acoustical parameters is especially important, when the access to one of the probes (driven) is not easy. To overcome this difficulty and to control the driven probe, the ponderomotive forces of magnetic systems located in the body of each of the probes can be employed. In this case, under the action of gravity, friction and inertia forces the mutual position of probes and parameters to be measured will change, requiring the optimization of the applied constructions. In addition, there arises a problem on designing reliable acoustical contact. For this to be realized, magnetic fluids (MF) can be used [5]. By applying the “liquid modeling” method, studies are made of the specific features of forming an acoustical field of probes operating in the through transmission regime; of the influence of the location of flaw model and also of the probe shift, of sizes of piezoelectric plates of the transmitting and the receiving probe upon the control sensitivity. Some aspects of designing through transmission control devices, including ultrasonic ponderomotive force-coupled facilities, are considered. Problems on MF application for designing acoustical contact are discussed.

1. Methods and experimental "liquid modeling" studies of acoustical processes

Experimental "liquid modeling" of acoustical processes has been performed on a computer-aided installation comprising standard blocks of a commercial flaw detector – a generator and a receiver of electric pulses, whose output is connected to a voltmeter V7-23 and to an oscillograph C1-71. Synchronizing all blocks of a metering circuit and measuring a time interval (with an accuracy of 1 – 2 ns) is performed using a device I2-26. The program for measured result processing contains the tables correcting the gain values of a measuring block, a subprogram for statistical processing of information input to remote facilities, controlling programs. Probes and flaw simulators are mounted on the adjusted holders in a water-filled immersion bath and move along the *x* and *y* coordinated by means of micrometric screws from the drive of step-by-step motors. The movement accuracy is of ±0.05 mm. Estimation values of temperature variations in the course of one measuring procedure are not more than 0.03 K. Absolute values of the radius of piezoelectric plates of the transmitting and the receiving probes are varied over the range 9÷4 mm, which corresponds to the range of their dimensionless values $R'=R/\lambda\approx 15\div 6.7$. Flaws are modeled by a foam plastic disc 1.5 mm in thickness.

2. Results of the study and their discussion

The main results of the first stage of work are presented in Figs.1-4, where the amplitude of an acoustic signal is plotted as a function of the value of the parallel shift of the transmitter and the receiver at different ratios of their radii $\varepsilon_R=R_{re}/R_E$; the coordinates of the model flaw $\{x,z\}$. It should be noted that it is rather difficult to perform comparative calculation of the parameters of the acoustical channel of an ultrasonic flaw detector by formula (1) based on the wave theory and the pulse behavior of elastic wave radiation. (So, earlier the A-D-F diagrams, when applied to through transmission control, are obtained using the liquid modeling method and only for the case of the same apertures of probes that are coaxial to each other [1]). In the case of liquid modeling of through transmission control, the ray acoustics approximation is proposed to describe how the signal amplitude on the receiving probe depends on the location coordinate of the model flaw ρ at the *x* axis and on the misalignment, δ, of the probes. Such an approach is motivated by the distinctive features of the operation of a real probe in the near (search light) field where there is a weak divergence of an acoustic beam and the transmission regime is pulse in character and differs from the plug one [1].

Fig.1 gives some explanation of the used computational scheme, according to which the signal amplitude on the receiving probe $P_A \sim S_c / S_{re}$, where S_c is the total surface area of projection of the transmitting probe area and the cross-section of the model flaw S_d onto the surface of the receiving probe S_{re} $(S_{re} > S_e)$. So, when $S_d \equiv 0$, $\delta = 0$, $P_A = 1$. It is no question that the proposed scheme is approximate but allows the main regular changes in P_A to be analyzed qualitatively for these conditions.

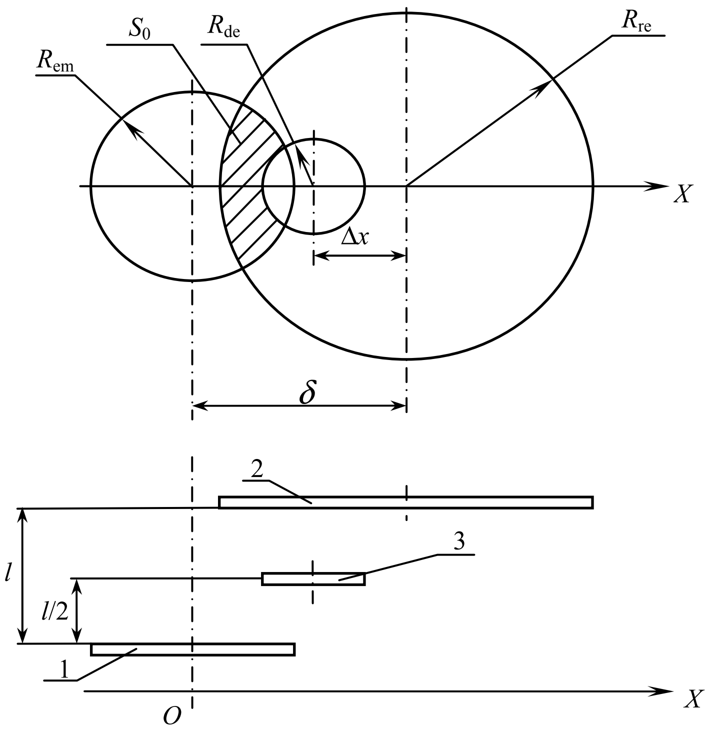

Fig.1.
Illustration for mathematical model: 1, 2 – transmitting and receiving probes; 3 – flaw model

Figs. 2-4 plot the signal amplitude as a function of the shift, δ, of the transmitter in the absence and in the presence of flaw model. If the flaw model is absent (Fig. 2), then the dependences $P_A(\delta')$ decrease monotonically, irrespective of the probe radius ratio. In this case, it is important to note that a 2.25-fold decrease of the transmitting probe′s aperture radius in comparison with the receiving probe′s radius does not essentially affect this dependence over rather a broad range of the dimensionless parameter $\delta' = \delta / R_{tr} = 0 \div 1{,}8$. At $\delta' > 1{,}8$ this dependence lies between the curves constructed for the equal-sized probes with the dimensionless aperture radius $R_{tr}' = R_{re}' = 15$ and 3.7.

It should be noted that very often in control practice the change in the level of a measured signal due to noise is considered to be permissible within ~2 dB. As has been found, when $\varepsilon_R = R_{re} / R_{tr}$ is varied from 1 to 2.25 ($R'_{re} = 15$), the value of the permissible shift of the probe at the mentioned level is over the range $\delta' \approx 1{,}3 - 1{,}5$. If $R'_{re} = R'_{tr} = 3{,}7$, then the value of the permissible shift of the probe at a level of 2 dB comes to only $\delta' \approx 0.7$. At a further shift of the probe to the values $\delta' \approx 1{,}3 - 1{,}5$, the signal amplitude decreases additionally to $\Delta P \approx 10$ dB. Thus, in the case of ultrasonic control in the absence of flaws, the increase in R_{re} in comparison with R_{tr} enhances the stability of a reference signal relative to the forced mutual shift of the probe′s axis, which diminishes the probability of additional rejection of controlled articles as defective.

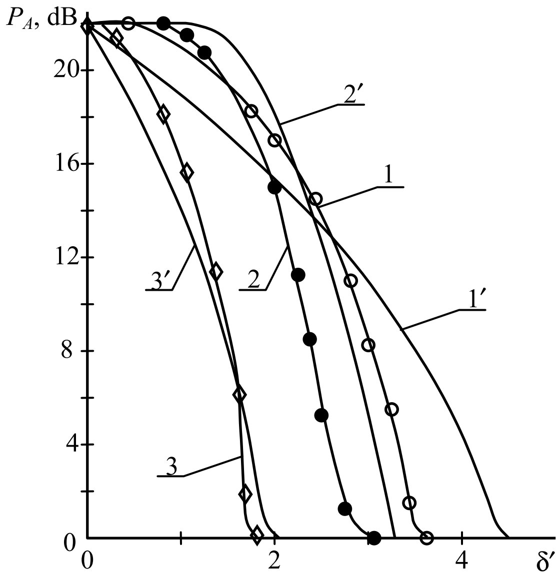

Fig.2.
Amplitude of P_A against δ′ when flaw model is absent: curves 1 and 1′ - R_{em} = R_{re} = 9 mm; 2 and 2′ - R_{em} = 4 mm, R_{re} = 9 mm; 3 and 3′ - R_{em} = R_{re} = 4 mm; data: experimental (1, 2, 3) and calculated (1′, 2′, 3′).

As the studies performed show, when the probes are operating in the search light field, it is possible to choose such aperture radii of R_{re} and R_{tr}, at which not only the high stability of a reference signal relative to the "parasitic" shift of the probes is attained, but also the high sensitivity to flaws to be realized only under quasi-stationary measurement conditions is preserved. As seen from the dependences $P_A(\Delta x)$ shown in Fig. 3, the change in the amplitude signal when a model flaw is introduced into the region of ultrasonic oscillation propagation is $\Delta P_A \approx 20 - 21$ dB, as in the case of both applying equal-sized ($R'_{re}=R'_{tr}$=3,7), non-equal-sized probes (R'_{re}=15*,* R'_{tr}=3.7). If $R'_{re}=R'_{tr}$=15*,* then despite the high stability of the reference signal the control sensitivity is less than 2 dB. Thus, the increase in the apertures of one of the probes does not exerts essential influence upon the sensitivity of a metering circuit under quasi-stationary conditions, and a simultaneous increasing of the both apertures noticeably reduces it. For $\delta < R_{re}-R_{tr}$ the influence of the probe shift on control parameters is essentially leveled. If $\delta > R_{re}-R_{tr}$, the amplitude of the reference signal decreases, which enhances the probability of additional rejections. (Besides, there appears an error in determining the flaw coordinate). As an example, Fig. 4 illustrates the data on the influence of the probe shift and the flaw coordinate on P_A . So, if δ, mm=$R_{re}-R_{tr}+2$, then in comparison with the case when $\delta \le R_{re}-R_{tr}$ and the flaw is absent, an additional signal attenuation is of ~2 dB. A further increase in δ reduces the sensitivity of the control method.

Comparison of the experimental and theoretical dependences in Figs. 2-4 points to their not bad qualitative and quantitative agreement, which allows the use of the proposed scheme for calculating the aperture of probes operating in the through transmission regime. It should be noted that when the acoustical base between the probes (N>1) grows, the control sensitivity decreases, which is associated with the peculiarities of wave front diffraction [3]. Relying upon elementary considerations and experimental check, we have proposed a somewhat refined expression that relates the distance L between the probes, their aperture and the misalignment parameter:

$$\frac{R_{re}}{Rtr} = 1 + \delta' + 0,5\Re(1 + \frac{|\Re|}{\Re} tg\theta),$$

where $\Re = \frac{L'}{R'_{re}} - R'_{re}$; $L' = L/\lambda$; θ - is the parameter for the expansion angle of the main blade of the diagram of the transmitting probe directivity.

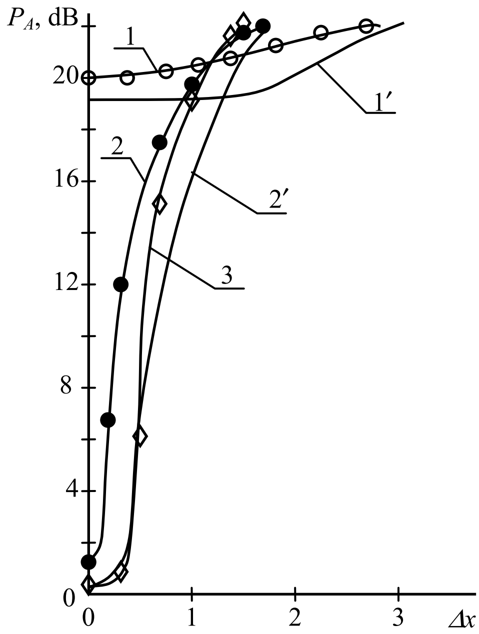

Fig.3.
Amplitude P_A against distance Δx between central axes of the transmitting probe and flaw model for δ=0.
Curves 1 and 1′ - $R_{em} = R_{re} = 9$ mm; 2 and 2′ - $R_{em} = 4$ mm, $R_{re} = 9$ mm; 3 - $R_{em} = R_{re} = 4$ mm.

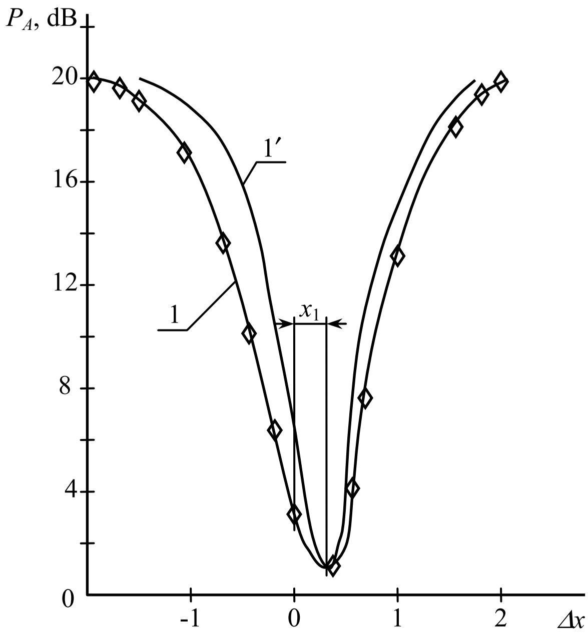

Fig.4.
Amplitude P_A against distance between central axes of transmitting probe and flaw model, when there is additive shift δ=δ*: 1, 1′ - $R_{tr} = 4$ mm, $R_{re} = 9$ mm.

It should be marked that if the shift of a probe occurs only in one direction (*x*), then for the sensitivity of the method to be improved, it is enough to increase the size of the probe aperture only in this direction. Based on the above proposed method, the problem on reducing the influence of random angular rotations of the transmitter on the measuring reliability and sensitivity is also being solved.

3. Some aspects of designing and applying probes for through transmission control

Using the proposed approach, several ultrasonic arrangements meant for high-efficient through transmission control over sheet materials, including bimetallic ones, have been designed. The first of them is operating at a frequency of 2.5 MHz and is meant for automated control over the quality of explosion welding of bimetallic materials (steel-aluminium, steel-brass, aluminium-brass, etc.) with the thickness from several mm to 35 mm. Because of the achieved high stability of the reference signal (when the sensitivity to non-coupling flaws of materials is preserved) a mechanical block for probe movement is made compact and portable. Water serves as an immersion medium.

The second designed arrangement is meant for through transmission control of large-size thin-plate objects over the presence of plane and volume flaws when the access to one of the surfaces is difficult. Its construction intended for manual control is explained in Fig. 5 and comprises two probes, a tread, and a magnetic holding system that is made using permanent uniformly magnetized magnets. The latter are positioned inside the body where three spherical bearings with a controlled height are placed. A driven probe relative to a driving one at any point in space relative to the contact surface of object with the normal $\vec{n}$ is held by the ponderomotive forces of two magnets of cylindrical or annular shape that are polarized to each other. To decrease the weight of both the driven and driving probes and also to eliminate scattering fields, the opposite ends are equipped with plates of high-magnetic material that plays the role of a peculiar "reflector of a magnetic flow". It is assumed that the axes of the magnets and the piezoelectric plates of each probe coincide. As before, designate the shift of the driven and driving probes through δ. The equations describing the necessary conditions for holding the driven probe with a mass *m* relative to the driving probe and the field energy of interacting magnetic systems *W* are of the form

$$F_\tau - m(\vec{n}\vec{g})k_f - m(\vec{\tau}\vec{g}) - F_n k_f > 0 \qquad (3)$$

$$F_n - m(\vec{n}\vec{g})k_f > 0 \qquad (4)$$

$$\partial W/\partial l = 0 \text{ and } \partial^2 W/\partial l^2 < 0 \qquad (5)$$

where $\vec{n}, \vec{\tau}$ - normal and tangential unit vectors; *m* – mass of the driven probe.

Relation (5) is for coaxial position of magnets (*l=0)*. Relations (3, 4) characterize the conditions for holding the probes normal to the contact surface of an object and tangential to it when $l \neq 0$; F_z and F_τ - are the normal and tangential components of the ponderomotive forces. Relation (5) is for coaxial position of magnets.

In determining the probe in an immersion medium, it is necessary to take into account the buoyancy force of an immersed body with a volume *V* by substituting instead of *m* the value $m^* = m - \rho^* V$ into (3) and (4). As the analysis of possible designs of magnetic systems of holding the driven probe shows, the optimal ones are disc and annular magnets of identical diameter that are manufactured from "magnetorigid alloys", e.g., Sm-Co and possess the largest specific energy. According to the scheme (Fig.6a), using the principle of solenoid representation of magnets, calculation is made of the components of the force that act upon the driven probe when it aligns relative to the driving probe in the scanning plane along the coordinate l. Below, the F calculations use the driven probe parameters R_1 dimensionalized over the magnet radius: magnet thickness b_i, magnet distance h and the coordinate l , along which the driven probe axis is shifted. For convenience, F_z and F_τ are dimensionalized by multiplying them by the coefficient $M_0^{-2}\mu_0^{-1}$, where M_0 is the magnetic moment of magnet material, and μ_0 is the absolute magnetic permeability of vacuum.

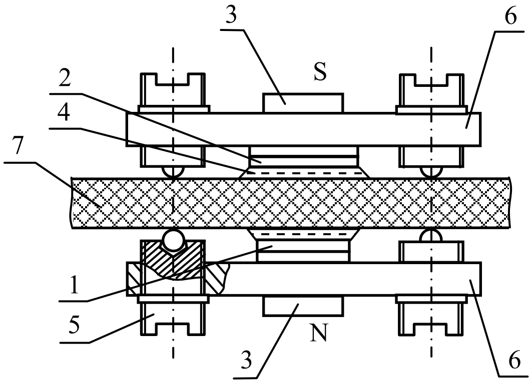

Fig.5.
Ultrasonic construction: 1, 2 –transmitting and receiving probes; 3 – magnetic system; 4 – magnetic fluid; 5 – controlled supports; 6 – housing; 7 – test article.

From the analysis of the force characteristics of a pair of interacting magnets of axial symmetry it follows that in the absence of other external forces, the condition for their the more stable equilibrium relative to tangential shifts l is satisfied only in the case when the magnets themselves, or the shape of their cross-section are identical. As the numerical results on the interaction of one-type disc or annular magnets (Fig. 6) show, the typical dependences of F_z and the friction forces applied to the driven probe at different thickness of plate material have the form of smoothly decreasing dependences on the value of the misalignment of the probe driven l. The dependence of the ponderomotive force acting upon the probe in the tangential direction $F_\tau(l)$ has maximum at some characteristic value of l^* and at some distance h^* between the magnets. In this case, as h^* is decreased, l^* decreases too. From the calculations, the approximating relations $\{F_z, F_\tau\} = f(z, l, b_i)$ have been obtained, which allow estimating the probe shift with an accuracy not worse than 15 % over the range l <0.35 for different geometrical parameters of magnets and the distance between them:

$$F_\tau = F_0\, l(1-\Upsilon z)[(\alpha_1 - z\alpha_2)l + ([(\beta_1 - z\beta_2)l^2] \; ; \; F_z = F_0(1-\Upsilon z)[1-(\chi_1 - z\chi_2)l], \qquad (6)$$

where Υ, α_i , β_i , χ_i are some tabular constants obtained for a particular value of the thickness of identical disc magnets over the range b=0÷1. Thus, knowing the quantities that destabilize the forces acting upon the driven probe, using formulas (3 - 6) it is possible to determine a permissible value of the shift l and adopting the methods outlined in Section 2.1 – to choose optimal size of probe apertures.

When the ultrasonic facility of the proposed design is operating, certain difficulties may appear in providing the acoustical contact with a not easily accessible (opposite) contact surface of object. For this, a magnetic fluid [ ] can be used, which represents a high-stable colloidal solution of ~100A^o dia stabilized magnetic particles in organic and inorganic-base carrying fluid. In this case, in the RHS of equation (3) describing the probe position there appears an additional term $F_{MF} = \iint_{S_k} P_{MF}\, dS_k$, and in relation (4) – the term

$k_f F_{MF}$, where $P_{MF}= \mu_0 \int_{\infty}^{x \subset S_k} MdH$, S_k is the area of contact of a magnetofluid sound duct with a test object.

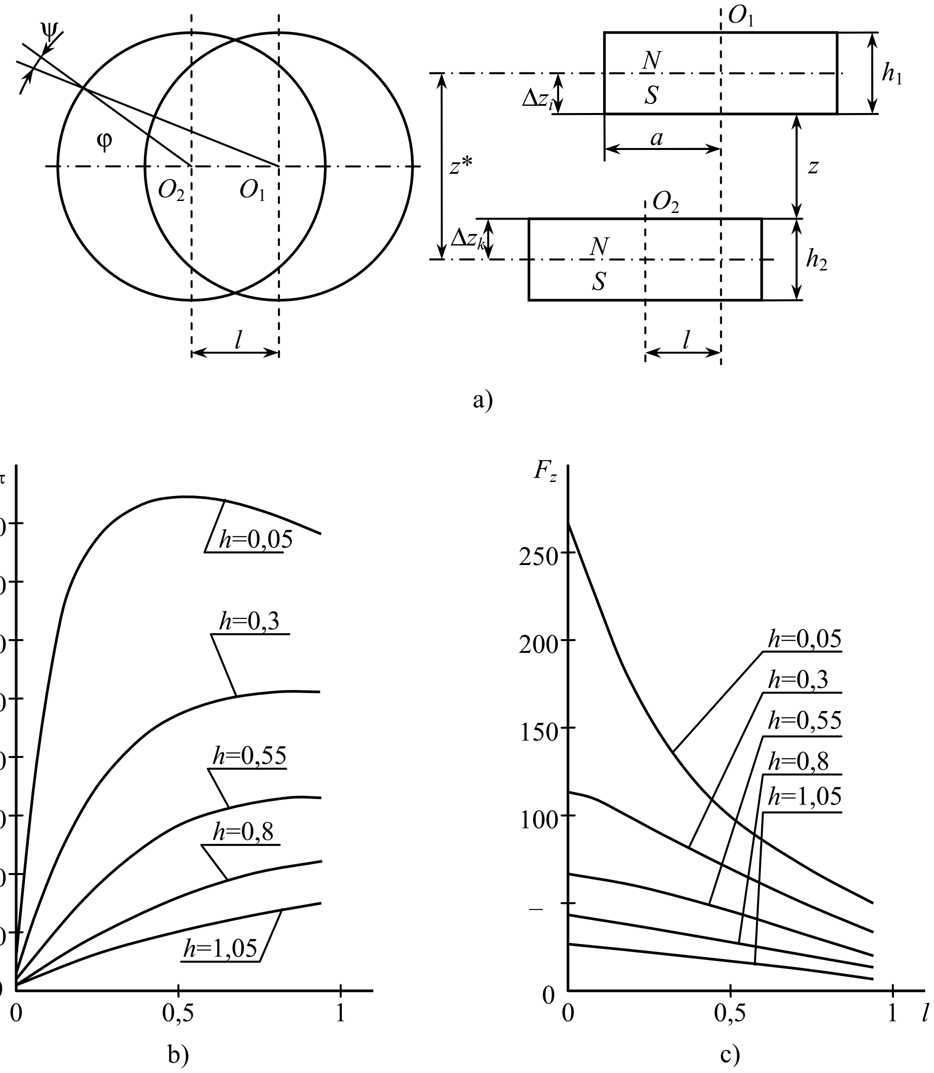

Fig.6.
Illustration for calculation of ponderomotive forces between magnets (a) and dependence of their tangential F_τ (b) and normal F_n (c) components for identical magnets (h_1=h_2=0,5).

As we have shown previously [5], just applying the disc magnets it is possible to provide a reliable magnetofluid acoustical contact (Fig.5). In this case, ∇H must be directed mainly to the central region of an acoustic sound conducting medium where the field strength attains a maximum value. This permits eliminating the penetration of air bubbles and other nonmagnetic inclusions into it. As an additional condition in choosing magnetic systems and magnetic contact fluid with optimal physical properties (density ρ, magnetization M, viscosity, etc.) that provide maximum stability of input (receving) of ultrasonic oscillations, we propose the principle of minimizing the functional t^* – the time, during which the sample nonmagnetic discontinuity (wave reflector) leaves the zone of the magnetofluid sound wire with a velocity v_f:

$$t^* = \int_0^{r_0} \frac{\Re^{1/n}}{G^{1/n}_{\tau}} dr ,$$

where $\vec{G}_\tau = [-\mu_0 M(\nabla H_\tau) + \rho \vec{g}_\tau + \vec{f}_\tau]V = \Re \ v_f^n;$ $\vec{f}_\tau$ is the tangential component of other mass forces; $\Re$ is the coefficient characterizing the hydrodynamic resistance to the motion of the discontinuity with a volume V from the sound conducting region; n is the power index.

It should be noted that the application of magnetic fluids as an acoustically contact medium is recommended for solving special problems that require a high reliability of acoustical contact and its localization for through transmission control of articles: at not easily accessible places, in the elevated radiation zone, under the weightlessness conditions, under the action of vibrations. To reduce a flow rate of magnetic fluid, some actions proposed by us [5] can be taken. The use of magnetic field-controlled magnetic fluids is very effective in ultrasonic measurements on rotating objects, e.g., in control of the quality of welding by high-cutting tool friction, where the centrifugal and hydrodynamic forces can be very large.

Results and conclusion

As a result of the studies performed by the liquid modeling method, the possibility is shown how to enhance the reliability and confidence of ultrasonic control of sheet materials and articles by the through transmission method in the near field when the transmitting and receiving probes are not equal-sized and their location is optimal. In this case, the influence of the parasitic misalignment of the receiving probes relative to the transmitting probes upon measurement results is leveled.

A construction of the ultrasonic arrangement of the probes with a ponderomotive coupling is proposed for control of nonmagnetic thin-sheet articles at the access from one side and optimal conditions for holding the driven probe by the ponderomotive forces are determined. The peculiarities of stabilization of acoustical contact with the use of magnetic fluids are considered.

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