Research of the influence of acoustic load on a piezoelectric emitter to control the cavitation erosion of materials

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Abstract. The paper analyzes the possibilities of research the cavitation erosion of materials that are subjected to cavitation effect. The study is carried out by a system for controlling the magnitude of the acoustic load on the piezoelectric emitter of the ultrasonic vibrating system. The analysis of the processes of interaction between the ultrasonic emitter and the processed environment was carried out on the basis of a research of the model, which was created on the basis of a system of electromechanical analogies. The analysis made it possible to reveal the dependence of the electrical impedance of the ultrasonic vibrating system on the magnitude of the acoustic load. The revealed dependencies made it possible to propose and develop a control system. It is able to provide a study of the properties that are located near the emitting surface of the ultrasonic emitter of materials influenced to cavitation ultrasonic, including under abnormal conditions (high temperatures and pressures).

1. Introduction
The implementation of ultrasonic effect on different technological processes in environment with a liquid phase requires control of the effectiveness of the action (the degree of development of cavitation) and changes in the properties of the processed environment or materials (coatings) in the affected zone. This is necessary to create a cavitation process that changes the structure, properties and dimensions of materials. Direct measurement is impossible in cases of ultrasonic processing of technological environment at high temperatures (up to 1000 degrees Celsius) and pressures, as well as in the implementation of processes in environments that are aggressive or hazardous to humans.

In this regard, it becomes necessary to create an indirect control system based on measurements of ultrasonic parameters of piezoelectric vibrating systems (emitters). These systems are placed during research, in whole or in part, under abnormal conditions (in terms of temperatures, pressures, composition and degree of danger) in hermetically sealed technological volumes. They carry out the transformation of electrical vibrations into mechanical ones, the formation of mechanical vibrations of the ultrasonic frequency, vibrations’ amplification and injection into the processed technological environment [1].

The possibility of practical implementation of such control is due to the availability of information about the influence of the parameters and properties of the processed environment on the electrical characteristics of the piezoelectric transducer of the ultrasonic vibrating system [2].

Unfortunately, the regularities of such an effect under various conditions (especially under abnormal conditions of cavitation effect) have not been identified previously. And regularities’ absence did not
allow proposing and developing a method for indirect monitoring of the state of environment that are affected to cavitation.

Therefore, it becomes necessary to identify the features and regularities of the influence of cavitating environment and materials in the environment under abnormal conditions on changes in the electrical characteristics of piezoelectric transducers. Only the knowledge of such regularities will make it possible to determine the possibilities and effectiveness of an indirect method of controlling the properties of the processed environment, materials and coatings.

The identification of such dependencies is possible on the basis of research the model of processes (primarily cavitation) that occur at the "ultrasonic emitter - liquid" interface and affect the changes in the properties of materials and coatings in a cavitating liquid [3-7].

To construct the model, the well-known system of electromechanical analogies was used, which makes it possible to research the effect of acoustic load on the electrical characteristics of piezoelectric transducers of the ultrasonic vibrating systems. The system of electromechanical analogies makes it possible to represent in the form of an equivalent electrical circuit the processes occurring during the mechanical vibrations of the components of the ultrasonic vibrating system in the environment. And this system also allows one to research the reverse effect of environment on the piezoelectric transducer through the elements of the ultrasonic vibrating system due to the coincidence of the mathematical descriptions of the elements of the environment and the ultrasonic vibrating system. Based on the analysis of the ultrasonic vibrating system model, it is possible to research cavitation processes in the region near the emitting surface without directly measuring the properties of the environment during ultrasonic influence in abnormal conditions. This is possible when taking into account changes in the acoustic parameters and properties of the treated environment and the design features of the waveguide.

2. Main body

Ultrasonic vibrating systems (ultrasonic emitters) contain many different components, the main of which are: a piezoelectric transducer, waveguide structures (boosters), concentrating waveguides (amplitude amplifiers), working tools (endings), attachment points, etc.

Consider an ultrasonic vibrating system consisting of a piezoelectric transducer and a concentrating waveguide (figure 1).

Element 1 is a half-wave piezoelectric transducer, where piezoceramic elements are used as transducer. Element 2 is a stepped half-wave concentrator, which, on the one side, is connected to the transducer, and on the other side, contacts the environment being processed 3 through the working end (or a special tool).

Based on the theory of electromechanical analogies, the considered vibrating system (which forms and emits ultrasonic vibrations) can be represented in the form of an equivalent electrical circuit shown in figure 2.

Such an equivalent electrical circuit with lumped parameters using the first system of electromechanical analogues proposed by Rayleigh describes a cylindrical half-wave waveguide (piezoelectric transducer) and a waveguide of variable cross-section (concentrator).
The physical equivalent circuit is a six-pole and it has one pair of electrical clamps (contacts) and two pairs of mechanical clamps. An “ideal” electromechanical transformer (converter) is used to connect electrical and mechanical circuits.

The problem of the different nature of the parameters of the circuit elements is solved by the transition from a "mixed" equivalent circuit to a homogeneous equivalent circuit. One part of the "mixed" circuit is characterized by electrical parameters (voltages, resistances, etc.), and the second part is characterized by mechanical parameters (mechanical forces, vibration speeds, etc.) Such a transition allows considering all components of the equivalent circuit as elements with active and reactive resistances regardless of their physical nature.

Elements $L_3$ and $L_4$ are reactive elements and participate in the description of the concentrating waveguide model. The values of the inductance of these elements characterize each of the steps of the rod stepped concentrator and represent their inertial properties. Element $C_2$ is determined taking into account the values of elements $L_3$ and $L_4$, the resonant frequency of the waveguide (chosen for calculations equal to 20 kHz), and it represent the elastic properties of the material from which the concentrator is made. When the elements $L_3$ and $L_4$ are equal, the work of a cylindrical waveguide is simulated. Waveguide has a transformation ratio equal to 1. With different elements $L_3$ and $L_4$ (when $L_3 > L_4$) it is possible to set the transformation ratio in a certain range. Thus, the operation of a stepped half-wave waveguide (concentrator) is simulated.

Elements $L_1$ and $L_2$ match to reflective and emitting quarter-wave pads that are in contact with piezoelectric elements in the equivalent circuit of the transducer. The values of these elements are determined by the geometry and material of the transducer. Element $C_1$ defines the elastic properties of the transducer material. The converter circuit also includes an electromechanical transformer $T_1$ and an element $C_0$ matching to the static capacitance of the piezoelectric elements.

Element $R_1$ characterizes the effect of air on the reflective pad of the transducer. Element $R_3$ characterizes the wave acoustic resistance (impedance) of the processed environment.

Let us further consider the influence of the active load resistance $R_3$ on the parameters and characteristics of the ultrasonic vibrating system (emitter) from the side of its electrical input.

An ultrasonic emitter must always work at its resonant frequency during the implementation of any technological process. Then the dependences characterizing the effect of the magnitude of the active acoustic load on the resonant frequency of the ultrasonic vibrating system. Figure 3 shows curves illustrating this effect, obtained for various transformation ratios $K$ of the concentrating waveguide (concentrator).

Ratio $K$ characterizes the amplification factor of the concentrating link (concentrator), providing an increase in the amplitude of mechanical vibrations of the working end. The intensity of ultrasonic influence on the processed environment depends on it.

The resonant frequency of the ultrasonic vibrating system was determined at the point where the reactive component of the input impedance of the ultrasonic emitter was equal to zero. For $K = 1$, no change in the resonance frequency is observed, for $K = 3$, an increase in the resonance frequency is observed with an increase in the value of the acoustic load. For $K = 5$ and more, the nature of the dependences changes. This is due to the fact that for $K = 5$ and more, the reactive component of the input resistance of the ultrasonic vibrating system is always present. The criterion of its minimum value was used to determine the resonant frequency of the electrical model of the ultrasonic vibrating system.

Figure 4 shows the dependence of the input impedance of the ultrasonic vibrating system on the magnitude of the acoustic load. It obtained when the ultrasonic vibrating system is working at its own resonant frequency.

The presented curves illustrate the presence of the dependence of the input impedance on the magnitude of the acoustic load. For $K = 1$, this dependence is close to linear, but the coupling coefficient between $Z$ and $R_L$ is minimal. An increase in the transformation ratio of the concentrator ($K = 3$) leads to an amplification in the relationship between the magnitude of the acoustic load and the input impedance of the ultrasonic vibrating system, but the nature of this dependence changes. For $K > 3$, the curves are distorted due to the reasons described above.
Figure 3. Changes in the resonant frequency of the ultrasonic vibrating system when changing the load $R_L$.

Figure 4. Influence of load $R_L$ on impedance.

Similar dependences on the load were separately analyzed for the real and imaginary parts of the impedance of the ultrasonic vibrating system because the impedance of the ultrasonic emitter is complex (figures 5, 6).

Figure 5. Influence of the load $R_L$ on the real part of the impedance $Z$.

Figure 6. Influence of the load $R_L$ on the imaginary part of the impedance $Z$.

From the presented dependences it can be seen that for $K < 3$ there is no reactance at the input resistance $Z$ in the considered load range and, therefore, $Z = R$.

The dependences presented in figures 4, 5, 6 were obtained when the imitation of the working of the ultrasonic emitter at the resonant frequency happened. It changes every time when $R_L$ changes. It is in this mode that all ultrasonic devices operate in which a phase-locked loop (PLL) system operates. Therefore, measurements will be carried out each time at a frequency matching to a certain value of the acoustic load $R_L$, which differs from the frequency of an unloaded ultrasonic emitter. This can introduce errors into the obtained results of the implemented control and must be eliminated. All changes should be made at the same frequency.

Figures 7, 8, 9 show the dependences of the impedance $Z$ (as well as its real and imaginary components) obtained for a frequency of 20 kHz. All reactive elements of the equivalent circuit were originally calculated (natural frequency of an unloaded ultrasonic vibrating system) for this frequency.

From the presented dependences it follows that at same measurement frequency (in this case 20 kHz) there is always reactivity at the input impedance of the ultrasonic vibrating system (for any $K$ and the entire range of acoustic loads). The $Z$ curves have no distortions, as was found in the first case (figure 4). An increase in $K$ leads to an amplification in the dependence of the impedance $Z$ on $R_L$ for the considered range of acoustic loads. However, for large $K$ (not really used in practice), «saturation» is observed.
Figures 7 and 8. Dependence of impedance on load $R_L$ for a frequency of 20 kHz.

Analyzing the dependences obtained taking into account the shift of the resonant frequency of the ultrasonic vibrating system (case 1) with similar dependences obtained at a fixed frequency (the frequency of the unloaded ultrasonic vibrating system) in the region of the resonant frequency of the ultrasonic vibrating system (case 2), it was possible to reveal the following features:

- dependences of $Z$ on $R_L$ for the second case have a monotonically increasing character, predictable for all values of $K$;
- dependences of $\text{Re}$ on $R_L$ for the second case have a monotonically increasing character, predictable for $K$ up to $K = 5$, instead of $K = 3$ for the first case;
- dependences of $\text{Im}$ on $R_L$ for the second case have a monotonically decreasing character, predictable for all values of $K$.

Additionally, the dependences of the quality factor of the ultrasonic emitter on the magnitude of the acoustic load were investigated in order to identify the possibility of monitoring changes in the acoustic properties of the treated environment. Figure 10 shows the dependences of the quality factor of the ultrasonic emitter (obtained from the amplitude-frequency characteristics of the current consumed by the ultrasonic emitter) from the voltage source.

Figures 9 and 10. Dependence of the imaginary part of the resistance $Z$ on the load $R_L$ at a frequency of 20 kHz.

Figure 10. Dependence of the quality factor of the ultrasonic vibrating system on the load resistance $R_L$.

From the dependences shown in figure 10, it follows that a nonlinear nature of the dependence is observed. With an increase in the transformation ratio $K$ of the concentrating link, the relationship between the quality factor and the magnitude of the acoustic load weakens. It should be noted that ultrasonic emitters with gains close to 1 are practically not used. In this case it is difficult to provide the
required intensities in the zone of ultrasonic influence on the environment. An increase in the coefficient K will allow providing the required intensity of ultrasonic influence. However, at the same time the relationship between the acoustic load and the quality factor of the ultrasonic emitter will be reduced.

Thus, the monotony and predictability of the revealed dependences make it possible to use them to control the effectiveness of the influence (the degree of development of cavitation) and change the properties of the processed environment or materials (coatings) in the zone of influence.

3. Conclusion
To provide indirect control of the properties of cavitating environments near the emitting surface of the ultrasonic vibrating system and changes in the materials (coatings) in the affected zone, both under normal and abnormal conditions (in terms of temperature, pressure and chemical properties), a control system was proposed and developed. It serves to control the magnitude of the acoustic load and is based on the use of the dependences of the electrical impedance of the ultrasonic vibrating system on the magnitude of the acoustic load.

The system for indirect control of the magnitude of the acoustic load on the electrical impedance of the ultrasonic emitter was based on the dependences. These dependencies were identified on the basis of the analysis of the "ultrasonic emitter - environment" system in the form of an electrical model. The developed model is based on a system of electromechanical analogies.

Analysis of the dependences of the parameters of the ultrasonic emitter on the magnitude of the acoustic load in order to identify the possibility of monitoring changes in the acoustic properties of the treated environment made it possible to establish the following:

- magnitude of the acoustic load affects the electrical input impedance of the ultrasonic emitter;
- transformation ratio of the concentrating waveguide enhances the relationship between the value of the controlled acoustic load and the impedance of the ultrasonic emitter;
- quality factor of the ultrasonic emitter decreases with an increase in the transformation ratio of the concentrating link of the ultrasonic vibrating system;
- transformation ratio’s increase of the concentrating link of the ultrasonic vibrating system on the one hand enhances the relationship between the value of the controlled acoustic load and the impedance of the ultrasonic emitter. But on the other hand it reduces the quality factor of the ultrasonic vibrating system. It complicates the work of the PLL system of electronic generators, making it impossible to tune the generator to the resonance of the ultrasonic emitter.

The revealed dependencies can be recommended for monitoring the erosion strength of metals and their coatings under abnormal conditions and without direct access to the objects of ultrasonic cavitation effect.

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