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EVALUATION OF ULTRASONIC CLEANING PROCESS

Purpose. To establish relationship between intensity of ultrasonic cleaning and an ultrasonic response fixed at a set point. To determine the influence of liquid contamination on this signal. To specify parameters of an ultrasonic signal to evaluate the course of cleaning a preset section of a body. To define limiting values indicating efficiency of ceasing the cleaning process.

Methodology. The research is based on simulation of ultrasonic wave propagation in the heterogeneous environment and subsequent analysis of the signals by using software.

Findings. Dependences are established to form evaluation of the course of the cleaning process by parameters of the ultrasonic response. It is found that both the body's state and that of the liquid affect the ultrasonic response obtained by the sensor at the set point during ultrasonic cleaning. With high contamination ($> 30\ \%$) the state of the liquid becomes a critical factor for forming the signal of the ultrasonic response. With that, there is an abrupt reduction of threshold signal arrival time and increase in the main amplitude, which is to be one of indicators of ceasing the cleaning process in case of its inefficiency. With lower contamination, suspended contaminant particles only correct the signal to some extent without distorting it. There is a relationship between reduction of contamination, the arrival time of threshold signal, on the one hand, and the value of the main amplitude and the *2nd* and *3rd*-order nonlinearity coefficients, on the other hand. The arrival of the threshold value of the signal is the major parameter determining intensity of cleaning, i. e. reduction of contaminant thickness, which is determined by the value of the main amplitude of the signal and the *2nd* and *3rd*-order nonlinearity coefficients.

Originality. For the first time, methods for evaluating the course of the ultrasonic cleaning process by analyzing ultrasonic responses at a specified point have been developed.

Practical value. To consider spatial distribution of the ultrasonic cleaning process, its control is to be based on evaluating the body's contamination in several preset points. To implement this, the character of dependences between changes in contamination of the body section and parameters of the fixed ultrasonic response is determined. Impacts are considered of suspended contaminant particles in the liquid on the signal analyzed. The observed relationship will provide the basis for building the spatially distributed control over ultrasonic cleaning considering the cleaned body's state.

Keywords: *ultrasonic cleaning, liquid contamination, nonlinear factors, simulation*

Introduction. Effective cleaning increases equipment life and enhances efficiency of current repairs. Compared with chemical and mechanical cleaning, the ultrasonic one has some advantages like absence of hazardous solvents, hard manual labour and high efficiency. Improvement of efficiency of ultrasonic cleaning involves two options. The former implies searching for new physical peculiarities of the processes that ensure ultrasonic cleaning. With this approach, new methods for investigating into cavitation activity depending on ultrasound frequency and intensity [1, 2], duration of insonation, the content of gas, and temperature of the liquid [3] are created. The latter includes new approaches to automation of the process [4, 5].

Like most complex physical processes, ultrasonic cleaning is characterized by spatial distribution of parameters due to the zonal distribution of cavitation, geometric features of the cleaned body and irregularity of contamination. In [5], the problem of irregular cleaning due to zonal distribution of cavitation and 'blind zones' where almost no cleaning occurs is solved through correcting the design of an ultrasonic container and adding extra water circulation. This enables redistribution of cavitation and increased efficiency of cleaning by washing out contaminant particles with extra water flows. A completely different approach is used in [6] to increase efficiency of the ultrasonic cleaning process. To address the issue of low cavitation activity zones, the authors propose an extra low-frequency radiator, which makes cavitation clusters in remote areas collapse. These studies confirm the necessity to form the control over ultrasonic cleaning taking into account its spatial distribution in order to build energy-efficient automation of the process. The issue of irregularity of contamination to be considered remains unsolved. Formation of ultrasonic cleaning control taking into account the state of the cleaned body would enable cleaning the areas that really need cleaning and stop the process when its efficiency makes no sense.

Conventional methods designed for systems with distributed parameters require rather complex mathematical models that cannot always be built and used in practice. New approaches involving educational algorithms, expert experience, and fuzzy logic can overcome this problem [7]. Therefore, to control ultrasonic cleaning, it is proposed to use a three-dimensional fuzzy controller [8] with an extra spatial coordinate that enables forming control considering spatial distribution of physical processes. The interval membership function allows using a flexible evaluation of input parameters. To provide a three-dimensional fuzzy controller with input data, a method for evaluating the state of the ultrasonic cleaning process by ultrasonic responses at specified points is required, this being the objective of this work.

Literature review. For a long time, duration of ultrasonic cleaning has been limited only by the time value preset by an operator. This requires constant monitoring and leads to inefficient use of ultrasonic energy, as duration of the process can be exceeded. To solve this problem, [4] suggests an approach that limits duration of ultrasonic cleaning depending on turbidity and conductivity of the liquid. No observed changes in these parameters indicate a logical conclusion of the cleaning process, i. e. either the product has already been cleaned or contamination of the liquid does not allow further cleaning. Formation of control using the above approach allows increase in energy efficiency of ultrasonic cleaning, but ignores its spatial distribution and irregularity of initial contamination, which results in processing previously cleaned sections.

More flexible approaches are applied in [9, 10], which deal with non-invasive evaluation of pipe cleaning duration. Ultrasonic sensors and machine learning are used in these studies. [9] concerns only pipe cleaning, so the author finds reasonable to use a convolutional neural network based on physical properties of ultrasonic cleaning, namely only positive orientation of cleaning. In [10], cleaning the pipe section is controlled by ultrasonic and optical sensors with subsequent result processing by means of a neural network regression model. This study proves effectiveness of ultrasonic sensors applied to determining contamination areas. Yet, similar methods for determining contaminant presence can be applied to a small number of cleaned products only.

Ultrasonic nondestructive measurement is widely applied to quantifying a large number of mechanical and structural properties of solids [11, 12] as well as for assessing the state of the object subjected to ultrasonic cleaning. Mechanical properties of bodies have been evaluated by means of ultrasonic measurements for a long time in various industries, this trend continuing nowadays [13, 14] indicating its high efficiency and accuracy. Yet, complexity of physical interpretation of ultrasound measurement results is one of the main constraints for their application.

A contaminated body is an object with distorted mechanical properties, i.e. there are areas of varied density. When being cleaned, the body's density becomes more homogenous. Evaluation of the product's contamination in its physical essence is close to finding damages and microfissures since both cases are characterized by heterogeneity of the body structure. Due to material nonlinearity, the ultrasonic response can be distorted and create concomitant harmonics and multiplication of waves of various frequency. In a number of experiments [15, 16], it is proven that the nonlinear component of ultrasound responses is the most significant parameter to evaluate the degree of heterogeneity of the body, the presence of microfissures and damages. Sensitivity of nonlinear methods to detecting signs of the body's heterogeneity is much greater than that of linear acoustic methods (measurement of wavelength speed and wave dissipation).

Formation of higher order harmonics, i.e. harmonic frequencies exceeding the frequency of the main input frequency as a result of distortion of the signal shape in the time area is a typical nonlinear phenomenon. To evaluate microfissures, changes in the ratio of amplitudes of the first and the square of the second harmonic [16] or the ratio of coefficients depending on amplitude of the *2nd* and *3rd*-order harmonics are analysed [15]. While in these works there is an increase in nonlinear components, i.e. deterioration in the product's mechanical properties, the opposite effect occurs in ultrasonic cleaning – a decrease of the nonlinear component in the cleaning process as an indicator of improvement of the body's mechanical properties. This feature may be assigned to developing a method for evaluating the state of ultrasonic cleaning taking into account spatial distribution of the process. To prove feasibility of this approach, the ultrasonic cleaning process is simulated and the signal received at different stages of cleaning for bodies of different configurations is analysed. Also, signal changes depending on the distance of the radiator location from the contaminated area are modelled. Spectral analysis of signals received during simulation makes it possible to form a method for evaluating the state of ultrasonic cleaning.

Unsolved aspects of the problem. Consequently, available evaluation approaches are based either on an indirect evaluation of the process by the state of the environment, or on evaluation applied only to cleaning certain objects. This prevents automation taking into account actual contamination of the cleaned object when its geometric shape is arbitrary. Therefore, in a general case, to consider spatial distribution of the ultrasonic cleaning process and irregularity of contamination, it is necessary to form evaluation guiding by the body's condition in specified positions. The number of positions depends on the size of the ultrasonic bath and the ratio of the cost of sensors and increase in energy efficiency.

Purpose. To take into account the spatial distribution of the ultrasonic cleaning process, the controlling action is to be based on a distributed evaluation of the course of the process [8]. As input parameters, the control impact formation algorithm obtains the difference between the latest measurements of the signal and its power. Signal change is the main sign indicating its alteration or, in other words, that it is cleaned. Any change may indicate only the course of the cleaning process. The signal's "purity" enables forecasting the required additional processing and is an extra parameter. The peculiarity of this parameter is in complexity of determining what exactly affects the signal: changes in the surface of the cleaned body or changes in the state of the liquid. To determine what parameters of the ultrasonic response allow us to specify the activity degree of contaminant detachment in a given area and how suspended particles affect the reflected signal, the process of cleaning bodies under different conditions is simulated. The resulting signal is converted by Rapid Fourier transformation and the value of the first three harmonics is analysed.

Methods. During cleaning, the thickness of the contaminant layer changes, this affecting the following ultrasonic response parameters: the signal return time, the value of the signal amplitude and additional harmonics. Considering the presence of at least three boundaries of different environments (liquid – contaminant, contaminant – body, contaminant – liquid), where refraction and reflection of ultrasonic waves will occur, a complex process of multiple dispersion is dealt with. Generally, such boundaries may be greater due to different contaminant density and its heterogeneous structure. At the same time, in the process of cleaning, a certain maximum number of boundaries of different environments occur, after which their number decreases. In ultrasound responses, there is an increase in the nonlinear component to a certain value followed by reduction to its minimum for a fully cleaned body and an increase when minor irregularities and holes on the surface of the body begin to be cleaned. In other words, there occurs deterioration in mechanical properties of the body due to destruction of the contaminant layer and improvement when the body is completely cleaned.

Many studies [12, 15, 16] suggest using the *2nd* or *3rd*-order acoustic nonlinearity coefficients to evaluate nonlinearity of the material structure

$$\beta_2 = \frac{8A_2}{k^2 x A_1^2} = \frac{2c^2 A_2}{\pi^2 f^2 x A_1^2}; \tag{1}$$

$$\beta_3 = \frac{24A_3}{k^2 x A_1^3} = \frac{3c^3 A_3}{\pi^3 f^3 x A_1^3}, \tag{2}$$

where β_2 is the ultrasonic nonlinearity coefficient of the *2nd* order; β_3 is the ultrasonic nonlinearity coefficient of the *3rd* order; A_1, A_2, A_3 are amplitudes of the main, first and second harmonics; x is the distance to the beam; f is the ultrasound frequency; c is the speed of ultrasound; k is the wave vector. For ultrasonic cleaning, taking into account constancy of values of most parameters, we will use relative parameters of acoustic nonlinearity

$$\beta_2 = \frac{A_2}{A_1^2}; \tag{3}$$

$$\beta_3 = \frac{A_3}{A_1^3}. \tag{4}$$

Ultrasonic cleaning is complicated by a significant change both in the body itself and in the properties of the liquid due to present suspended particles of solid contamination.

Let us consider the section of the contaminated body as well as absorption and reflection of ultrasonic waves on it (Fig. 1). Conventionally, we denote the liquid by L, the contaminant by C and the cleaned body by B. Hereafter, we assume to consider the metal with the ultrasonic wave propagation speed c_B = 5900 m/s and density ρ_B = 7800 kg/m^3, contamination with the distribution speed of the ultrasonic wave c_C = 2500 m/s and density ρ_C = 3100 kg/m^3 and the liquid with the ultrasonic wave propagation speed c_L = 1500 m/s and density ρ_L = 1000 kg/m^3.

If the contaminant thickness is significant, ultrasonic waves fall on the boundary with the double surface. On the boundary "L–C", part of the wave is reflected into the layer

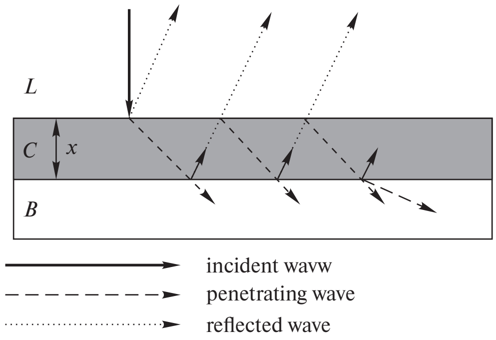

Fig. 1. The section of the contaminated body and wave refraction there

"*L*", and part falls into the layer "*C*". Passing the "*C*" layer, the beam partially falls into the "*B*" layer, and is partially reflected. This process occurs sequentially. As a result, there are reflected waves moving in both directions between *L* and *B*. Besides, interference between penetrating and reflected waves determined by the difference of phases may take place. At the same time, with the thickness of the "*C*" layer of a multiple of half the wavelength, we obtain the maximum transmission of ultrasonic energy, with the thickness of a multiple of quarter of the wavelength, transmission of ultrasonic energy will be minimal.

Since the thickness of "*C*" is constantly reduced arbitrarily, interference may cause jumping changes in the amplitude of the reflected signal, which is fixed by the sensor. In general, the loss of signal intensity is described by the indicator dependence

$$I(x) = I_0 e^{-2\alpha x}, \tag{5}$$

where I_0 is the intensity of the sound wave at the input into the material; α is the value of the attenuation coefficient, which significantly depends on the frequency of the ultrasonic wave. In other words, at the final stages of cleaning there will be a more significant change in signal intensity than at the initial ones, since there will be a change in properties of the boundaries.

So, when falling, part of the energy is reflected, and part passes to another layer. The angles of incidence and reflection are the same, and the angle of the penetrating wave depends on the sound speed in both environments. The ratio of intensity of the reflected and penetrating wave is calculated by the Rayleigh ratio for the ideal case (the flat boundary with no irregularities), but since it is not characteristic of ultrasonic cleaning, we will consider the case of a normal wave fall on the boundary of the environment division. The value of the amplitude reflection coefficient is

$$\Gamma = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}, \tag{6}$$

where ρ_1, c_1, ρ_2, c_2 are the body's density and the ultrasound velocity for environments 1 and 2.

For different transitions during ultrasonic cleaning $\Gamma_{LC} = 0.68$, $\Gamma_{CB} = 0.71$, $\Gamma_{LB} = 0.94$. That is, for the cleaned body, reflection of 0.94 of the initial wave is observed, for the contaminated body – 0.68 (reflection from the cleaned body with the available contaminant will be $(1 - 0.68) \cdot 0.71 \cdot (1 - 0.68) = 0.072$ – that is less by an order of magnitude considering the fact that we take penetration instead of reflection on the boundary of "*L–C*" and "*C–B*".

Or for intensity

$$\Gamma_I = \left(\frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}\right)^2. \tag{7}$$

Thus, we obtain intensity of the reflected signal that makes

$$I(x) = I_0 e^{-2\alpha x} \left(\frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}\right)^2. \tag{8}$$

During cleaning, contaminant particles enter the liquid, this significantly correcting attenuation and dispersion of ultrasonic waves. The dispersion of waves on contaminant particles will be significant if the wavelength λ is comparable to the size of the particles themselves. If a wave passes through the environment with a large number of randomly positioned particles, the phases of waves scattering in a given direction and coming from randomly located centres are incoherent [17]. Therefore, the full intensity of the ultrasonic wave at a given point is equal to the sum of the wave intensities from all dispersion centres. Then dispersion intersections will be additive, and linear absorption $\Sigma\_(\lambda)$ and dispersion $\Sigma_S(\lambda)$coefficients are determined

$$\Sigma\_(\lambda) = n\sigma_c(\lambda); \quad \Sigma_S(\lambda) = n\sigma_S(\lambda), \tag{9}$$

where *n* is particle concentration; $\sigma_c(\lambda)$ and $\sigma_S(\lambda)$ are full dispersion and absorption on a particle.

Full intersections of absorption and dispersion depend on wavelength and particle size *r*.

The main characteristic of the ultrasound radiation field is determined from the kinetic equation. The kinetic equation, whose solution will be $I_\lambda(\vec{r},\vec{\Omega})$, is obtained through considering the energy balance in the elementary volume of the phase space (14)

$$\begin{gathered} \vec{\Omega}\nabla I_\lambda(\vec{r},\vec{\Omega}) = -\Sigma(\lambda) I_\lambda(\vec{r},\vec{\Omega}) + \\ + \int d\Omega' \Sigma_S(\vec{\Omega}' \to \vec{\Omega}) I_\lambda(\vec{r},\vec{\Omega}') + S_\lambda(\vec{r},\vec{\Omega}), \end{gathered} \tag{10}$$

where $S_\lambda(\vec{r},\vec{\Omega})$ is the ultrasound radiation density function determining the average size of the energy value per unit of time by a single phase volume; $\Sigma_S(\vec{\Omega} \to \vec{\Omega}') = n\sigma_S(\vec{\Omega} \to \vec{\Omega}')$, where $\sigma_S(\vec{\Omega} \to \vec{\Omega}')$ is angle differential energy dispersion on solid phase particles. Phase coordinates are a total of variables *r* and *W*, the elementary phase volume is $d\vec{r} \cdot d\vec{\Omega}$.

Thus, the change in the intensity of the ultrasonic beam with the direction $\vec{\Omega}$ at the point $\vec{r}$ occurs due to absorption and dispersion (the first item in the right part), as a result of dispersion of the energy flow of the $\vec{\Omega}'$ direction, the $\vec{\Omega}'$ direction (the second item in the right part) and due to the energy entering this beam from the radiators (the last item of the right part). In the integral form, equation (10) looks like

$$\begin{gathered} I_\lambda(\vec{r},\vec{\Omega}) = \int d\vec{r}' \int d\vec{\Omega} \sum_s (\vec{\Omega}' - \vec{\Omega}) \frac{e^{-\tau(\vec{r}',\vec{r},\lambda)}}{\left|\vec{r} - \vec{r}'\right|} \times \\ \times \delta\left[\vec{\Omega} - \frac{(\vec{r} - \vec{r}')}{\left|\vec{r} - \vec{r}'\right|}\right] I_\lambda(\vec{r}',\vec{\Omega}') + I_\lambda^0\vec{(}\vec{r},\vec{\Omega}), \end{gathered}$$

where $\tau(\vec{r}',\vec{r},\lambda) = \Sigma(\lambda)\left|\vec{r} - \vec{r}'\right|$; $\sigma(\cdot)$ is the Dirac delta function; $I_\lambda^\circ(\vec{r},\vec{\Omega}) = \int\limits_0^\infty S_\lambda(\vec{r} - \xi\vec{\Omega},\vec{\Omega}) e^{-\tau(\xi,\lambda)} d\xi$ is a free member determining intensity of the undeflected ultrasonic wave $\xi = \left|\vec{r} - \vec{r}'\right|$.

There is no analytical solution to the equation, so numerical methods are used [17].

Let us consider the effect of liquid-suspended contaminant particles on the signal response that the ultrasonic sensor receives.

To simplify, we assume that contaminant particles have a spherical shape of the radius *r* and the density ρ_c, the absorption intersection on such a particle is determined

$$\sigma_S(\lambda) = \frac{4\pi r^3}{3} k \left(\frac{\rho_c}{\rho_p} - 1\right)^2 \frac{S}{S^2 + (\rho_c/\rho_p + \tau)^2}, \tag{11}$$

where $k = 2\pi/\lambda$ is the wave number; ρ_0 is the liquid density; $S=\frac{9}{4Br}\left(1+\frac{1}{Br}\right)$; $B=(\pi\nu/\mu)^{\frac{1}{2}}$; $\tau=\frac{1}{2}+\frac{9}{4Br}$; $\mu = \eta/\rho_0$; η is the liquid viscosity coefficient; ν is the frequency of ultrasonic oscillations.

Diffraction phenomena caused by contaminant particles in the liquid lead to dispersion of sound waves energy. The intersection of this process is determined by the formula

$$\sigma_S(\lambda)=\frac{2\pi}{9}\cdot r^6\cdot k^4, \qquad (12)$$

where k is the wave number; r is the particle radius.

The latest expression reveals that $\sigma_S(\lambda)\sim\frac{1}{\lambda^4}$, so increased frequency makes dispersion intersection greater $(\sigma_S) \sim \nu^4$.

Let us consider the case when the radiation detector is on the axis of the acoustic oscillation beam. Then the detector readings are proportional to

$$I_\lambda^\circ(Z)=I_{\circ,\lambda}e^{-\Sigma(\lambda)}, \qquad (13)$$

where $\sum(\lambda)=n_1\sigma_p(\lambda,R)+n\sigma(\lambda,r)$, where n_1 is gas bubble concentration; n is solid particle concentration; $\sigma_p(\lambda, R)$ is the absorption intersection of ultrasonic waves of the wavelength λ on the air bubble of the radius R; $\sigma(\lambda, r)$ is the full intersection of ultrasonic oscillation attenuation of the wavelength λ on the solid particles of the radius r.

For ultrasonic cleaning, a degassed liquid is used, so we omit the air component.

The average intensity passing through the liquid with suspended contaminant particles will be determined by the expression [17]

$$\left\langle I_\lambda^\circ(Z)\right\rangle=I_{\circ,\lambda}\exp\left\{-V[\bar{n}(1-\eta)]\right\}, \qquad (14)$$

where $\eta=\int_\circ^\infty\exp\left\{-\frac{1}{V}\sigma(\lambda,r)Z\right\}\varphi(r)dr$ is concentration by sizes; $\varphi(r)$ is the function of distributing particles by sizes; $V=\frac{\pi d^2}{4}Z$ – where d is the radiator's diameter; Z is the distance to the body; $\bar{n}$ is the average concentration of solid particles in the liquid.

Then total intensity to be reflected by the body and returned to the detector is

$$\begin{aligned} I(x)&=I_0e^{-V\bar{n}(1-\eta)}e^{-2\alpha x}\left(\frac{\rho_2c_2-\rho_1c_1}{\rho_2c_2+\rho_1c_1}\right)^2e^{-V\bar{n}(1-\eta)}= \\ &=I_0e^{-2\alpha x}\left(\frac{\rho_2c_2-\rho_1c_1}{\rho_2c_2+\rho_1c_1}\right)^2e^{-2V\bar{n}(1-\eta)}= \qquad (15) \\ &=I_0e^{-2\left(\alpha xV\bar{n}(1-\eta)\right)}\left(\frac{\rho_2c_2-\rho_1c_1}{\rho_2c_2+\rho_1c_1}\right)^2. \end{aligned}$$

Consequently, the change in intensity will significantly depend on the contaminant thickness, its concentration in the liquid and size distribution of particles. Losses of intensity when the liquid absorbs the signal are not considered, since they, with the exception of dispersion from contaminant particles, will be constant. As the ratio of environment boundaries changes significantly in the final stage of cleaning, there should be a significant change in the sensor's readings.

The task of this work is to build an evaluation method based on ultrasonic responses to determine two parameters: the degree of the body's cleaning, i. e. how close the process is to the final stage, and the intensity of contaminant detachment in a given area. The second parameter will be the main one when forming the control action, since high intensity of cleaning indicates the necessity to continue the ultrasonic processing for a better result. The first parameter will be used to correct the value of the controlling action and evaluate relative contamination of this area as compared to others.

Results. The k-wave software is used for simulation. The advantage of this product is simulation of large-scale ultrasonic wave propagations in an acceptable time. The following initial conditions are set: location of the radiator and the sensor, the thickness of the site and contaminants (Fig. 2). The cleaned object and contamination are set by density and speed of ultrasonic wave propagation. The density of the section is $\rho = 7800$ kg/m^3 and the distribution rate of the ultrasonic wave c = 5900 m/s, which corresponds to the metal product. The contaminant density is ρ = 3100 kg/m^3 and the distribution rate of the ultrasonic wave is c = 2500 m/s, which corresponds to corrosion. The contaminant thickness during simulation is changed in equal parts.

At the first stage, an ideal case is simulated when the contaminant in the liquid is so small that it can be neglected. Ultrasonic responses obtained during ultrasonic cleaning simulation are transformed by rapid Fourier conversion and the value of the first three harmonics (Table 1) is obtained. In addition, Table 1 provides the time of the threshold value recorded by the sensor.

Consequently, there is a constant, almost linear, increase in the arrival time of the threshold signal (Fig. 3).

The behavior of the main harmonic amplitude corresponds to the analytically predicted one, that is, a sharp increase in case of full cleaning.

There are coefficients calculated according to formulae (1) and (2) to determine the degree of nonlinearity of the signal and their possible application to determining the state of the ultrasonic cleaning process is analysed (Table 2).

During cleaning, we have an increase in the nonlinear component, which is associated with deterioration in mechanical properties, due to irregular density of the body surface. For a clean body, on the contrary, this figure drops sharply. There is an increase in the coefficients of the *2nd* and the *3rd*-order nonlineanity to the maximum value with the minimum contaminant thickness considered with a sharp increase for a fully cleaned body. Consequently, the behaviour of the *2nd* and the *3rd*-order coefficients and the value of the threshold signal arrival time are the basis for developing a method for evaluating the course of the ultrasonic cleaning process, especially for the current cleaning stage.

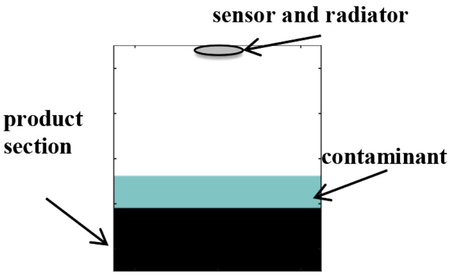

Fig. 2. Location of the sensor, the radiator and the contaminant

Table 1

Values of ultrasonic response parameters during ultrasonic cleaning in the uncontaminated liquid

Contaminant thickness	Signal time	Amplitudes of the first three harmonics (10^{-3})		
60	3101	3.224	2.922	1.965
40	3366	2.946	2.663	1.962
20	3631	2.709	2.419	1.946
0	3886	4.242	4.103	1.8

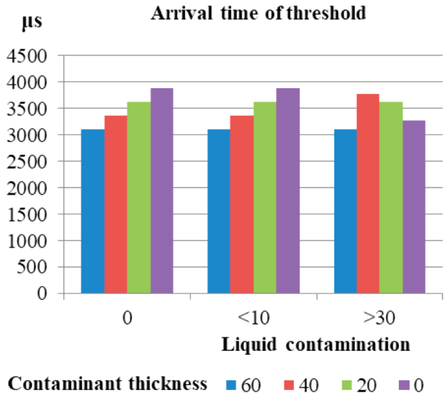

Fig. 3. Changes in the arrival time of the threshold signal depending on the contaminant thickness and liquid contamination

Table 2

Nonlinearity coefficients of the *2ⁿᵈ* and *3ʳᵈ* orders for the uncontamined liquid

Contaminant thickness	$\beta_2 = \frac{A_2}{A_1^2}$	$\beta_3 = \frac{A_3}{A_1^3}$
60	0.281	0.059
40	0.307	0.077
20	0.330	0.098
0	0.228	0.024

To improve evaluation quality, simulation of dispersion and absorption formed by suspended contaminant particles in the liquid is carried out. To do this, the cleaning process is simulated, during which contaminant particles partially settle, and partially remain suspended in the liquid. Liquid contamination is considered low and high. This is due to the fact that when the liquid contamination increases, the parameters of the received ultrasonic responses change significantly.

The degree of liquid contamination will depend on the properties of the liquid and the contaminant: part of the contaminant remaining in the suspended state, the ratio of the amount of contaminants and the liquid.

Available dispersion caused by suspended particles significantly changes the arrival time of the threshold signal, that is no longer directly dependent on the distance to the contaminated body (Tables 3, 5).

With low liquid contamination (< 10 %) during cleaning, there is an unstable decrease in the *2ⁿᵈ* and *3ʳᵈ*-order coefficients with the increase in the value of the main amlitude (Table 4). The arrival time of the threshold value varies slightly compared to the ideal case. The general situation of behaviour of the response parameters is similar to that observed in the clean liquid.

With higher contamination (> 30 %), the situation radically changes in several aspects (Table 6). The *2ⁿᵈ* and *3ʳᵈ*-order nonlinearity coefficients continue to drop, while the main amplitude stops growing which is accompanied by reduction of contamination and the arrival time of the threshold value.

Table 3

Values of ultrasonic response parameters with low contaminant concentration in the liquid

Contaminant thickness	Signal time	Amplitudes of the first three harmonics (10^{-3})		
60	3101	3.224	2.922	1.965
40	3366	3.008	2.35	1.931
20	3634	2.503	2.201	1.804
0	3887	4.19	4.139	1.702

Table 4

Values of nonlinearity coefficients with low contaminant concentration in the liquid

Contaminant thickness	$\beta_2 = \frac{A_2}{A_1^2}$	$\beta_3 = \frac{A_3}{A_1^3}$
60	0.281	0.059
40	0.268	0.071
20	0.351	0.115
0	0.235	0.023

Table 5

Values of ultrasonic response parameters with high contaminant concentration in the liquid

Contaminant thickness	Signal time	Amplitudes of the first three harmonics (10^{-3})		
60	3101	3.224	2.922	1.965
40	3773	2.904	1.198	0.255
20	3630	3.116	2.977	1.898
0	3277	19.179	3.239	0.649

Table 6

Values of nonlinearity coefficients with high contaminant concentration in the liquid

Contaminant thickness	$\beta_2 = \frac{A_2}{A_1^2}$	$\beta_3 = \frac{A_3}{A_1^3}$
60	0.281	0.059
40	0.142	0.01
20	0.307	0.063
0	0.0088	0.0001

With high liquid contamination, the response codes are formed not by reflecting the ultrasound from the cleaned body, but from suspended contaminant particles. At the same time, there is a sharp decrease in the arrival time of the threshold value to the minimum and a sharp jump of the main amplitude by almost an order of magnitude (from 3.116 to 19.179).

With the highest liquid contamination, it becomes impossible to evaluate the state of ultrasonic cleaning. But at the same time, with high liquid contamination, the expediency of cleaning becomes also questionable.

Thus, the behaviour regarding the minimum value of the *2ⁿᵈ*-order nonlineanity coefficient for the cleaned body in case of any contamination of the liquid and the maximum value of the main amplitude (Figs. 4, 5) is stable.

Conclusions. Ultrasonic cleaning for liquids with varying degrees of contamination is simulated to determine the effect of suspended contaminant particles on evaluation of the course of the ultrasonic cleaning process.

The following parameters are observed: the main amplitude and amplitudes of the first and second harmonics, the coefficients of the *2ⁿᵈ* and *3ʳᵈ*-order nonlinearity, the time of the arrival threshold value. For clean liquids, as well as for those with low contamination, there are clear dependences between increasing the signal threshold and reducing contamination. The main amplitude changes less linearly growing and declining in turns, but the greatest value in all testings is characteristic of the pure body. Similar behavior is characteristic of the *2ⁿᵈ* and *3ʳᵈ*

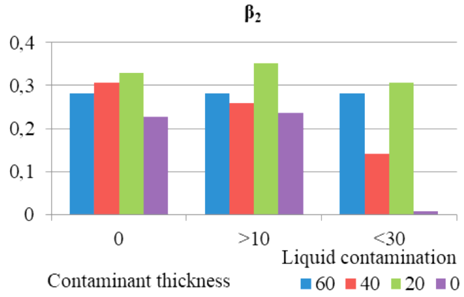

Fig. 4. Changes in the second order nonlinearity coefficient and the main amplitude depending on the contaminant thickness and liquid contamination

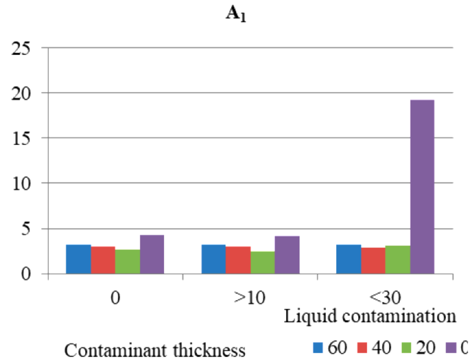

Fig. 5. Changes in the main amplitude depending on the contaminant thickness and liquid contamination

nonlinearity coefficients: they generally have the least value for the cleaned body. With high contamination of the liquid, it is not the state of the body, but that of the liquid that is evaluated, although the behavior of nonlinearity coefficients similar to those described above is also observed when reducing the arrival time of the threshold value and at a sharp increase in the main amplitude (almost by an order of magnitude).

Thus, to form evaluation of the course of ultrasonic cleaning, it is necessary to take into account the following:

1. The necessity to stop the process if there are no changes in the input data and when the amplitude increases and the arrival time of the signal threshold value reduces.
2. The area with the lowest nonlinearity coefficients and the greatest main amplitude is considered the cleanest.
3. Changing the arrival time of the threshold signal is the main indicator of cleaning. The greater it is, the more expedient it is to continue cleaning in a given area. The area with the greatest changes in the coefficients of nonlinearity and the main amplitude requires the greatest cleaning.

Thus, by finding the arrival time of the threshold signal, the values of the main harmonica and the *2nd* nonlinearity coefficient, it is possible to form evaluation of ultrasonic cleaning for further formation of a spatially distributed controlling action.

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Оцінка перебігу процесу ультразвукового очищення

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Мета. Виявити залежність між інтенсивністю перебігу стану ультразвукового очищення та ультразвуковим відгуком, що буде зафіксований датчиком у заданій позиції. Встановити вплив забрудненості рідини на цей сигнал. Виявити параметри ультразвукового сигналу, за якими можна оцінити перебіг процесу очищення заданої ділянки тіла. Виявити граничні значення, що вказують на доцільність зупинення процесу очищення.

Методика. Дослідження за допомогою засобу симуляції розповсюдження ультразвукових хвиль у гетерогенному просторі з наступним аналізом сигналів за допомогою комп'ютерних програм.

Результати. Виявлені залежності, що дозволяють за параметрами ультразвукового відгуку сформувати оцінку перебігу процесу очищення. Встановлено, що на ультразвукових відгук, отриманий датчиком у заданій точці при ультразвуковому очищенні, впливає як стан тіла, так і стан рідини. При високій забрудненості (>30 %) стан рідини стає вирішальним фактором, що формує сигнал ультразвукового відгуку. При цьому спостерігається різке скорочення часу надходження порогового сигналу та збільшення головної амплітуди, що має бути одним із маркерів переривання процесу очищення, як неефективного. За нижчої забрудненості зважені частинки забруднення лише дещо корегують сигнал, не спотворюючи його. Простежується залежність між зменшенням забруднення, часом надходження порогового значення сигналу та значенням основної амплітуди й коефіцієнтів нелінійності 2-го та 3-го порядку. Основним параметром, що визначає інтенсивність очищення, тобто зменшення товщини забрудненості, є час надходження порогового значення сигналу. А товщина наявного забруднення визначається за значенням основної амплітуди сигналу та коефіцієнтів нелінійності 2-го та 3-го порядку.

Наукова новизна. Уперше розроблена методика оцінювання перебігу процесу ультразвукового очищення шляхом аналізу ультразвукових відгуків у заданій точці.

Практична значимість. Для врахування просторової розподіленості процесу ультразвукового очищення керування ним має формуватися на основі оцінки стану забрудненості тіла в декількох заданих точках. Для практичної реалізації цього був встановлений характер залежностей між зміною забрудненості ділянки тіла та параметрами зафіксованого ультразвукового відгуку. Враховано вплив зважених частинок забруднення в рідині на сигнал, що аналізується. Відстеженні залежності стануть основою для побудови просторово розподіленого управління процесом ультразвукового очищення з урахуванням стану очищувального тіла.

Ключові слова: *ультразвукове очищення, забруднення рідини, нелінійні коефіцієнти, моделювання*

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