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# Methods of Experimental Research of Broadband Piezoelectric Transducer for Medical Applications

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The article discusses methods of experimental research of broadband ultrasonic therapeutic piezo transducers, and devices that provide these methods. The broadband piezo transducer under investigation has a frequency band from 1 MHz to 3 MHz, and consists of a plate piezo element with a large mechanical quality factor and electromechanical coupling factor with one transition layer of duralumin, and two correcting electrical links. The method of monitoring acoustic contact with the patient's body, which is used in narrow-band piezo transducers, is not suitable for wide-band ones, so a high-frequency wattmeter was developed, which, together with the radiometer, is designed to control the effectiveness of the therapeutic procedure in ultrasonic therapeutic devices of the new generation for contact control and simultaneous measurement of consumed electrical and emitted acoustic power. The operation of the high-frequency wattmeter is based on a simplified quadrature multiplication scheme, which does not require additional power sources. The radiometer for measuring the radiated acoustic power is implemented in the form of a free float, which ensures the high sensitivity of the radiometer and the portability of the design. The scheme and ratio of the method of measurement and analysis of their amplitude-frequency characteristics, which are important for broadband converters, are given. In the process of manufacturing or operation of piezo transducers, deviations of their parameters from the calculated ones may occur. In this case, it is necessary to measure the main electrical parameters. For this, a method of two voltmeters and a phase meter was developed, which is based on obtaining and processing the amplitude-frequency characteristic of the active and reactive components of the electrical impedance of the piezo transducer, which is also described in detail in the article. In addition, the results of an experimental study of a broadband therapeutic emitter using the specified devices and based on the proposed methods are presented.

**Keywords:** Piezoelectric transducer, Piezoelectric emitter, Method of two voltmeters and phase meter, Wattmeter, Radiometry.

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## 1. INTRODUCTION

Ultrasonic therapeutic emitters are widely used in medicine [1]. They are usually made in the form of disks of high-quality piezoceramic zirconate – lead titanate, for example, RZT-8 [2], and are placed in a waterproof case, the reverse side of the piezoceramic disk borders the air. Contact of the emitter with the human body is made through a thin layer of contact liquid (gel). The radiation mode can be either continuous or pulsed. The operating frequency range from 1 MHz to 3 MHz was initially overlapped with the help of single-frequency narrow-band emitters. The permissible intensity of ultrasonic vibrations is 1.5 W/cm$^2$ in continuous and 3 W/cm$^2$ in pulsed modes of radiation. Ultrasound therapeutic devices are intended for the treatment of: peripheral nervous system, musculoskeletal system, internal organs, dental, urological, obstetrics and gynecological, ophthalmological, they are also widely used in cosmetology. Accordingly, we have a wide variety of emitters.

It should be noted that for the generation of oscilations with frequencies of 1 MHz and 3 MHz, plate piezoelectric transducers are used, only for the generation of 3 MHz - the third harmonic. At the same time, to emit the same power as at the first harmonic, three times the amplitude of the voltage of the high-frequency generator is needed.

A significant disadvantage of therapeutic single-frequency emitters, especially when working with maximum intensity, is the need to move them during the procedure. This is due to the need to avoid local damage due to the possible formation of standing waves.

In order to obtain a more homogeneous cross-section of the ultrasonic beam, it was proposed, as it is used in acoustic non-destructive testing and in ultrasonic medical diagnostics, to use transducers with a wide spectrum of radiation. And as transducers, piezoelectric transducers were proposed, which are used in flaw detection – piezoelectric transducers of variable thickness [3]. They have a number of disadvantages, namely, with their help, it is difficult to create a broadband emitter of sufficient intensity in a continuous mode. In addition, different areas of biological tissue in the cross-section of the ultrasound beam are irradiated with different frequencies, which is unacceptable for therapy.

Based on the analysis of the methods of constructing broadband piezoelectric emitters [4], the requirements for the bandwidth (from 1 MHz to 3 MHz) and the power of the emitters, as well as for the materials used in the design of the transducer, an electroacoustic system was developed, consisting of a lamellar isoelement with a high mechanical Q factor and electromechanical coupling coefficient, with one transition layer made of duralumin, and two correcting electrical links (Fig. 1).

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(a) (b)

**Fig. 1** – Developed therapeutic device(a) and broadband plate piezo transducer(b)

Since the method of monitoring acoustic contact with the patient's body, which is used in single- and multi-frequency piezo transducers, is not suitable for broadband ones, a device for monitoring contact and simultaneous measurement of consumed electric power was also developed.

The purpose of the article is to describe such a device – a high-frequency wattmeter that allows you to measure electric power, as well as another device – a radiometer that measures acoustic power. The article also describes the method of measuring and analyzing the amplitude-frequency characteristics (frequency response) of converters, which is important for broadband converters.In the process of their manufacture or operation, deviations of the parameters of piezo radiators from the calculated ones may occur. It was for measuring these parameters that the method of two voltmeters and a phase meter was developed, which is based on obtaining and processing the frequency response of the active and reactive components of the electrical impedance of the piezo transducer, which is also described in detail in the article. In addition, the results of an experimental study of a broadband therapeutic emitter (Fig. 1) using the specified devices and based on the proposed methods are given.

## 2. THE METHOD OF TWO VOLTMETERS AND A PHASE METER

The scheme of the method is shown in Fig. 2.

High-frequency voltage from a generator with a given frequency and constant amplitude $U_1$ through a ballast resistor $R_b$ is fed to the piezo transducer. The voltage amplitude on the piezo transducer is measured $U_2$ and phase shift between voltages $U_1$ and $U_2$ using a phase meter (Fig. 2).

Next, we will consider the frequency response analysis method of the piezo transducer.

A piezoelement is a system with distributed parameters. But for its analysis, an electrical equivalent circuit with concentrated parameters, shown in Fig. 3a, is often used.

Here:

$C_0$ – static capacitance of the piezo element;

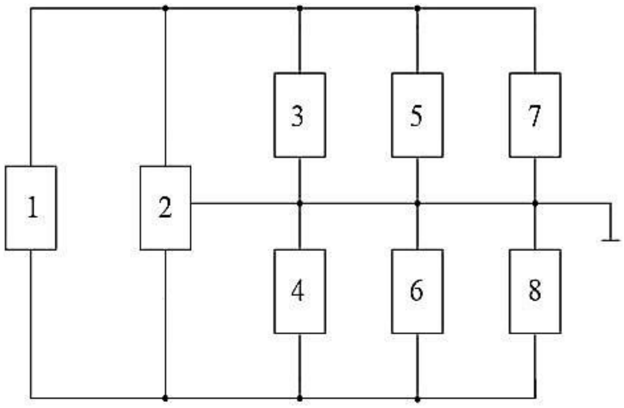



**Fig. 2** – Scheme of electrical structural measurement of the total electrical resistance module of the piezo transducer: 1 – generator; 2 – phase meter; 3 – frequency meter; 4 – oscilloscope; 5, 6 – voltmeter; 7 – ballast resistor; 8 – experimental sample

$C_d = \frac{8C_0k_t^2/\pi^2}{1-8k_t^2/\pi^2} \approx \frac{8C_0k_t^2}{\pi^2}$ – dynamic capacity;

$L_d = \frac{1}{C_Д\omega_1^2}$ – dynamic inductance;

$R_d \approx \frac{\pi(k_1+k_2)}{4k_t^2\omega_1 C_0}$ – dynamic resistance to radiation losses;

$\omega_1$ – resonant frequency;

$\omega_0$ – anti-resonant frequency.

The resonant frequencies are connected for the case $R_a = 0$ ratios:

$$\frac{tg(\pi\omega_1/2\omega_0)}{(\pi\omega_1/2\omega_0)} = \frac{1}{k_t^2} \quad (1)$$

or

$$\frac{\omega_1}{\omega_0} \approx \sqrt{1-\frac{8k_t^2}{\pi^2}}, \quad (2)$$

were $k_t$ – coefficient of electromechanical coupling of piezoceramics; $k_1$, $k_2$ – relative wave resistances of the air load of the piezo element from the rear side and the biological tissue with which the working side of the piezo element is in contact.

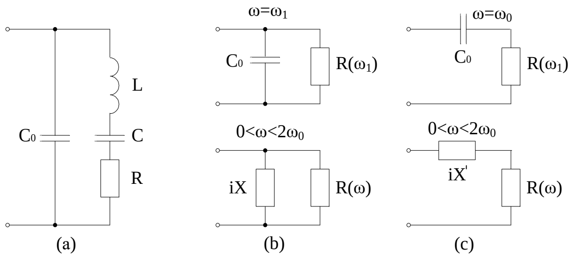



**Fig. 3** – Electrical equivalent circuit

The scheme in Fig. 3a is the most accurate when $(k_1 + k_2) \ll 1$, in accordance with that at the frequency $\omega_1$it is a parallel connection of the capacity $C_0$ and equivalent load resistance $R(\omega_1)$ (Fig. 3b), and on the frequency $\omega_0$ – serial connection of the same capacity $C_0$ and resistance $R_{a0}$ (Fig. 3c):

$$R_{a0} = \frac{1}{\omega_0 C_0}\frac{4k_t^2}{\pi}\frac{1}{k_1+k_2} \approx \frac{1}{(\omega_0 C_0 R)} \quad (3)$$

Then parallel and series connection schemes of active and reactive resistances for the entire frequency range are possible $0 < \omega < 2\omega_0$.

$$R_a = R_b \frac{U_2}{U_1} \frac{\cos\varphi - U_2/U_1}{\sin^2\varphi + (\cos\varphi - U_2/U_1)^2},$$
$$X' = R_b \frac{U_2}{U_1} \frac{\sin\varphi}{\sin^2\varphi + (\cos\varphi - U_2/U_1)^2}. \quad (4)$$

Moving from the diagram in Fig. 3a to the diagram in Fig. 3b, we will get:

$$R_a = \frac{R_{a0}}{1+(Q_a(1/x-x))^2}$$
$$X' = \frac{R_{a0}Q_a(1/x-x)}{1+(Q_a(1/x-x))^2} - \frac{1}{x\omega_0 C_0}, \quad (5)$$

where

$$x = \frac{f}{f_0},\ Q_a = \omega_0 C_0 R_{a0} = \frac{\pi}{2(k_1+k_2)},\ k_1 + k_2 = \frac{\pi}{2Q_a}. \quad (6)$$

From the analysis of expression (5) it follows:

1. Anti-resonant frequency $f_0$ is determined by the position of the maximum $R_a$.
2. $X_{c0} = \frac{1}{\omega_0 C_0} = X'(f_0)$.
3. $\frac{R_{a0}}{X_{c0}} = \frac{8k_t^2}{\pi^2} Q_a$, whence:
$$k_t^2 = \frac{\pi^2}{8} \frac{1}{Q_a} \frac{R_{a0}}{X_{c0}}. \quad (7)$$
4. $R_a = R_{a0}/2$, with $\left|Q_a\left(\frac{f_0}{f} - \frac{f}{f_0}\right)\right| = 1$, whence $f \approx f_0$ follows: $Q_a \approx f_0/(2\Delta f)$, where $\Delta f = |f - f_0|$ (the frequency band is determined by the curve $R_a(f)$ at the level of 0.5 because $K_p \sim \sqrt{R_a}$).
5. Marking $\bar{X} = X'/X_{c0}$ and finding the derivative of $\bar{X}$ on $x$ (in case the frequency $x = 1$), we get: $Q_{a(5)} = \frac{1+d\bar{X}/dx}{2(R_{a0}/X_{c0})}$.

The Q-factor value is found according to the formulas of points 4 and 5, $k_t$ – according to formula (7), and the acoustic load from expression (6).

## 3. METHOD OF HIGH-FREQUENCY WATTMETER

The expression for the time-averaged power consumed by a linear passive two-pole at a sinusoidal voltage has the form:

$$W = 1/T \cdot \int_0^T I(t) \cdot U(t)dt \quad (8)$$

This value can be obtained by multiplying the current and voltage values and then integrating over time. The most common scheme for multiplying two voltages is determined by the dependence:

$$U_1 U_2 = 1/4 \cdot [(U_1 + U_2)^2 - (U_1 - U_2)^2]. \quad (9)$$

The ring balance circuit (Fig. 4), which is widely used in radio engineering as a frequency mixer on semiconductor diodes, allows the power source to be excluded from the circuit.

In the mixers, it is recommended to use HF silicon diodes, which have a higher ratio of reverse and forward resistance and a small capacitance of the pn junction. All four diodes must have the same characteristics, and especially VD1-VD2, VD3-VD4. Specially selected pairs of diodes are made for such mixers. In addition to the diodes themselves, the level of balance depends on the equality of the arm resistances.

Provided $U_{out} \ll U_1, U_2$, the amplitude of the output voltage is equal to $U_{out} = \sqrt{2}U_=$:

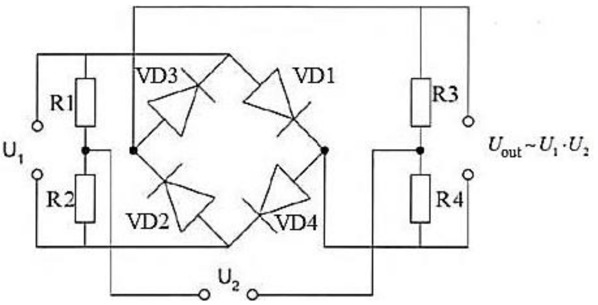



**Fig. 4** – Ring balance circuit

$$U_{out} = 8Ra_2 U_{1m} \cos\varphi = 4Ra_2 U_{1e} U_{2e} \cos\varphi. \quad (10)$$

In radio engineering, one of the voltages, usually $U_1$, is the voltage of the local oscillator, which is conveniently chosen as the maximum possible to maintain a constant value of the quadratic coefficient $a_2$, and dependence $U_{out}$ from $U_2$ – linear. With $U_2 \ll U_1$, therefore the above condition takes the form:

$$8Ra_2 U_2 \ll 1. \quad (11)$$

In our case, condition (11) is not fulfilled. In addition, there is an unevenness in the frequency band of the piezo receiver $U_2 \ll U_1$ can, through equality $U_1 \sim U_2$, change to the opposite $U_2 \gg U_1$. However, relation (9) must hold.

Value $U_1/2$ and $U_2$ should not exceed values of 1 V. To obtain the value $U_1 \sim I_{p/e}$ we will use a current transformer. In the classic version, it is a closed solenoid wound on a ferromagnetic core, through which a conductor with a current to be measured is passed, and the beginning and end of the solenoid winding are connected to a resistor $R_p$.

Connection $U_{out}$ and $I$ is obtained from Maxwell's equation, which has the following form in the SI system:

$$\oint H \cdot dl = \sum I, \quad (12)$$

where $H$ – magnetic field strength, $\sum I$ – the sum of the currents penetrating the surface based on the integration curve. Multiplying both parts of equation (12) by $\mu S$ ($\mu$ – magnetic permeability of the frame material, $S$ – branch cross-section) and taking into account that $dl = ln/N$, where $l$– contour length; $n, N$ – the number of turns per unit length and the total number of turns, and taking the time derivative, we obtain the value of the e.r.s. $\xi$ at the ends:

$$\xi = 4\pi\mu(S/l)N^2(1/N) \cdot dl/dt = (L/N) \cdot (dl/dt), \quad (13)$$

where $L$ – inductance of the toroidal winding.
Provided that $R_p i \ll L \cdot di/dt$ (or $R_p \ll \omega L$, where $\omega$ – the frequency of the harmonic current, or the lower frequency of the non-harmonic current):

$$\xi = Ldi/dt, \quad (14)$$

So,

$$(L/N) \cdot L(di/dt) \approx L(di/dt); i = I/N. \quad (15)$$

In accordance

$$U_{out} = (R_p/N)$$

Condition (14) determines the bandwidth of the current transformer.

For the manufacture of the transformer, a carbonyl iron core was taken, which has the following parameters: the length of the middle line of the magnetic drive $L_{mid}$ = 6.8 cm became determined by the size of the core and the properties of the magnetic material, $m$ = 4.4; coil inductance $L$ and the number of turns $N$ connected by the formula: $N = m\sqrt{L}$.

One incomplete turn serves as the primary winding of the transformer (for ease of inserting and removing it from the core). They were located in the window $N = 11$ turns of the secondary winding. So:

$L = (11/4.4)^2 = 6.2$ μH

Which coincided with the value that was measured using a universal digital bridge.

A practical scheme of a HF wattmeter (Fig. 5) was developed for the experimental study of the broadband emitter of the therapeutic device [5].

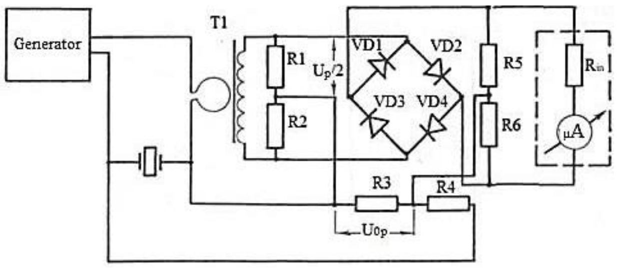



Fig. 5 – Practical diagram of a HF wattmeter with a piezo-emitter (PE)

Elements of the scheme satisfy the conditions [5]:

1. $\omega L \gg R_p = 2R_1 = 2R_2 (R_1 = R_2)$;
2. $R_3 + R_4 \gg |Z_{in}|$, but $R_3 + R_4 \ll R_{ex} = 1k\Omega$;
3. $R_3 \ll R_1 + R_5 \approx R_{vd} \approx 100\ \Omega$ (determined by the choice of diode brand),$(R_5 = R_6)$;
4. $\frac{U_p}{2} + U_{Op} \ll 1\ V$, to work on a quadratic area;

$$U_p/2 \ll U_{Op}. \qquad (16)$$

The calibration of the HF wattmeter was carried out according to the power released by the resistor (which is turned on instead of the piezoemitter) and is determined by the formula:

$$W_e = U_{pe}^2/R_l,$$

where $U_{p/e}$is the effective voltage on the resistor$R_l$.

The obtained calibration dependence has a linear character in the interval $0{,}24\ W \ll W_e \ll 3{,}29\ W$:

$$W_e = 0{,}065 \cdot I_{=}(\mu A).\ [W]$$

Sufficient balancing accuracy by selecting the same diodes, pairs of resistors $R1$, $R3$ was checked by shorting the secondary winding of the current transformer ($U_p = 0$), while the microammeter showed 0.

Thus, by measuring the value of the current $I_{=}$, then it is possible to convert it into the desired value of the electric power consumed by the piezo emitter based on the measured calibration dependence of the high-frequency wattmeter of the ultrasonic therapy device, which is presented in Fig. 6.

The high-frequency wattmeter is connected to the piezo radiator of the ultrasonic therapy device (Fig. 5) through the primary winding of the current transformer T1, which is a closed solenoid wound on a ferromagnetic core, through which a conductor with the current flowing through the piezo radiator is passed. The current is measured to determine the electrical power consumed by the piezo emitter. The start and end of the solenoid winding are connected to resistors R1 and R2, respectively. The balance circuit multiplies the value of the current from R1 and R2, flowing through the piezo emitter, and the value of the voltage applied to the piezo emitter from the generator of the ultrasonic therapy device, to determine the electrical power consumed by the piezo emitter. Voltage dividers of the balanced circuit R1-R6 provide the necessary voltage values of the ring circuit according to relations (16). As a result, the readings of the DC microammeter indicator are proportional to the electrical power consumed by the piezoemitter.

In the event of a change in the readings of the direct current microammeter indicator, which indicates a violation of the contact of the piezoemitter with the patient's skin, a decision is made to interrupt the operation of the ultrasound therapeutic device until the contact is restored.

## 4. ACOUSTIC RADIOMETER METHOD

The simplest construction of an acoustic radiometer is a float. The connected float was successfully used to control physiotherapeutic devices [6]. The developed design of the free float is simple and easy to use (Fig. 6) [7], and its general appearance is shown in Fig. 6b.

The diagram of a radiometer for measuring the acoustic power of a piezotransducer with a piezoelement 6 and a lens 5 is shown in Fig. 6a. The radiometer consists of a housing 2, which is filled with air, with a diameter of 12 mm, a lead mass 3, a measuring tube 4 with a diameter of 3 mm with a scale. In the absence of acoustic radiation, the float is balanced in such a way that the zero of the scale coincides with the water level that fills the housing 1. This level is adjusted so that the bottom surface of the float is at the level $\left(r_f - \triangle r_f/2\right)$, where$r_f$is the focal length of the converter, $\triangle r_f$ – the size of the focal zone. In the case of unfocused radiation, the bottom surface of the float should be within the near zone of the piezo transducer.

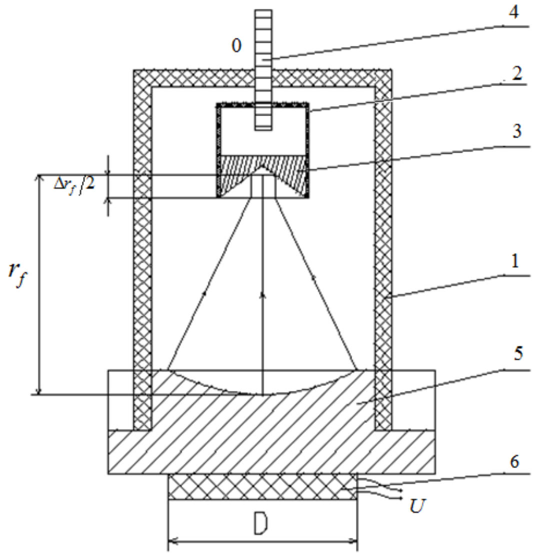
In the case when the ultrasound beam with time-averaged acoustic power$W$falls on the float, the latter, under the action of radiation force $F_p$, rises to a height $h$ such that:

$$F = \rho g S h, \qquad (17)$$

where $\rho$ – specific integrity of water; $S$ – cross-sectional area of the tube with the diameter $d$; $g$ = 9.8 m/s² – gravitational acceleration.

For the case of a plane wave that falls perpendicularly to the surface of a body with a reflection coefficient $0 \le R \le 1$:

$$F_p = K \cdot W/c, \qquad (18)$$




(a)

(b)

**Fig. 6** – Diagram of a free float radiometer (a), general view of the original radiometer (b)

where $c$ – speed of sound in water; $K = 1$ for $R = 0$ and $K = 2$ for $R = 1$ ($R$– amplitude reflection coefficient).

From (17) and (18) it follows:

$$W = c\rho Sh/2 \approx 6{,}05 \cdot 10^6 d^2 h. \quad (19)$$

The power required to test the float on $h = 1$ mm, that is, sensitivity, for $K = 2$ with different $d$, given in Table 1.

**Table 1** – Power required for float tests on $h = 1$mm

| $d$, mm | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $W$, mW | 6.05 | 24.2 | 54.5 | 97 | 151 | 212 | 296 | 388 |

In the left part of the expression (17), we neglected the additional force of the acoustic flow, which occurs in the ultrasound beam in the presence of wave absorption. It can be shown that under the condition $\alpha l \gg 1$ (where $l$ is the length of the ultrasound beam,$\alpha$ is the absorption coefficient), this force is equal to:

$$F_{a.m} = W\alpha lc = F_p(\alpha l/K) \ll F_p. \quad (20)$$

It should be noted that the method of measuring radiation pressure for calibrating hydrophones is adopted by the IEC (International Electrotechnical Commission) in addition to the reciprocity method.

## 5. RESULTS OF AN EXPERIMENTAL STUDY OF A BROADBAND THERAPEUTIC EMITTER

We will present the results of the development, creation and experimental research of a sample of a broadband therapeutic emitter (Fig. 1, b).

Consider the acoustic system (Fig. 7) and determine the parameters that provide the widest bandwidth of the piezoemitter, with the maximum possible power transmission coefficient of the piezoemitter.

To do this, we will use the power transmission coefficient:

$$P_E = \frac{P_a}{P_g} = \frac{4Q\mathrm{ReY}_p'}{\left|1+(Q+Z_{\mathrm{E2}})(Y_1+Y_p')\right|^2}, \quad (21)$$

where $P_g = \frac{U_g^2}{8R_g}$, $P_\mathrm{a} = \frac{1}{2}U_p^2\mathrm{ReY}_p$, $\varPi_B \le 1$;

$P_g$ – electric power;

$U_p$ – voltage on the piezoelement;

$Y_p = \mathrm{i}\omega C_0 \frac{\varDelta_0}{\varDelta_0 - \varDelta_1} = \omega_0 C_0 Y_n'$ – conductivity of the converter;

$Y_p' = \mathrm{ix}\frac{\varDelta_0}{\varDelta_0 - \varDelta_1}$; $x = \frac{\omega}{\omega_0}$;

$Y_1 = -i\frac{m_1^2}{x}$ – conductivity of inductive shunt L1;

$Z_{\mathrm{E2}} = \frac{i}{\alpha_2}\left(\frac{x}{m_2^2} - \frac{1}{x}\right)$ – electrical impedance of the circuit L2C2;

$m_2 = \frac{\omega_2}{\omega_0}$ – setting parameter ($\omega_2$ – resonant frequency of the circuit L2C2);

$\alpha_2 = \frac{C_2}{C_0}$ – relative capacity of the circuit L2C2.

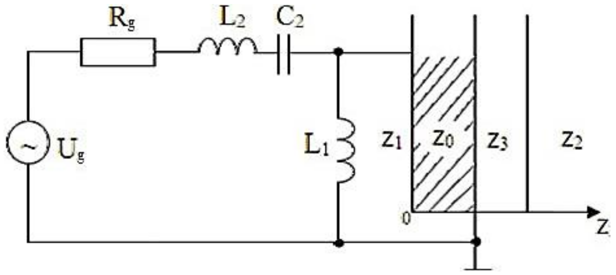



**Fig. 7** – Electroacoustic calculation scheme of a piezo element with a transition layer and electrical correction circuits

Using the theoretical methods for calculating the transmission coefficients of broadband piezo transducers described in [4] and expression (21), we will determine the parameters of the piezo emitter's structural elements:

- a transition layer made of aluminum with a relative thickness $n_3 = 0.27$ and a wave resistance $z_3 = 17.5 \cdot 10^6$ Pa·s/m;
- piezo plate made of PZT-8 ceramics ($z_0 = 35 \cdot 10^6$ Pa·s/m) with a large mechanical $Q$ factor $Q_m = 1000$ and electromechanical coupling coefficient $k_t = 0.51$;
- electrical correction circuits with setting parameters $m_1 = 0.75$, $m_2 = 0.79$, $Q = 1.44$ and relative capacitance of the second circuit $\alpha_2 = 0.5$.

Under these parameters, the operating frequency band of the piezo emitter ranges from 1 MHz to 3 MHz (Fig. 8).

In Fig. 8 shows the frequency response of the power transmission coefficient $P_E$, under the condition of optimal values of the matching layer thickness and Rg.

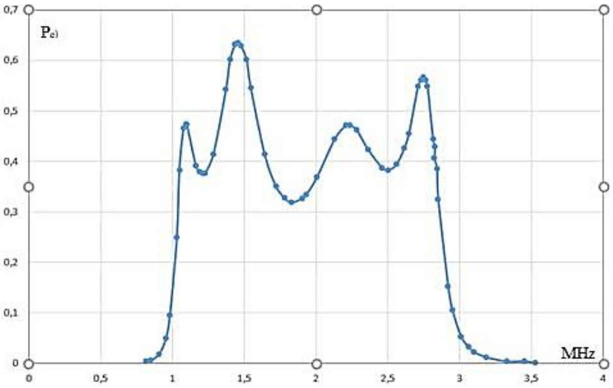



**Fig. 8** – Frequency response of the power transmission coefficient $\Pi_B$ piezo emitter for optimal matching layer thickness

In Fig. 9 shows the optimal calculated – 1 and measured – 2-3 (with a discrete change of one of the parameters of the second link) frequency dependence of the radiated acoustic power $P_a$, at low generator voltage values $U_g$. It can be seen that by selecting the parameter of the second link, these dependencies can be brought closer together.

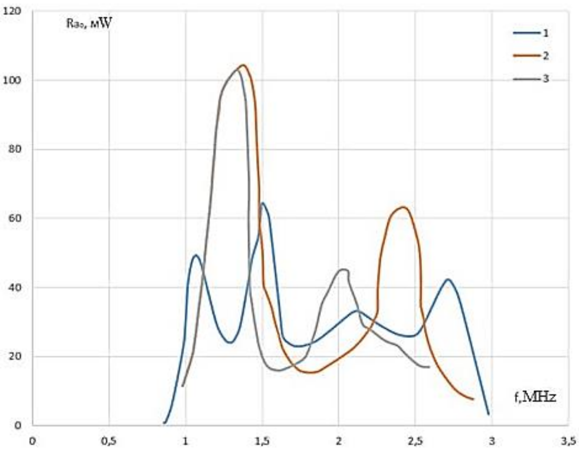



**Fig. 9** – Frequency dependence of the radiated power at a low value of the generator voltage

The degree of non-uniformity of the frequency response in the formed frequency band, as in the case of bandpass electric filters, depends significantly on the value of the resistance $R_g$. To demonstrate this in Fig. 10 shows the experimental frequency response of the ratio of the measured power to the square of the generator voltage at emitter parameters close to optimal, but at $R_g = 0$, obtained at lower (curve 1) and higher (curve 2) values $U_g$. In this case, all the active power taken from the generator goes into the radiated power, but the frequency response unevenness is greater. It can be seen that in the band from 1 MHz to 3 MHz, four well-defined peaks of approximately the same magnitude are observed (curve 1), so that in this mode the emitter can be used as a four-frequency with a switching frequency. At the same time, its efficiency at a frequency of 3 MHz is much higher than the efficiency at the third harmonic of a narrowband emitter with a fundamental frequency of 1 MHz, which, as is known, is 9 times less than at the first. In addition, the width of the corresponding peak is much larger than that of a narrow-band emitter, which ensures that the frequency of the generator falls into it (for example, when the temperature changes).

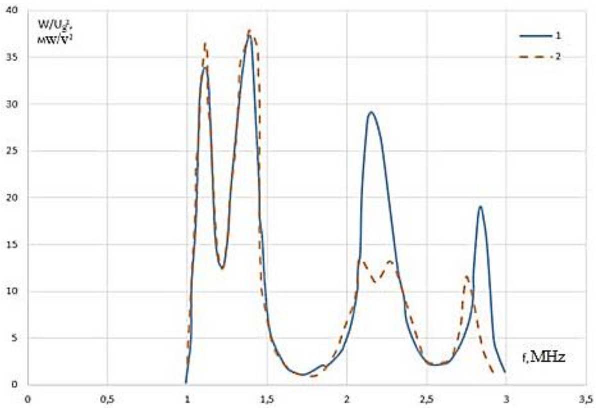



**Fig. 10** – Experimental frequency response of the ratio of the measured power to the square of the generator voltage, provided $R_g$ = 0 and close to the optimal emitter parameters

From Fig. 10 also shows that in the region of 2.2 MHz, the height of the peak is 2.7 times lower at higher values of $U_g$. (curve 2) than at 5 times lower $U_g$. (curve 1).

In Fig. 11 frequency response ratios are given $P_a/U_g^2$ (curve 1) and the amount of current consumed at $U_g$ = const (curve 2), as well as the average value over the frequency band $P_a/U_g^2$ at $U_g$ = const for close to the optimal emitter parameters. It can be seen from them that the frequency response of the consumed current does not correlate with the frequency response of the acoustic power, as in the case of a converter operating at one frequency. It follows that the broadband emitter cannot be coherent with the generator over the entire frequency band, and the voltage on the transducer cannot be used to indicate acoustic contact with human skin.

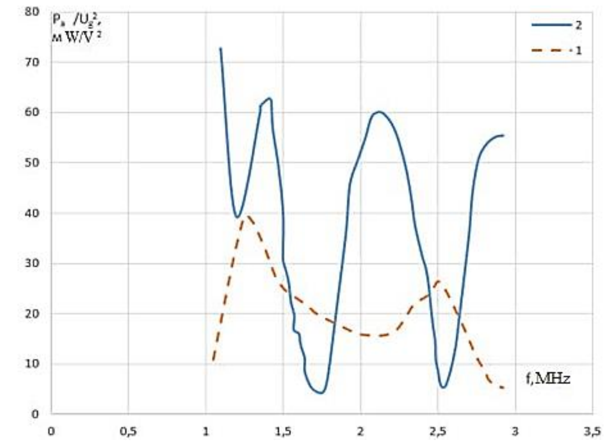



**Fig. 11** – Frequency response ratio $P_a/U_g^2$ (curve 1) and the amount of current consumed at $U_g$ = const (curve 2)

From the value of the average value, it is possible to determine the voltage of the generator necessary to obtain the given acoustic power.

## 6. CONCLUSIONS

The developed and experimentally researched therapeutic emitter can be used to carry out medical procedures without moving it, since the occurrence of standing waves is excluded (eliminated). The consumed HF power does not exceed the power of two-frequency devices (produced by foreign companies) which, in addition to working at the main frequency of the thickness fluctuations of the piezo disk, also work at its third harmonic.

Comparison of calculated and measured (using a radiometer and the method of two voltmeters with a phase meter) frequency response shows that two-dimensional oscillations in the disc are not excited. This can be explained by the presence of a matching layer with a relatively large acoustic wave resistance.

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## Методи експериментального дослідження широкосмугових п'єзоелектричних випромінювачів для медицини

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У статті розглядаються методи експериментального дослідження широкосмугових ультразвукових терапевтичних п'єзоперетворювачів, і пристрої, які забезпечують ці методи. Широкосмуговий п'єзоперетворювач, який досліджується, має смугу частот від 1 МГц до 3 МГц, і складається з пластинчатого п'єзоелементу з великою механічною добротністю і коефіцієнтом електромеханічного зв'язку з одним перехідним шаром із дюралюмінію, і двома коригуючими електричними ланками. Метод контролю акустичного контакту з тілом пацієнта, який застосовується у вузькосмугових п'єзоперетворювачах, для широкосмугових не підходить, тому було розроблено високочастотний ватметр, який, разом із радіометром, призначений для контролю ефективності терапевтичної процедури в ультразвукових терапевтичних приладах нового покоління для контролю контакту і одночасного вимірювання споживаної електричної і випромінюваної акустичної потужності. В основу роботи високочастотного ватметра покладена спрощена схема множення через квадрування, яка не потребує додаткових джерел живлення. Радіометр для вимірювання випромінюваної акустичної потужності реалізований у вигляді вільного поплавка, що забезпечує високу чутливість радіометра та портативність конструкції. Наведені схема і співвідношення важливого, саме для широкосмугових перетворювачів, методу вимірювання і аналізу їх амплітудно-частотних характеристик. В процесі виготовлення або експлуатації п'єзопретворювачів можуть виникнути відхилення їх параметрів від розрахованих. В такому випадку необхідно провести вимірювання основних електричних параметрів. Для цього був розроблений метод двох вольтметрів та фазометра, який базується на отриманні та обробці ампітудно-частотної характеристики активної та реактивної компонент електричного імпедансу п'єзоперетворювача, який теж детально описаний в статі. Крім того, наводяться результати експериментального дослідження широкосмугового терапевтичного випромінювача за допомогою зазначених пристроїв, і на основі запропонованих методів.

**Ключові слова**: П'єзоелектричний перетворювач, П'єзоелектричний випромінювач, Метод двох вольтметрів та фазометру, Ватметр, Радіометр.