The Design Of The Ultrasonic Vibrating Systems With Multi-Packet Piezoelectric Transducer And Multi Half-Wave Radiator

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Abstract **– Article is devoted to on the development of design techniques of ultrasonic oscillatory systems of high power. Highlighted the problems existing in the development of this type of systems, solutions are shown, to significantly a significant increase in the efficiency of ultrasonic technological devices.**

Index Terms **– Piezoelectric transducer, multi half-wave radiator, cavitation.**

I. INTRODUCTION

INTENSIFICATION of the processes in heterogeneous media with the help of high-intensity ultrasonic vibrations is one of the perspective line of development of modern industry.

Among present achievements of ultrasonic technologies nowadays are acceleration in thousands of times of extraction, dissolution, emulsification, dispersion processes, increase of yield of useful substances at the extraction in 10...50%, obtaining of materials with new unique properties, such as sterility, nanodimension, impulsion stability, etc.

At the realization of processes in liquid and liquid-dispersed media maximum efficiency of the processes is provided, wwhen the intensity of ultrasonic influence achieves 5...15 W/cm^2, i.e. at the realization of mode of developed cavitation. The zone of effective cavitation influence is limited by damping of propagated vibrations in viscous and dispersed media or change of wave resistance of liquid due to cavitation (practically to wave resistance of gaseous medium) limiting energy output of ultrasonic vibrations from the radiator.

At the realization of technological processes with the help of traditional piezoelectric transducers based on maximum in size piezoelectric elements (with the diameter of 5×10^{-2} m), the diameter of radiating surface cannot exceed 4×10^{-3} m^2 (taking into account double-sided radiation of working tool of mushroom shape). The size of cavitation zone (with the diameter of 5×10^{-2} m) does not exceed several diameters of radiating surface (from 2…3 for oils, from 5…10 for water). Thus at the realization of different technological processes the volumes to be treated effectively do not exceed: for viscous liquids they will be 4×10^{-4} m^3; for water they will be 2×10^{-3} cm^3. As required for the realization of processes duration of ultrasonic influence exceeds tens of minutes, running apparatuses of continuous operation do not solve the problem.

Such restrictions in volumes of simultaneously processed liquid media cause existing limitations of the application of ultrasoic technologies (the absence of industrial mass serial production) by laboratory scale-plants and plants with low productivity.

As an efficiency increase of the processes of chemical technology and realization of possibilities of high-efficiency ultrasonic influence in industrial scale is a primary task of the developers of ultrasonic technological devices, and rise of productivity is possible due to increase of energy of ultrasonic vibrations entered in the mode of developed cavitation. It is evident the necessity of industrial application of piezoelectric vibrating systems with enlarged in no less than 5...10 times area of radiating surface (up to 3×10^{-2} m^2 and more), which are able to provide simultaneous processing of liquid media in volumes of no less than 0.1…0.3 m^3.

One of the most effective way of solving the problem is an application of the ultrasonic vibrating systems with multi-packet piezoelectric transducer and multi half-wave radiator (working tool).

Such ultrasonic vibrating systems are characterized by increased power of generated vibrations achieved due to summation of power of piezoelectric ring elements (packets) on common frequency-lowering cover plate and increased power entered to the medium, which is provided by multi half-wave radiator.

Unfortunately, such vibrating systems designed by different producers [1,2] essentially vary in embodiment, performance features (intensity, uniformity of radiation, etc.) and efficiency of influence (output power, efficiency output, etc.).

It causes impossibility of the choice of optimum construction for solving particular task and proves the absence of unified scientific approach to the design of such systems.

II. PROBLEM STATEMENT

The necessity of power increase of the piezoelectric transducer due to the application of multi-packet construction and simultaneous enlargement of radiating area due to the use of multi half-wave radiator requires the formation of unified approach to the development of the transducers and the radiators and design of the piezoelectric vibrating system in a whole.

In the general case such ultrasonic vibrating systems of increased power structurally consist of sequentially placed and acoustically joined multi-packet ultrasonic transducer, half-wave booster unit and ultrasonic radiator made by joining in series of resonance modules. The piezoelectric transducer is made of frequency-lowering reflecting cover plates, number of which corresponds to the number of packets consisting of even numbers of the piezoelectric elements of ring form installed on common frequency-lowering cover plate acoustically joined with the booster [3,4].

In the ultrasonic transducer the faces, at which the packets of the piezoelectric elements are placed, are made at the angle to the acoustic axis of all vibrating system, that acoustic axes of each packet of the piezoelectric elements are directed to the center of flat end surface.

Produced according to this design map ultrasonic vibrating systems have a number of important disadvantages:

1. Irregularity of the value of vibration amplitude of radiating surfaces of half-wave resonance modules determined by the fact, that each following module is an additional load for previous modules and it changes their resonance frequency. At the absence of special actions of compensation of this influence the decrease of vibration amplitude of each following resonance unit occurs.

2. Low coefficient of conversion of energy of alternating electric current of ultrasonic frequency into elastic mechanical vibrations in multi-packet transducer due to non-optimal slope angle of flat faces relative to acoustic axis of all vibrating system.

Complexity of proposed construction, presence of interference of separate units, large quantity of calculated parameters require the development of design procedure of similar ultrasonic vibrating systems and optimization of the construction of each element taking into account influence of surrounding factors.

III. The Development of The Design Procedure and Optimization of The Construction

For production of the piezoelectric transducers of increased power following design procedure was developed.

At the *first stage* maximum consumed power of the piezoelectric transducer is determined and amount of used packets of the piezoelectric elements and overall dimensions of all multi-packet piezoelectric transducer are chosen.

At that we proceed from following conditions:

1) input diameter d_1 of radiating cover plate should satisfy the condition of possibility of placing on its planes the number of piezoelectric packets, which is necessary for obtaining of required consumped power, based on the fact, that maximum external diameter of produced piezoelectric rings *d* is 50 mm;

2) Output diameter of radiating cover plate d_2 being input diameter of booster unit should satisfy the condition $d_2 < \frac{\lambda}{2}$.

At the *second stage* having input and output diameters of radiating cover plate the slope angle of the planes is chosen, at which piezoelectric packets will be placed (see Fig. 1).

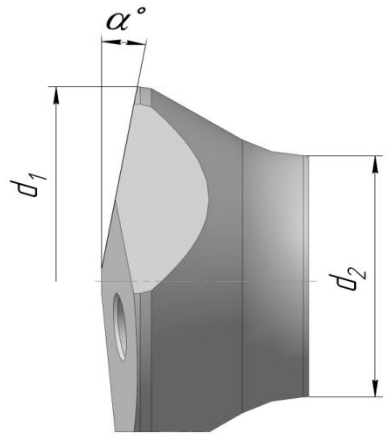


Fig. 1. Radiating cover plate of the piezoelectric transducer

The faces are made at the angle to acoustic axis defined from the expression 1:

$$\alpha = \frac{d\sqrt{\frac{4c_2^2}{f^2} - d_2^2 + 4d^2} - d_2^2\frac{c_2}{f}}{2\left(d^2 + \frac{c_2^2}{f^2}\right)} \qquad (1)$$

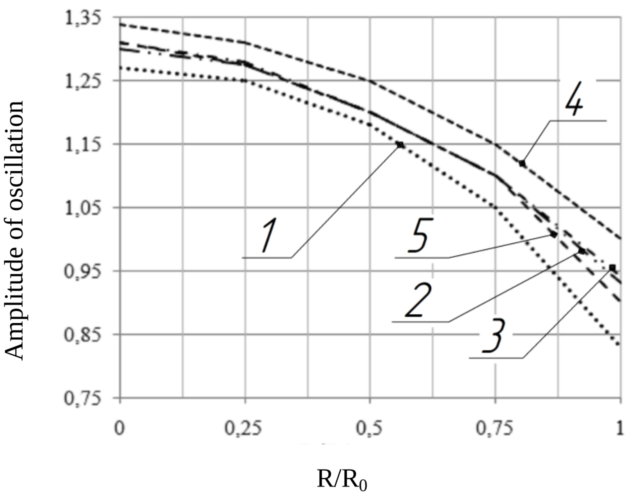
where *d* is an external diameter of the piezoelectric element of ring form, m;

d_2 is a diameter of end surface, which is in contact with booster unit, m;

c_2 is a speed of propagation of ultrasonic vibrations in the material of frequency-lowering radiating cover plate, m/s.

To verify the accuracy of obtained expression for determining of optimum slope angle of plane to the axis of the transducer the investigations were carried out, which were devoted to modelling of the formation of ultrasonic vibrations by the piezoelectric transducers with different slope angles. The aim of the investigations was to determine uniformity of distribution of vibration amplitude along radiating surface (along the radius *R)* and dpendence of the transformation ratio (gain) of the transducer on slope angle of the faces.

The results of modelling for different slope angle of the plane to the axis for one type of radiating cover plate are shown in the graphics (see Fig. 2 and Fig. 3).



1 – 3 degree; 2 – 5 degree; 3 – 7 degree;
4 – 9 degree; 5 – 11 degree

Fig. 2. The distribution of vibration amplitude along radiating surface of the cover plate

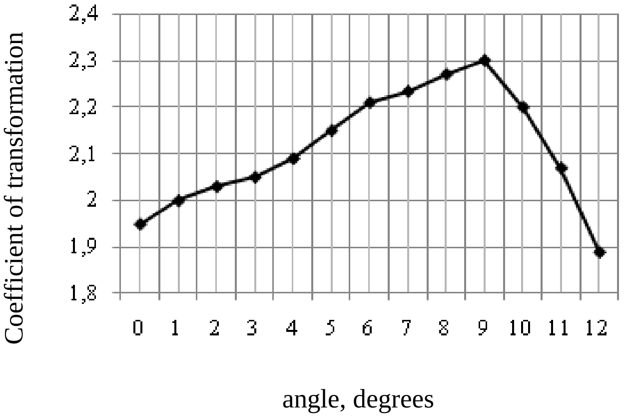


Fig. 3. The dependence of gain coefficient of the transducer on slope angle of the plane

From Fig. 2 it is evident, that when there is no slope angle, minimum gain coefficient is observed, when the slope angle is 9^0, maximum gain coefficient is observed. Further rise of the slope angle leads to decrease of gain coefficient of the transducer. It is determine by significant rise of bending vibrations of the piezoelectric packets and reduction of the efficiency of the piezoelectric transducer in a whole.

When the slope angle is 9^0, maximum gain coefficient of the transducer is observed.

It can be concluded, that the angle of 9^0 is optimum at the production of such type of radiating cover plates.

At the *third stage* longitudinal size of radiating cover plate is calculated. This size is defined by required resonance frequency of the transducer and it depends on the material of radiating and reflecting cover plates. The longitudinal size is calculated according to the procedure of engineering calculations of the transducer of Langevin described in details in the work [5].

Taking into considerations these conditions Fig. 4 shows developed types of the piezoelectric transducers with indication of consumed power, amount of installed packets of the piezoelectric elements, input and output diameters.

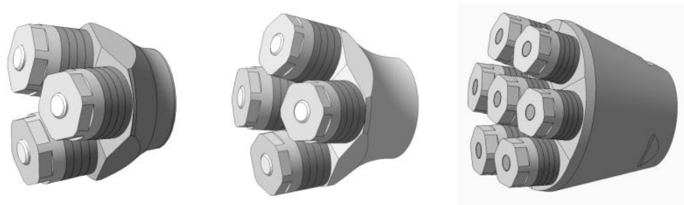


Fig. 4. Developed types of the piezoelectric transducers

At the *fourth stage* intermediate (booster) half-wave unit is calculated, which is necessary for transfer with simultaneous concentration (amplification) of acoustic energy (vibration amplitude) propagated from the end radiating surface of the piezoelectric transducer to working radiating tool. Moreover the application of booster unit is caused by the necessity to perform fastening unit of the flange in minimum of vibrations for installation of the ultrasonic vibrating system into suitable technological equipment.

The booster is half-wave resonance construction (see Fig. 5) designed for operating frequency of the trasnducer. Fastening belt is made in the zone of minimum vibrational displacement.

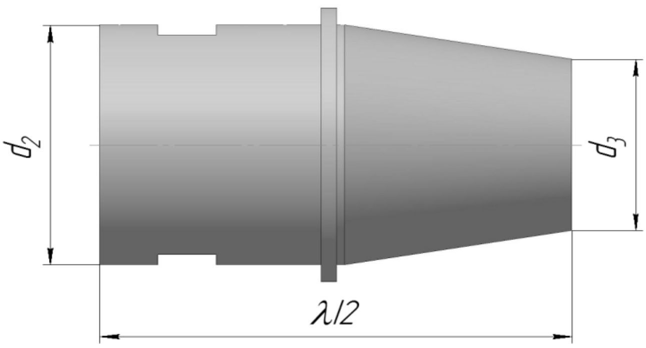


Fig. 5. The booster unit

For the design of booster unit with conic junction following conditions should be met:

1) input diameter of the booster unit d_2 is set by the type of used piezoelectric transducer.

2) output diameter of the booster unit d_3 is chosen from the condition of achievment of necessary gain coefficient.

The application of the booster unit brings additional boundary of the materials and threaded connection into the construction, that leads to increase of mechanical stress at the zone of junction. It causes frequency mismatch with the piezoelectric transducer and additional losses of acoustic energy (heating of the junction).

To reduce losses of acoustic energy it is proposed to reject to use half-wave booster unit and apply two half-wave transducer made in one detail (see Fig. 6).

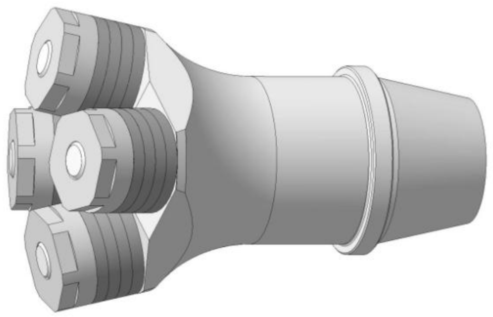


Fig. 6. The transducer and the booster unit made in one detail

It gives the possibility to achieve maximum gain coefficient and optimum frequency matching of the transducer with the concentrator.

At the *fifth stage* working radiating tool is developed, which allows to process large volume of simultaneously treated liquid medium in cavitation mode. The design of working tool of this type is in following: the first element of the wave-guide with the length, which equals to half of wave length of longitudinal vibrations in the material of the wav-guide, is made (see Fig. 7).

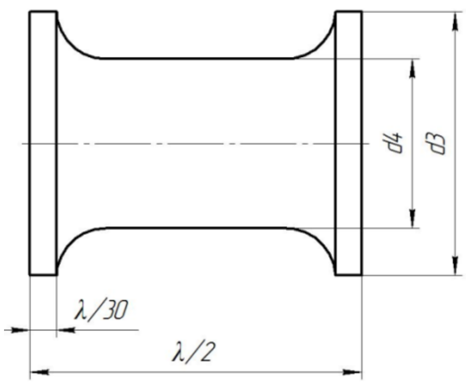


Fig. 7. The half-wave element of radiating tool

At that following conditions should be met:

1) The diameter d_3 is chosen on the basis of the output diameter of the booster unit calculated at the previous stage;

2) The diameter d_3 is chosen according to the condition, that $\frac{d_3}{d_4} \leq 2$;

3) The thickness of the lugs located in longitudinal antinode should be λ/30.

For the design of working tool with large radiating surface serial butt-jointing of such half-wave wave-guides is carried out. However at the butt-jointing in single working tool with the length of 2λ/2 – 7λ/2 the increase of operating frequency of working tool of united construction takes place. In order to maintain resonance frequency of working tool of 22 kHz it is necessary to decrease resonance frequency of initial half-wave element.

That is why the ultrasonic radiator is designed taking into account the fact, that the length of each module of the ultrasonic radiator installed in series from the transducer is chosen from the expression (2):

$$L_n = \frac{c_1}{2 f n^{-0,026}} \quad (2)$$

where c_1 is a speed of propagation of ultrasonic vibrations in the material of the ultrasonic radiator, m/s;

f is an operating frequency of the transducer, Hz;

n is a number of modules of the ultrasonic radiator.

The development of all constituent units allows to design the ultrasonic vibrating system as a single construction.

Developed ultrasonic vibrating systems were tested in laboratory and industrial conditions. Determining of optimum construction allows to achieve even distribution of vibrations along the length of working radiating tool. The power of radiation into water medium of developed ultrasonic vibrating systems containing proposed ultrasonic transducers on the base of 3, 4 and 7 packets of the piezoelectric elements is up to 5 kW at the efficiency of up to 0.8.

IV. Conclusion

Developed according to proposed procedure ultrasonic vibrating systems were tested in laboratory and industrial conditions. The power of radiation into water medium of developed ultrasonic vibrating systems containing proposed ultrasonic transducers on the base of 3, 4 and 7 packets of the piezoelectric elements is up to 5 kW at the efficiency of up to 0.8.

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