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SPATIAL CONTROL OVER ULTRASONIC CLEANING OF MINING EQUIPMENT USING A PHASED ARRAY TECHNOLOGY

Purpose. To develop methods for spatial control over ultrasonic cleaning by using ultrasonic phased array of radiators. To simulate the cleaning process using the developed methods to prove their effectiveness.

Methodology. Application of the ultrasonic array as a basic radiator for ultrasonic cleaning enables redistribution of intensity in the bath by increasing it in the most contaminated zones of the cleaned object. Geometric and physical laws provide analytically defined parameters of the beam.

Findings. The authors determine basic parameters for the ultrasonic beam through considering input and output data of the 3-D fuzzy interval controller. The focus distance is calculated by means of the arrival time of the threshold signal considering distances between the sensor and the array. The azimuth is directed into the bath center and dependent on its height only. The zenithal angle is calculated as a ratio of intensities of the current arrays and the nearest adjacent ones towards the greatest one. By default, the beam is directed to the bath center for the phased array with the greatest intensity. The simulation reveals that the applied approach enables a 41.5 % increase in intensity in the contamination zone, this improving energy efficiency of cleaning and reducing time required for ultrasonic treatment.

Originality. The authors suggest new methods for forming control over ultrasonic cleaning, which enables considering spatial distribution of this process by optimizing energy losses.

Practical value. The new approach to spatial control over ultrasonic cleaning enables redirecting intensity in the bath to the most contaminated zones, this allowing an increase in energy efficiency of large mining machines of complicated configuration.

Keywords: *mining equipment, ultrasonic cleaning, ultrasonic phased array transducer, simulation, automated control*

Introduction. The mining industry is noted for increased contamination of technological processes. This negatively affects not only employers' health, but also equipment operation. Timely high-quality cleaning of such structural elements as parts of mining transport engines, reusable filters, pumps, brakes, and others not only enables scheduled repairs, but also increases their operation period and reduces downtime. There are various methods of industrial cleaning applied depending on requirements set. Among them one can mention chemical cleaning, the disadvantage of which is application of hazardous solvents. There are also mechanical and manual types of cleaning characterized by hard human labour. Unlike them, ultrasonic cleaning is devoid of these drawbacks and reveals high quality, being one of the most promising types of cleaning.

The number of areas of its application is constantly growing. Now this type of cleaning is used from the aerospace industry to jewelry. New areas of application of ultrasonic cleaning and research on existing ones are also constantly offered. In [1] the technique of development and marinating of radiators for ultrasonic cleaning of pipelines at considerable depth is investigated. In [2] the ultrasonic cleaning of the ceramic membrane used for sewage treatment is considered. The use of this type of cleaning is also expanding in the medical field, for which the use of ultrasound in general has become revolutionary. Dental implantation requires an increased level of cleanliness, which is best provided by ultrasound [3]. Ultrasound is also the optimal choice for titanium purification [4].

Ultrasonic cleaning can be also effectively used for cleaning dust, soot, coal, coke, mineral and metal particles, thus possessing high competitiveness in mining in particular. Yet, large sizes of cleaning machines and their complex configuration require high capacity and great power costs, this fact making increased efficiency of ultrasonic cleaning one of the ways to cut down total production expenses.

Literature review. There are various research studies into ways of improving energy efficiency of the ultrasonic cleaning process. On the one hand, it is the study on physical and chemical processes that occur and condition this particular cleaning type [5, 6]. This approach makes it clear that ultrasonic cleaning is a rather complex spatially distributed process with a large number of interconnected factors and their optimization makes it possible to improve quality and energy efficiency of the whole process [7, 8]. Such factors include the frequency of ultrasound, the geometric features of the bath and the location of the emitters, the temperature and composition of the liquid, the intensity of the radiation, and so on [9].

Ultrasonic cleaning can also be improved through introducing the latest developments of this process being automatized.

Three driving effects formed under the action of ultrasonic treatment of liquid – cavitation, acoustic currents and radiation pressure – constitute the basis of ultrasonic cleaning. All these effects are spatially distributed and depend on the location of radiators. In [10], efficiency of ultrasonic cleaning is improved by selecting appropriate sizes of the ultrasonic bath and introducing additional liquid circulation due to which sound streams are redirected. Yet, all this is simulated for a

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particular ultrasonic bath by selecting the most efficient parameters without concluding a general dependence.

Most modern ultrasonic baths have only indicators of processing time and intensity of ultrasonic radiation as control parameters. More advanced approaches are suggested in [11] in which the ultrasonic cleaning process is controlled by using indicators of illumination and conductivity of the cleaning liquid. This enables forming duration of the cleaning process by considering its real efficiency taking into account indirect evaluation of the liquid's condition and neglecting that of the cleaned body. This approach can lead to the entire object being cleaned, while contaminants will be concentrated in a certain area, all this causing overconsumption of power. In the case of cleaning products to large size complex configuration, which is typical for the equipment mining industry is inappropriate. To avoid this, ultrasonic cleaning should be evaluated separately in various positions by analysing ultrasonic responses in preset points after each performance cycle of radiators.

Efficient control of complex spatially distributed systems requires new methods that take into account their distribution [12, 13]. In order to form effective control, besides spatial evaluation, a distributed controlling action is required. To form the control taking into account spatial distribution of the ultrasonic cleaning process based on evaluating the current state of the cleaned body, a 3-D fuzzy interval controller [14] is proposed which is an expanded 3-D fuzzy controller [13] when there is no clear evaluation for the membership function. Evaluation of the object's condition is based on analysing ultrasonic responses from several sensors located in preset positions similar to those in [15]. The controller's performance results in calculated values of intensity for each of the basic radiators on the basis of spatial fuzzy logic. At the same time, the interval three-dimensional membership function is used to take into account spatial distribution of sensors' indicators on the final intensity value for the radiator in a given position. This approach allows more intensive treatment of the areas contaminated according to the data from measuring devices. Yet, there are no shifts of acoustic streams and cavitation towards the greatest contamination.

According to [16], the use of an additional low-amplitude radiator allows improving efficiency of ultrasonic cavitation due to cavitation clusters collapsing in remote areas. Therefore, to increase efficiency of control over the cleaning process, it is suggested not to limit spatial control only to the intensity value of radiators, but add another angle at which radiation will occur. Changing the angle and, accordingly, the focal points of the ultrasonic beam is based on the use of ultrasonic phased array technology, which is widely used in modern industry and medicine [17, 18]. This enables redistribution of intensity values to evaluate the course of ultrasonic cleaning and redirect this intensity at the most contaminated areas as well as changing the direction of acoustic streams. The performance of the 3-D fuzzy interval controller changes only at the final stage by directing inclination angles towards greater intensity.

Unsolved aspects of the problem. According to the analysis of the available research, the urgency of increase in efficiency of ultrasonic cleaning is revealed. One approach is to improve the quality of process management. The method for estimating the course of ultrasonic cleaning has already been described [19] and the efficiency of using the algorithm for determining the intensity for each emitter depending on its distance from contamination by simulation has been proved [20]. But this approach did not take into account the possibility of ultrasonic developments to focus the beam in a given area. The use of ultrasonic phased array technology makes it possible to redirect the intensity of ultrasonic radiation to the area with the greatest pollution, thus reducing energy consumption and cleaning time. There is no technique that determines the parameters of the beam during ultrasonic cleaning, so the task of this study was its development.

Purpose. To increase the energy efficiency of treatment, it is necessary to form a control action with maximizing the impact in the areas of greatest pollution. The determination of such zones takes place according to the analysis of ultrasonic responses described in [19], the algorithm for determining the intensities for each emitter is described in [14], the efficiency of the algorithm is confirmed by modulation in [20]. But the use of conventional ultrasonic transducers limits the process control, so in this paper we propose the use of ultrasonic phased arrays of transducers, which allows redirecting power in the desired direction. The time delay for each transducer is calculated according to certain values of the distance to the focus and the azimuth and zenith angles, which are from the geometric dependences in the bath and the analysis of ultrasonic responses. Modelling of cleaning using the above technique proves its effectiveness in the possibility of increasing the intensity of ultrasound in the most contaminated areas.

Methods. There is a set model of ultrasonic cleaning having p ultrasonic sensors and m emitters. Cleaning is controlled by using a 3-D fuzzy interval controller of type 2 [14]. The change in the arrival time of the signal threshold value and that in the 2nd-order nonlinearity coefficient are used as input parameters. The input parameters are obtained in P spatial positions Z_1, $Z_2, \ldots, Z_p$. According to the algorithm described in [19, 20], the input data is phased, reduced in space, reduced in size, fuzzy inference is formed and defasified. As a result of the controller, we obtain the value of the "intensity" of cleaning for each position of the emitters. Assuming that cleaning is unidirectional and its intensity is dependent upon the need to continue ultrasonic treatment in this area, the input indicator is used as the intensification coefficient of the radiator in a set area. Yet, this constrains formation of the ultrasonic action on the required area and does not allow redirection of acoustic streams.

To improve formation of control over ultrasonic cleaning, input parameters include not only intensity values but also those of the ultrasonic beam angle. Thus, cleaning is performed by means of m ultrasonic phase arrays of transducers located in set positions and preset by intensity coefficients $u(z) = (u(z_1), u(z_2), \ldots, u(z_m))$ and according to these coefficients of the ultrasonic beam inclination $\alpha(z) = (\alpha(z_1), \alpha(z_2), \ldots, \alpha(z_m))$. P and m are mutually independent.

Fig. 1 depicts an ultrasonic bath with spatially distributed control using ultrasonic arrays as radiators.

To perform the set task, it is necessary to calculate the distance to the focal point and the inclination angle of the ultrasonic beam in the direction of the fixed higher "intensity" of cleaning (Fig. 2).

The distance to the focal point is determined by the arrival time of the signal threshold value to two adjacent sensors (Fig. 3).

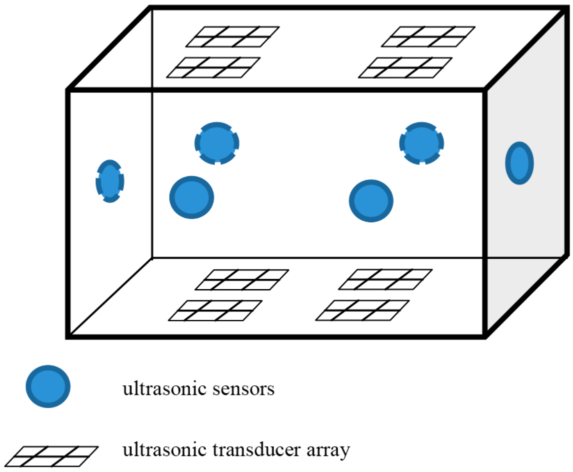

Fig. 1. Schematic representation of the ultrasonic bath

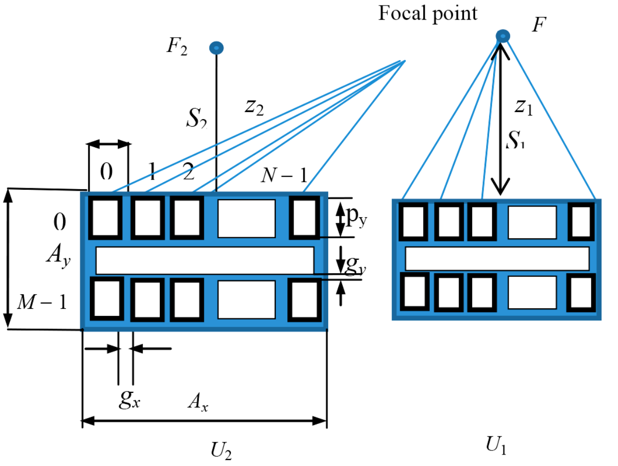

Fig. 2. Schematic representation of two interacting phased arrays

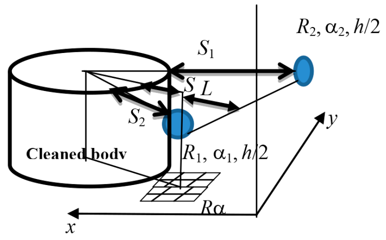

Fig. 3. Schematic representation of calculating parameters of the ultrasonic beam

$$S_1 = \frac{ct_1}{2};$$

$$S_2 = \frac{ct_2}{2};$$

$$L = \frac{|aR\cos\alpha + R\sin\alpha + d|}{\sqrt{a^2+1}},$$

where c is the distribution velocity of the ultrasound in the liquid; t_1 and t_2 are the arrival time of the signal threshold value to two adjacent sensors; R and α are polar coordinates of the radiator,

$$a = -\frac{R_2\sin a_2 - R_1\sin a_1}{R_2\cos a_2 - R_1\cos a_1};$$

$$d = -R_1\sin a_1 + aR_1\cos a_1,$$

where R_1, α_1, R_2, α_2 are polar coordinates of the sensors adjacent to the radiator.

In this case, the distance from the projection of the radiator into the sensors plane to the body is calculated as follows

$$S = \frac{R_2|\alpha_1 - \alpha| + R_1|\alpha_2 - \alpha|}{|\alpha_1 + \alpha_2|} - L.$$

This distance in the plane of the sensors will be the focal one to be found.

The beam angle is determined by the intensity of the adjacent sensors in the direction of the highest intensity value. Yet, in any case, the inclination angle of the formed beam should not exceed 45°, as this will cause the appearance of lateral petals and deteriorated control efficiency [21]. Therefore, we assume that the control angle is within 0–45° and changes in proportion to the ratio of intensity coefficients

$$\varphi = 45^\circ \cdot \frac{u(z_1)}{u(z_2)},$$

where $u(z_1) < u(z_2)$. For the phased array with the largest intensity $\varphi = 0$.

The direction in the azimuth plane is determined so that the beam is directed at the half-value of the height of the ultrasonic bath (Fig. 4).

The value of the focal distance is determined as

$$R = \sqrt{S^2 + \frac{h^2}{4}}.$$

The value of the azymuth angle is determined as

$$\theta = \text{atn}\left(\frac{2S}{h}\right).$$

By the described parameters of the ultrasonic beam, we determine the delay time for each element of the ultrasonic array. The represenation of the coordinate system is shown in Fig. 4. For a transducer located in the position $x = (x_n, y_m)$ for the angular beam from the point F we have the following time difference [21]

$$\Delta\tau_{nm}(x, F) = (|F - x_0| - |F - x|)/c,$$

where x_0 is the coordinate of the massif center, i. e. it is the centre of the ultrasonic phased array that is the beginning of the coordinates. In the spherical coordinates of the focal point which are calculated above we have

$$F = (F_1, F_2, F_3) = (R\sin\theta\cos\varphi,\ R\sin\theta\sin\varphi,\ R\cos\varphi).$$

The time difference makes

$$\Delta\tau_{nm}(x, F) = \frac{R\left[1 - \sqrt{\begin{pmatrix} (\sin\theta\cos\varphi - x_n/R)^2 + \\ + (\sin\theta\sin\varphi - y_m/R)^2 + \cos^2\theta \end{pmatrix}}\right]}{c}.$$

If we limit the influence only by the direction without taking into account the distance to the body R, we get a simplified value for the time delay law

$$\Delta\tau_{nm}(x,\theta,\varphi) = \Delta\tau_n(x,\theta,\varphi) + \Delta\tau_n(x,\theta,\varphi) =$$

$$= \frac{x_n\sin\theta\cos\varphi}{c} + \frac{y_m\sin\theta\sin\varphi}{c}.$$

Thus, all the parameters are determined to form a directed impact on the area requiring it. This will enable redirection of acoustic streams to the required areas and intensity increase in ultrasonic radiation in a given direction. This will result in optimization of energy efficiency and quality of ultrasonic cleaning.

Results. To confirm efficiency of the developed approach to controlling the ultrasonic cleaning process using a phased array guided by the developed algorithm, this process is simulated by using *k*-wave [22]. The location of radiators, sensors, and the contaminated body is preset (Fig. 5). The cleaned object and contamination are set by the density and velocity of ultrasonic wave propagation. The body density is ρ = 7,800 kg/m^3, the velocity of ultrasonic wave propagation is c = 5,900 m/s, which corresponds to the metal product. The contamination is set by the density ρ = 3,100 kg/m^3 and the velocity of ultrasonic wave propagation s = 2,500 m/s, which corresponds to corrosion.

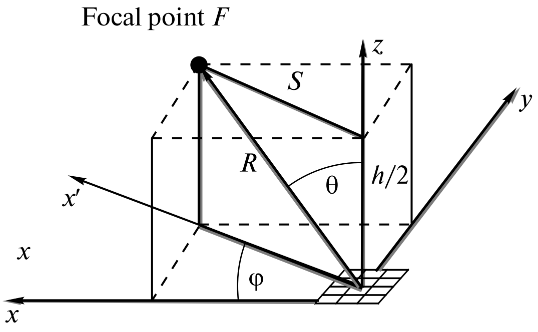

Fig. 4. Parameters of the ultrasonic beam

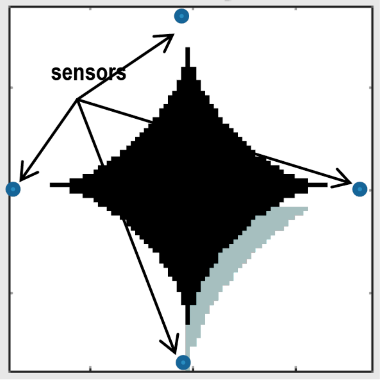

Fig. 5. Initial conditions of the experiment

The density of the surrounding liquid is $\rho = 1{,}000$ kg/m^3 and the ultrasonic wave propagation velocity is $c = 1{,}500$ m/s, which corresponds to water.

Control efficiency is evaluated by fixing the total of the maximum pressure in the contaminated area and finding its relation to the total pressure produced by radiators.

First, the ultrasonic cleaning process is simulated through directing all the ultrasonic beams into the centre of the bath (Fig. 6). After that, the resulting field is calculated, which is the total for all the beams (Fig. 7).

Simulation is performed in two stages, since the first cycle of the treatment forms the basis for assessing the course of the ultrasonic cleaning process, in any case, at the first stage, all the radiators operate at full capacity. At the second stage for this case, the cleaning is performed in the direction of the centre of the bath with maximum capacity. The obtained values of the total maximum capacity in the contaminated area amount to 42.78 Pa for each stage, while power consumption is $4 \cdot 10^6$ Pa for each stage. As can be seen from Fig. 7, the maximum power concentration is observed in the centre of the ultrasonic bath.

The ratio of the total maximum pressure in the contaminated field to the total power consumption is taken as the relative efficiency factor. In case of no contamination control, this factor makes $42.78/(4 \cdot 10^6) = 0.106 \cdot 10^{-4}$ per unit.

To transfer capacity to the contaminated area and reduce power consumption in cleaned sections, the algorithm with the 3-D fuzzy interval controller is applied to calculating intensities for each radiator.

The algorithm described above enables calculating angles for beam redirection. At the first stage, all radiators operate without constraints. After that, the maximum capacity in the contaminated area is analysed and where it exceeds the specified value, cleaning occurs.

Before the second stage of ultrasonic cleaning, the course of the process is evaluated by the difference in the return time of the threshold signal and the *2nd*-order nonlinearity coefficient. These values in the normalized form are processed according to the algorithm of the 3-D fuzzy interval controller and the values for intensities are obtained in the normalized form making $u = [0.0093\ 0\ 0.9854\ 1]$. According to the described algorithm of calculation, redirection makes 44.3429° for angle 3 of the ultrasonic phased array. The body with these parameters is processed again and Fig. 8 shows the corresponding beam direction.

The total distribution of the maximum capacity looks like it is shown in Fig. 9. Therefore, it should be noted that the maxi-

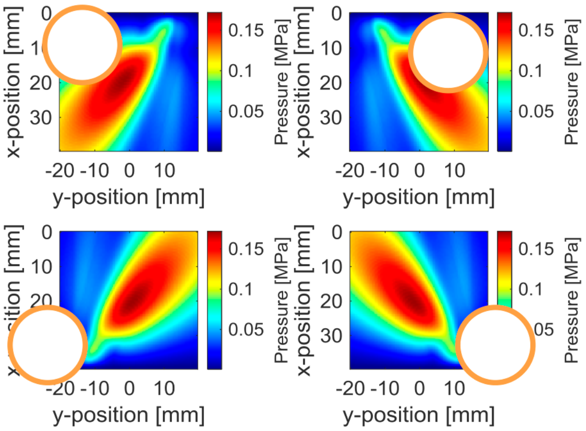

Fig. 6. Directing ultrasonic beams in the bath

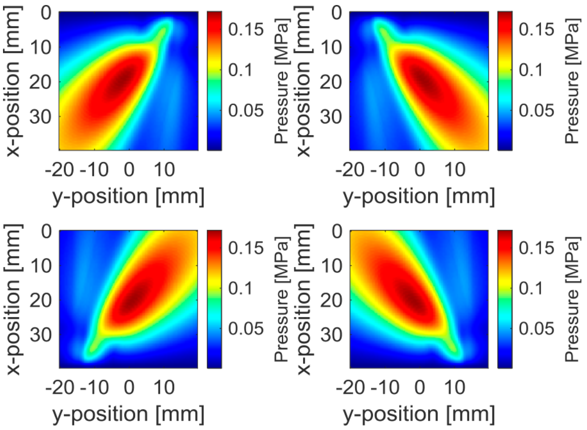

Fig. 8. Directing ultrasonic beams in the bath at the second stage

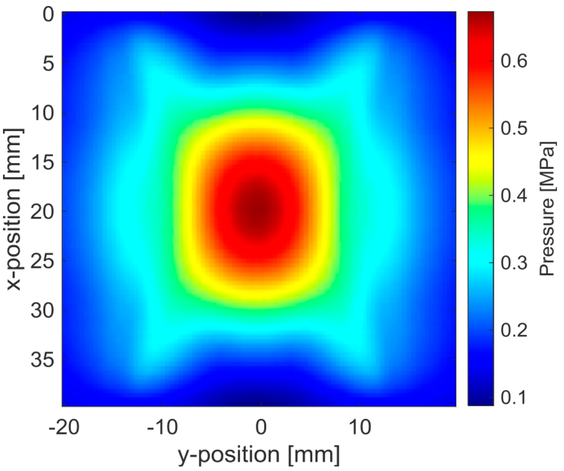

Fig. 7. Total distribution of the pressure field in the bath

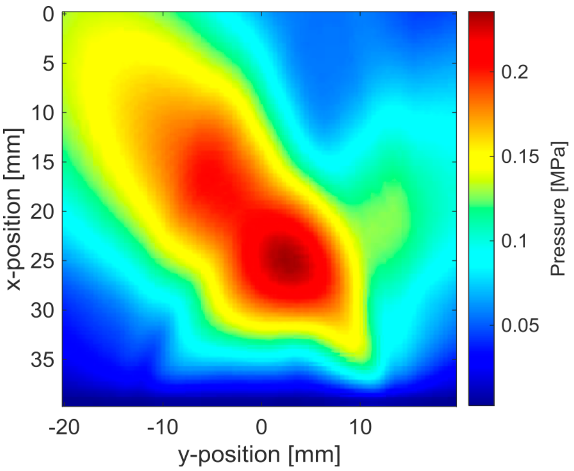

Fig. 9. Total distribution of the pressure field in the bath

mum pressure field takes into account only the direction of the beams without reflection from the body, as this makes the calculation task rather time-consuming. So, when obtaining the resulting field, there is reduction to 0 of the square power located opposite the radiator. After that, the total capacity in the contaminated area is found, which amounts to 29.84. The relative efficiency factor makes $29.84/(1.9947 \cdot 10^6) = 0.15 \cdot 10^{-4}$. Consequently, power concentration in the contaminated area is improved relative to total power consumption. The increase makes $(0.15 \cdot 10^{-4} - 0.106 \cdot 10^{-4})/0.106 \cdot 10^{-4} = 41.5\ \%$.

After that, simulation is carried out taking into account not only the direction angle, but also changes in the focal distance. Prior to this, for all the radiators, the focal distance is accepted to be 8 mm. According to the algorithm described above, simulation is carried out with a change in the focal distance for each radiator depending on the arrival time of the threshold signal. At the same time, the maximum capacity in the contaminated area does not change significantly.

Thus, to increase efficiency of ultrasonic cleaning, it is advisable to use ultrasonic phased arrays and form the control using the beam directional angles calculated according to the described algorithm.

Conclusions. The complex configuration and variety of forms of equipment in the mining industry for energy-efficient ultrasonic cleaning require optimized management of this process. To increase energy efficiency of ultrasonic cleaning, it is necessary to form the control of the highest intensity in the most contaminated areas. To determine such areas, ultrasonic responses are analysed by changes of two parameters – the arrival time of the threshold signal and the *2nd*-order nonlinearity coefficient. The data are used as input ones to determine the intensity of each radiator using a 3-D fuzzy interval controller. However, the control limited by intensity values only does not enable redirection of power distribution to maximize efficiency. Therefore, this research suggests a new approach based on the ultrasonic phased array technology. The intensities obtained at each stage allow calculating the angle for the ultrasonic beam, which is proportionate to their ratio towards the largest intensity. The conducted simulation of cleaning by using the ultrasonic phased array technology reveals a 41.5 % increase in power concentration, which will reduce the time for ultrasonic treatment of equipment and reduce energy consumption.

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Просторове керування ультразвуковим очищенням гірничого обладнання за допомогою технології фазованої решітки

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Мета. Розробка методики формування просторового керування процесом ультразвукового очищення з використанням ультразвукового фазованого масиву випромінювачів. Моделювання процесу очищення на основі розробленої методики для доведення її ефективності.

Методика. Використання ультразвукового масиву в якості основного випромінювача при ультразвуковому очищенні дає змогу перерозподілити потужність у ванні, збільшивши її в зонах найбільшого забруднення очищувального об'єкта. Аналітичне визначення параметрів променю проведене на основі геометричних і фізичних законів.

Результати. Були визначені основні параметри для ультразвукового променю на основі вхідних і вихідних даних 3-D нечіткого інтервального контролера. Фокусна відстань була визначена за часом надходження граничного сигналу з урахуванням відстаней між датчикам і масивом. Азимутний кут спрямовано до центру ванни та залежить лише від її висоти. Значення зенітного кута розраховано як співвідношення інтенсивності поточного масиву й найближчих сусідніх у напрямку найбільшої. За замовчуванням та для фазованої решітки з максимальною інтенсивністю промінь спрямовано до центру ванни. Проведене моделювання довело, що подібний підхід дозволяє збільшити концентрацію потужності в зоні забруднення на 41,5 %, що призводить до підвищення енергоефективності очищення та зниження часу обробки тіла ультразвуком.

Наукова новизна. Розроблена нова методика формування керуючого впливу при ультразвуковому очищенні, що дозволяє врахувати просторову розподіленість цього процесу, оптимізувавши витрати енергії.

Практична значимість. Новий підхід до просторового керування при ультразвуковому очищенні дозволяє переспрямувати потужність у ванні до зони з найбільшим забрудненням, що призводить до підвищення енергоефективності очищення великогабаритного гірничого устаткування зі складною конфігурацією.

Ключові слова: *гірниче обладнання, ультразвукове очищення, ультразвуковий фазований масив, моделювання, автоматичне керування*

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