

The Construction Development of the Resonance Concentrating Link with Enlarged Radiating Surface

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Abstract – Annotation in the article the results of studies of functional possibilities of the optimization of geometric sizes and the construction development of specialized resonance concentrating link with enlarged radiating surface are presented. Developed theoretical model lets determine the value of longitudinal and transverse sizes of each part of concentrating link providing the achievement of required features of the ultrasonic vibrating systems (gain factor of the unit and its resonance frequency). To verify the efficiency of designed model the determining of geometric sizes of resonance concentrating link was made by the finite-element complex, which showed, that the disagreement did not exceed 10%. The efficiency of proposed model at the determining of size and resonance characteristics of concentrating link was proved by the experiments. Theoretical and experimental studies help to optimize the size of concentrating link, vibrating system developed on its base provides the enlargement of radiating surface in more than 6 times without decrease of radiation intensity for the realization of technologies of cavitation treatment of liquid media.

Index Terms – Ultrasound, ultrasonic vibrating system, concentrating resonance link, concentrator, gain factor.

I. INTRODUCTION

THE ULTRASONIC TECHNOLOGICAL equipment applied nowadays is based on general principles of design and that is why, it has similar structure. Any ultrasonic technological apparatus consists of the electronic generator and the ultrasonic vibrating system. Vibrating system is a device, which provides the transformation of energy of electrical oscillations coming from the generator into elastic mechanical vibrations, their amplification and introduction into processed media. The amplification of the amplitude of mechanical vibrations to the value, which is suitable for different technological processes, is realized by the concentrators.

The concentrators of ultrasonic vibrations are rods of variable cross-section connected to the transducer by input part of larger cross-section. The increase of vibration amplitude generated by the piezoelectric transducer due to the application of the concentrators helps to accomplish cavitation processing of liquid media, ultrasonic welding, dimensional processing of brittle materials and other ultrasonic technological processes.

II. PROBLEM STATEMENT

Operating principle of the concentrator is based on the increase of amplitude of particle vibrational displacement of the rod due to the reduction of its cross-section according to the law of conservation of movement. As a result of many studies [1, 2] it is shown, that the most perspective concentrator among applied ones are stepwise concentrators with transition radial zone. The scheme of the stepwise-radial concentrator is shown in Fig.1.

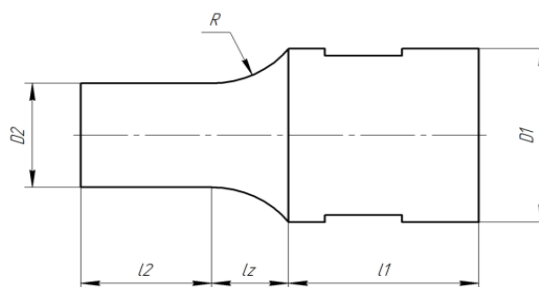


Fig. 1. Appearance of the stepwise-radial concentrator

The calculations of the zones l_1 , l_2 , l_z , were realized on the base of well-known calculation procedures described in detail in [1, 2].

The concentrators used in modern ultrasonic apparatuses have high gain factor, well strength characteristics matching the piezoelectric transducer with liquid media. However, the application of the concentrators with high gain factor (about 10) is not always possible in practice, as the reduction of the diameter of output zone decreases strength characteristics of transition zone and decreases area of radiating surface. The attempts to enlarge input cross-section of the concentrator do not solve the problem, as it requires to increase the size of the piezoelectric transducers, that is not always possible due to the limits of the diameters of produced piezoelectric elements.

At the same time it is known one solution of considered problem, it is based on the use of concentrating link connecting classic concentrator with additional mass resonating on its own frequency.

For the first time such construction was proposed in [3, 4] and it was a base for the design of the ultrasonic vibrating systems

used in a number of high-production chemical cavitation reactors. The application of similar construction lets obtain required gain factor at equal input and output diameters of the link.

The main point of the link construction is shown in Fig.2. The zone with the diameter D_1 is input and it is chosen equal to the output diameter of the piezoelectric transducer. At practical application the linear sizes l_1, l_2, l_3 are chosen according to the sizes of the stepwise-radial concentrator. The diameter D_2 is intermediate and it determines necessary gain factor. The size l_4 usually corresponds to the size l_2 , and the influence of the angle α on the parameters of amplification is not considered. The size l_5 is chosen from the condition, that $l_4+l_5=\lambda/2$, where λ is a wavelength in the material of concentrating link. the choice of the output diameter D_3 usually corresponds to the diameter D_1 , thus its value should be determined by the requirements of the technological processes and it requires further studying.

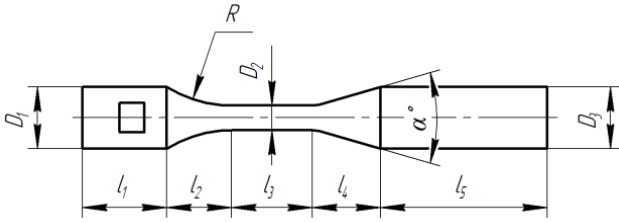


Fig. 2. Structural diagram of concentrating resonating link

Unfortunately, the concentrating link uniting the classic concentrator with the resonating mass does not have wide practical application. It is caused by the lack of theoretical and experimental investigations aimed to working-out of procedural recommendations on the optimization of the construction to achieve maximum gain factor in different conditions, at different diameters and sizes of radiating surface.

Thus the presence of a large number of transition and longitudinal zones of various diameters in concentrating resonating link requires detailed studies of the construction for revealing of optimum relation of zone lengths and diameters at given ratios of the areas of input and output ends of the concentrator.

This paper is devoted to the studies of concentrating resonating link.

III. THEORETICAL CALCULATIONS

To make theoretical model, which is able to provide theoretical calculations of concentrating resonating link, we proceed from the assumptions, that:

- in the rod plane wave is propagated, i.e. stress and velocity of particles along the area of optional cross-section are constant;
- there is no transverse contraction;
- vibrations of the construction are harmonic.

In this case the distribution of amplitudes of vibrational displacement of the zones with small diameters of considered link depending on longitudinal coordinate can be described by the following equation of longitudinal vibrations of the thin rod (1):

$$S(x) \frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial}{\partial x} \left(S(x) \frac{\partial u}{\partial x} \right), \quad (1)$$

where $S(x)$ is the cross-section area of concentrating resonating link in longitudinal coordinate x , u is the value of vibrational displacement of the link in the point with longitudinal coordinate

x , c is the propagation velocity of longitudinal vibrations in the material.

As described resonance link is a linear system, it is true statement, that all zones of the link vibrate with the same frequency ω :

$$-\omega^2 S(x) U = c^2 \frac{\partial}{\partial x} \left(S(x) \frac{\partial U}{\partial x} \right), \quad (2)$$

where U is the amplitude of vibrational displacement.

For further consideration the link is divided into several zones of the following types:

- the zone of the uniform cross-section;

$$S(x) = const,$$

The value of vibrational displacements can be presented as follows:

$$U(x) = A \cos(kx) + B \sin(kx),$$

where k is the wave number of concentrating link.

2) the zone with the linear profile. The area of cross-section is represented by the following dependence on the coordinate:

$$S(x) = \left(\sqrt{S_0} + \frac{\sqrt{S_1} - \sqrt{S_0}}{L} x \right)^2,$$

where S_0 is the area of the input end, S_1 is the area of the output end, L is the length of the zone.

The value of vibrational displacements is:

$$U(x) = AG_{1,S_0,S_1,k,L}(x) + BG_{2,S_0,S_1,k,L}(x),$$

3) the zone of the link with the radial profile. The area of the cross-section is presented by the following dependence on the coordinate:

$$S(x) = S_1 \left(\frac{d_1 + R - \sqrt{R^2 - (x-d_1)^2}}{d_1} \right)^2,$$

where S_1 is the area of the output end, d_1 is the diameter of the output end, L is the length of the zone, R is the radius of curvature of the longitudinal profile.

The value of the vibrational displacements is represented in a following way:

$$U(x) = AE_{1,S_0,S_1,k,L}(x) + BE_{2,S_0,S_1,k,L}(x),$$

Functions G and E are defined from the solution of the equation (2).

Using stated representations the system of equations from the following system of boundary conditions of the equality of displacements and stresses at the borders of the zones (uniform cross-section – radial – uniform cross-section – with linear profile – radial) is formed:

$$\begin{aligned} A_0 &= U_0 \\ A_0 \cos(kL_1) + B_0 \sin(kL_1) &= A_1 E_{1,S_0,S_1,k,L}(L_1) + B_1 E_{2,S_0,S_1,k,L}(L_1) \\ -kA_0 \sin(kL_1) + kB_0 \cos(kL_1) &= A_1 E_{1,S_0,S_1,k,L}'(L_1) + B_1 E_{2,S_0,S_1,k,L}'(L_1) \\ A_1 E_{1,S_0,S_1,k,L}(L_2) + B_1 E_{2,S_0,S_1,k,L}(L_2) &= A_2 \\ A_1 E_{1,S_0,S_1,k,L}'(L_2) + B_1 E_{2,S_0,S_1,k,L}'(L_2) &= kB_2 \\ -kA_2 \sin(kL_3) + kB_2 \cos(kL_3) &= A_3 G_{1,S_0,S_1,k,L}(L_3) + B_3 G_{1,S_0,S_1,k,L}'(L_3) \\ A_2 \cos(kL_3) + B_2 \sin(kL_3) &= A_3 G_{1,S_0,S_1,k,L}(L_3) + B_3 G_{1,S_0,S_1,k,L}(L_3) \\ A_3 G_{1,S_0,S_1,k,L}(L_4) + B_3 G_{1,S_0,S_1,k,L}(L_4) &= A_4 \\ A_3 G_{1,S_0,S_1,k,L}'(L_4) + B_3 G_{1,S_0,S_1,k,L}'(L_4) &= kB_4 \\ A_4 G_{1,S_0,S_1,k,L}'(L_5) + B_4 G_{1,S_0,S_1,k,L}'(L_5) &= 0 \end{aligned}$$

The solution of obtained system of equations by Gauss method relative to constant coefficients $A_1, \dots, A_4, B_1, \dots, B_4$ allows to determine the distribution of vibration amplitudes along the concentrating resonance link.

Obtained amplitude distribution of longitudinal vibrational displacements along the acoustic axis of the concentrating link is shown in Fig.3 at different lengths of the zone l_4 and the diameters of the input and output cross-sections (10, 15, 27 mm).

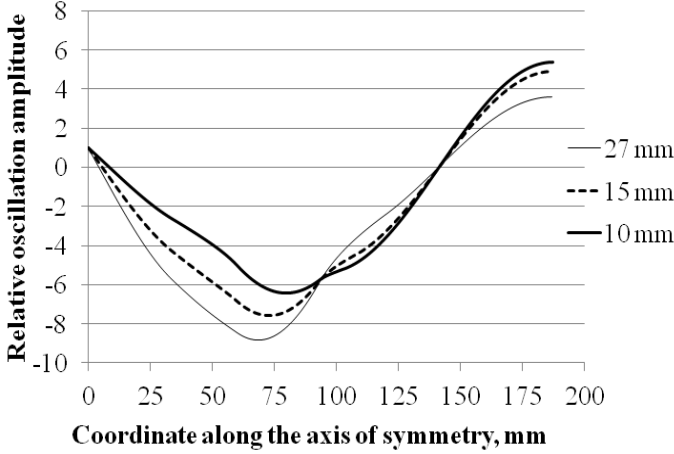


Fig. 3. Distribution of the amplitudes of longitudinal vibrations of concentrating link at different lengths of the zone l_4

Obtained distributions of the vibration amplitudes along the concentrating resonance link helps to determine, that the choice of length of the zone l_4 at constant total length of amplifying link can provide additional increase of gain factor in 1.5 times without changes of the diameters D_2 and D_3 .

Fig.4 shows the dependence of gain factor on the ratio of the areas of input (S_{ex}) and output (S_{obx}) end for stepwise-radial two half-wave concentrator obtained using developed model.

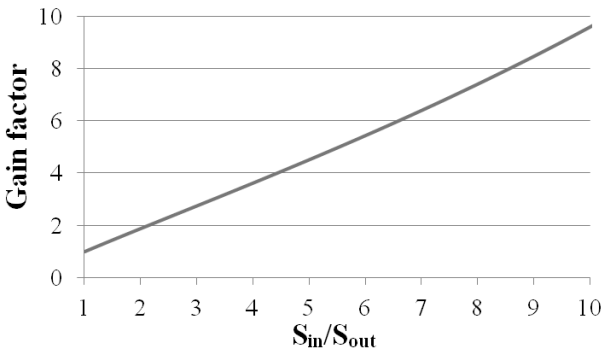


Fig. 4. Distribution of amplitudes of longitudinal vibrations of the concentrating link at different lengths of the zone l_4

At the determining of relations between the areas of input and output cross-section of the concentrating link, which equal to the relation of the areas of the zones of maxim and minimum cross-section (l_5 and l_3) of developed amplifying link it is possible to achieve the gain factor (in this case equals to 5.7) by the optimization of the length of the zone l_4 .

However due to increase of the area of the output end in 6.25 time in considered link it is possible to achieve the rise of entered acoustic energy in more than 6 times, that proves high efficiency of this concentrating link. Fig.5 and Fig.6 show the dependences of gain factor on the diameter and length of the zone l_4 .

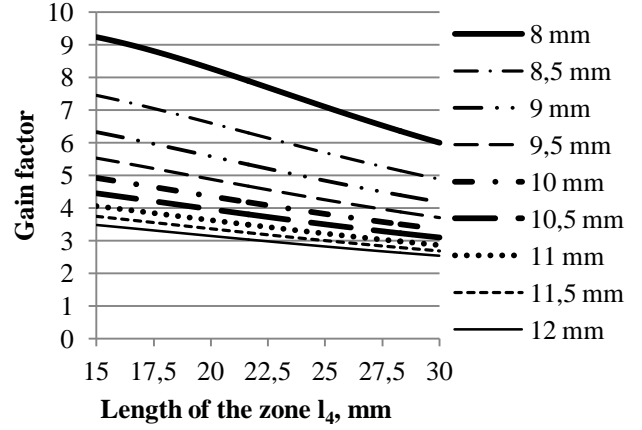


Fig. 5. Dependence of the gain factor on the length of the zone l_4 at different diameters D_2

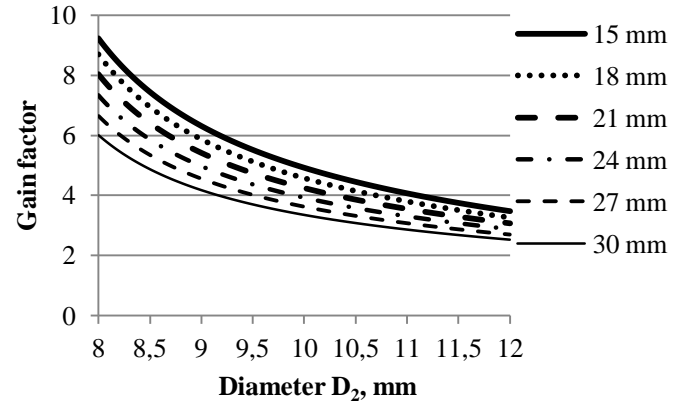


Fig. 6. The dependence of gain factor on the diameter of the zone l_3 at different diameters of the zone l_4

Presented dependences allow to draw a conclusion, that the diameter of the thin zone l_3 the most essentially influences on the gain factor.

However the attempt to reduce the diameter from 10 to 8 mm aimed at the increase of gain factor in two times is inadmissible, as it leads to the growth of mechanical stress, which can cause the breakage of the link. That is why optimum diameter providing allowable mechanical stress is about 10 mm. At the same time the analysis of the model demonstrates the possibility to rise gain factor in 6...7 times by the reduction of the length of the zone l_4 (the increase of the angle α , see Fig.2).

Thus developed model allows to perfect the construction of the concentrating unit by the determining of optimum design factors.

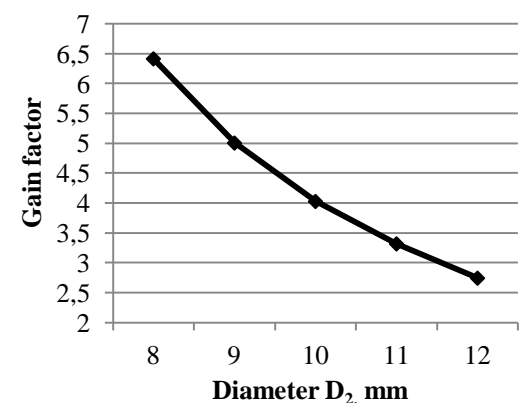
IV. THE MODELLING OF CONCENTRATING LINK BY FINITE ELEMENT METHOD

As a result of consistent carrying out of all stages of the calculations of proposed model the main design sizes of the concentrating link are determined. To verify adequacy of proposed model the comparison with the calculations obtained by direct numerical method of finite elements was made [5]. The development of 3d solid models of the units of the ultrasonic vibrating system was realized by the system of automated solid design.

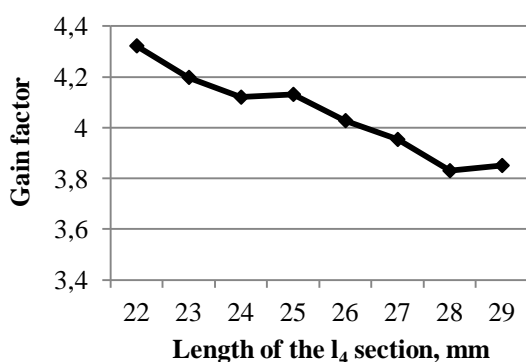
As initial sizes we take: input diameter $D_1=25$ mm (it equals to the output diameter of the piezoelectric transducer), $D_2=10$ mm, the output diameter $D_3=25$ mm. The zones l_1, l_2, l_3 are calculated

by the design procedure given in [1, 2] at this $l_1+l_2+l_3=\lambda/2$, the zone l_4 is chosen equal to the zone l_2 . The zone l_5 is calculated on condition, that $l_4+l_5=\lambda/2$. As a result total length of the construction is resonant, it equals to $2\lambda/2$.

As initial sizes of the concentrating link we take the dimensions of the zones obtained at the stage of theoretical calculations. After that concentrating links with the step of 0.5 mm around this basic sizes are modelled. Obtained results are given in Fig.7. Fig.7a shows the dependence of gain factor on the diameter D_2 , Fig.7b shows the dependence of gain factor on the length of the zone l_4 .



a)



b)

Fig. 7. Results of modelling by finite element method

From the dependence shown in Fig.7a it follows, that if the diameter D_2 is 8 mm, maximum gain factor can be achieved at constant diameter of the output part. However as it was mentioned above, such diameter of middle part of the link as its further reduction leads to the increase of mechanical stress in this zone, and finally causes breakage. That is why, optimum diameter satisfying the conditions of the achievement of maximum gain factor at mechanical stresses, which do not exceed threshold value for the material of the link, equals 10 mm.

From the dependence shown in Fig.7b it is evident, that at fixed size of the zone D_2 the highest gain factor is achieved at minimum length of the zone l_4 of the concentrating link.

At modelling the length of the concentrating link was determined for the purpose of assignment of exact value of proper resonance frequency of the construction. By the calculations with the application of proposed model resonance frequency of the construction is 29.9 kHz. Thus at the stage of modelling optimal lengths of all zones of the concentrating link at set resonance frequency were determined and chosen, that

allowed to produce the concentrating link for ultrasonic technological apparatuses.

As a result of the calculations it is ascertained, that the difference between the results of modelling by finite element method and by proposed model is not more than 10%. The presence of such error is caused by the fact, that proposed model does not take into account transverse radial vibrations of the concentrating link, as longitudinal vibrations are the most interesting for the realization of ultrasonic technologies. Nevertheless this model is satisfactory for the calculations of main geometric and resonance parameters of the concentrating link.

V. EXPERIMENTAL STUDIES

The experimental studies on determining of performance specifications of developed link were devoted to the measurements of proper resonance frequency of the construction and gain factor of the ultrasonic vibrating system, amplitude of mechanical vibrations at the output end of the link and measurements of electroacoustical efficiency of the ultrasonic apparatus.

The appearance of the concentrating link and the ultrasonic device "Aljona" used vibrating system with such link is shown in Fig.8.



Fig. 8. Appearance of developed concentrating link and ultrasonic apparatus

As a source of ultrasonic vibrations the piezoelectric transducer consisting of 2 piezoceramic rings of standard size 24x12.5x6.35 mm is used. It has frequency-lowering radiating cover plate made of aluminium alloy V95 and frequency-lowering reflecting cover plate made of steel 45. The connection of the transducer with the concentrating link is carried out by pin joint.

The measurements of resonance frequency of the vibrating system and gain factor were carried out by the piezoelectric probe with dry point contact at the power supply of the ultrasonic vibrating system from the low-voltage generator. The resonance frequency was defined by maximum value of vibration amplitude, the gain factor was defined as a ratio of maximum vibration amplitude on radiating end of the ultrasonic vibrating system to vibration amplitude on back reflecting cover-plate of the piezoelectric transducer. The results of the measurements are given in Tab. I.

TABLE I
THE RESULTS OF MEASUREMENTS OBTAINED BY THE
PIEZOELECTRIC PROBE

Link	Amplitude at the end, V	Amplitude at the back reflecting cover-plate, V	Resonance frequency, kHz	Gain factor
Piezoelectric transducer	2.4	1.6	29.71	1.5
+ concentrating link	5.8	0.8	29.76	7.25

Thus the results of the measurements show, that measured value of the gain factor of the concentrating link is 4.8, that in turn varies in no more than 5% from the value of the gain factor obtained by theoretical calculations. The discrepancy of the definition of the resonance frequency is 0.6%.

Amplitude of mechanical vibrations at the end of the concentrating link was measured by stroboscopic method [7]. For this purpose we used stroboscope for measuring of the amplitude of mechanical vibrations and microscope. The measurements of vibration amplitude during the operation of the apparatus showed, that the amplitude of mechanical vibrations at output end of the concentrating link was 40-45 μm . Obtained data also proved the values of gain factor of the ultrasonic vibrating system with the concentrating link, at that obtained value of the amplitude is sufficient for the realization of many ultrasonic technologies.

As the presence of diametrical vibrations of the concentrating unit was not considered. There is a special interest to study the distribution of vibrations of the cylindrical zone l_5 . The distribution of vibration amplitude obtained by described above method is shown in Fig.9.

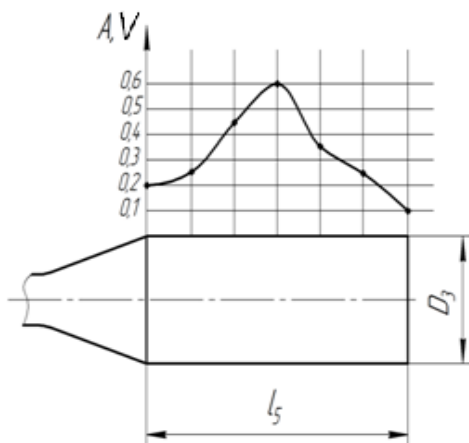


Fig. 9. Distribution of vibration amplitude along the cylindrical zone l_5

As it is evident from the graph the concentrating link has a high level of transverse vibrations (maximum value of the amplitude does not exceed 5 μm at the operation of the apparatus), that can cause additional energy output from the side surface. This part can be easily defined by the experiments, we immerse the cylindrical zone into water partly.

Total (at overall immersion of the cylindrical zone) efficiency of the ultrasonic device was determined by calorimetric method. This method is one of the most widely used and suitable for the determination of available acoustic power of the ultrasonic devices intended for the operation in liquid and liquid-dispersed media [6]. The procedure of the measurements is based on the practical realization of the calorimetric method standardized by the IEC. The measurement of electroacoustic power was carried out by the quality analyzer of electric power. Two types of liquids –

tap water and engine oil (SAE10-W40) were measured. The number of set of measurements for each type of liquid was 10, than the values were averaged.

The results of the measurements are given in Tab. II.

TABLE II
THE MEASUREMENTS OF THE EFFICIENCY OF THE DEVICE
OBTAINED BY THE CALORIMETRIC METHOD

Type of liquid	Consumed power of the device from electric line, W	Acoustic power, W	Efficiency, %
Tap water	390	244	61,5
Engine oil	410	235	57,3

From obtained results it is evident, that acoustic power radiated by the apparatus at the use of the piezoelectric transducer with the diameter of 25 mm with considered concentrating link exceeds radiated power (approximately in 4 times) at the application of vibrating systems with the traditional concentrator. It proves the fact, that studied type of the concentrating link allows to bring out more energy to processed medium. The value of the efficiency of the ultrasonic device with the concentrating link is rather high and it corresponds to the values of the efficiency of the ultrasonic apparatuses with traditional concentrators and mushroom-shaped working tools.

VI. CONCLUSION

As a result of carried out work new type of the concentrating resonance link for the ultrasonic vibrating systems was studied. As a result of theoretical calculations main dependences of the lengths of the zones composing the concentrating link were revealed, under given initial conditions we determined the conditions providing maximum gain factor of the link. On the base of the results of the theoretical investigations improved concentrating resonance link for the ultrasonic vibrating system was developed, and new technological apparatus for such system was produced. The results of experimental studies of developed ultrasonic technological device helped to verify the possibility to generate ultrasonic vibrations with specified amplitude (upto 45 μm) and provide the increase in 4 times of acoustic energy entered to processed media (when the efficiency was more than 60%).

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