EXPERIMENTAL DETERMINATION OF MECHANICAL PARAMETERS OF PIEZOELECTRIC TRANSFORMERS

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Abstract: *The paper proposes a methodology for experimental determination of the mechanical parameters of piezoelectric transformers (PTs) in case of unknown piezoelectric ceramic material and electro-mechanical parameters. Stationary modes have been used in this case for finding out both the resistance of the mechanical losses and the mechanical resistance, registering elasticity, while the dampening coefficient of the PT under consideration and its mechanical inductance have been determined by means of a transient process. The mechanical parameters of three types of PTs have been calculated with the help of both experimental tests and the proposed methodology. The obtained results have been compared to calculations, carried out by means of three different methodologies.*

Key words: *piezoelectric transformer, transient process, inertness, dampening coefficient, mechanical parameters*

1. Introduction

Piezoelectric transformers are more and more widely used in industry due to their high workability, compactness, low cost and capability to work under electrical and mechanical overloads [1]. At low voltages they replace the traditional magnetic transformers, since the latter cause electromagnetic interference, and high harmonics with relatively big amplitudes often appear with them [2].

Piezoelectric transformers convert electrical energy into mechanical and then they convert it back into electrical again [3]. Normally PTs - either high or low voltage – operate in stationary modes. Paper [4] considers circuitry of low-voltage piezoelectric transformers, power supplied by a sinusoidal source for small electric power in stationary modes.

Very often in practice the mechanical parameters of PTs are needed and they are usually determined by using methods, based both on their geometric dimensions and a number of electromechanical parameters of the particular piezoelectric ceramics they have been made of [5-7].

This paper proposes a methodology for experimental determination of the mechanical parameters of three types of piezoelectric transformers. These mechanical parameters have been calculated by means of this methodology in combination with experiments and then compared to the corresponding calculations, carried out with the help of three different methodologies.

2. Exposition

A possibility for experimental determination of the mechanical parameters of various types of piezoelectric transformers is studied in this paper. Stationary mode and second resonance in the output section of the PT are used for determining the resistance, registering the mechanical losses in the PT. The mass of the PT is determined by means of the dampening coefficient of the oscillatory process in it. The resistance, registering elasticity, is found from the expression for the circular resonant frequency in stationary mode. By means of experiments and the proposed methodology, the mechanical parameters for three basic types of PTs are calculated.

. Fig. 1 illustrates the circuit of the low frequency switch, and fig. 2 presents the electric circuit of the experimental set used for determining the coefficient of mechanical waves, dampening in PTs.

The experimental set works as it follows: phase voltage $V_f(t)$ with effective value of 230V goes into the step-down transformer, where it is reduced to $V_2(t)$=6V, fig.1. In case of a positive half-wave of $V_2(t)$, current flows through the relay R_1 and the contact S_1 closes for 10 ms, fig. 2. Meanwhile the electrical signal from the sine wave generator 4 is fed into the input section /piezoelectric actuator/ of the PT-2, where it is converted into mechanical oscillations due to the reverse piezoelectric effect. The generator 4 is set at the resonant frequency ω_0 of the PT. These mechanical oscillations propagate in the studied PT and when they reach the output section /the piezoelectric harvester/3, due to the forward piezoelectric effect, they are converted again into an electrical signal and registered by the digital oscilloscope 5, fig. 2.

In case of a negative half-wave of the reduced phase voltage $V_2(t)$ current flows through the second relay R_2 and the contact S_2 closes, while S_1 opens. The two electrodes of the input section are then connected to the mass and the mechanical oscillations in the PT fade away. This transient process is also registered by the digital oscilloscope 5.

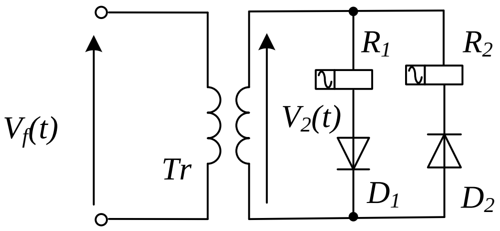


Fig. 1. Electric circuit of the low frequency switch

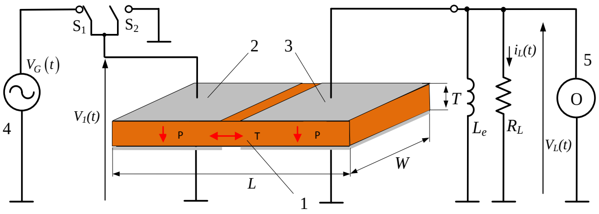


Fig. 2. Experimental set

A coil L_e is connected in parallel to the output capacitor C_{e2}, fig. 2. Thus parallel resonance is obtained at the output. Active resistance R_L is also connected in parallel to the coil, so that the current $i_L(t)$ flows through it. Fig. 3 represents the electromechanical circuit of the PT, containing both electrical input and output areas and a mechanical area between them. The process of energy conversion from electrical to mechanical and vice versa is shown by the ideal transformers Tr_1 and Tr_2.

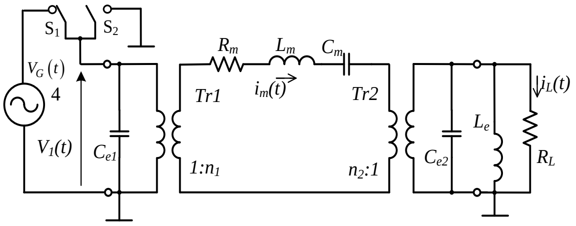


Fig. 3. Equivalent electromechanical circuit of the PT

The equivalent electrical and mechanical quantities in the electromechanical circuit of the PT are denoted as it follows:

$V_1(t)$ - input voltage;
$V_L(t)$ - output voltage;
n_1, n_2 - coefficients of electromechanical conversion at the input and output;
$i_m(t)$ - mechanical current (oscillatory speed);
R_m, L_m, C_m - equivalent mechanical resistances;
C_{e1}, C_{e2} - electrical capacity of the input and output sections.

3. Modeling

First the stationary mode, in which the switch S_1 is on (fig.3) and the first transient process of increasing the voltage $V_L(t$ (fig.6) has taken place, is considered. The sine wave generator $V_G(t)$ is assumed ideal and can be illustrated in the simplified equivalent circuit by the input voltage of the PT

$$V_G(t) = V_1(t) \qquad (1)$$

Since the sine wave generator is tuned to the resonant frequency ω_0 of the PT, then the coil L_e is selected so that it has the same resonant frequency as the capacitor C_{e2}.

$$\omega_0 = \frac{1}{\sqrt{L_m C_m}} = \frac{1}{\sqrt{L_e C_{e2}}} \quad . \qquad (2)$$

By using (2), the practical value of the inductance can be calculated

$$L_e == \frac{1}{\omega_0^2 C_{e2}} \quad . \qquad (3)$$

Two resonances with the same circular frequency are thus obtained. The first one is serial in the mechanical part of the PT, while the second is parallel in its output section. Thus both the reactive resistance for the serial resonance X_m and the reactive conductivity of the output B_e for the parallel resonance are equal to 0.

$$X_m = \omega_0 L_m - \frac{1}{\omega_0 C_m} = 0 \quad , \qquad (4)$$

$$B_e = \frac{1}{\omega_0 L_e} - \omega_0 C_{e2} = 0 \quad . \qquad (5)$$

Then the equivalent electromechanical circuit of the PT can be significantly simplified

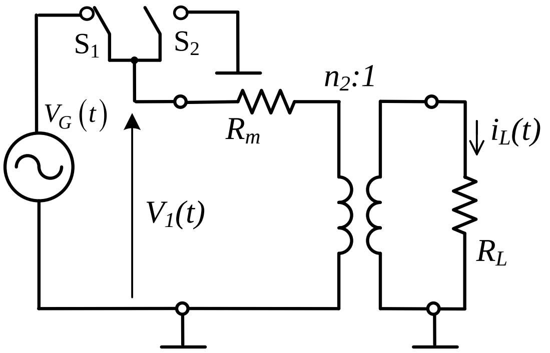


Fig. 3. Simplified equivalent electromechanical circuit of the PT

After bringing the mechanical part of the PT to the electrical one

$$R_{m1} = \frac{R_m}{n_2^2} \quad , \qquad (6)$$

an equivalent electric circuit in instant form is obtained for the stationary mode, fig. 4.

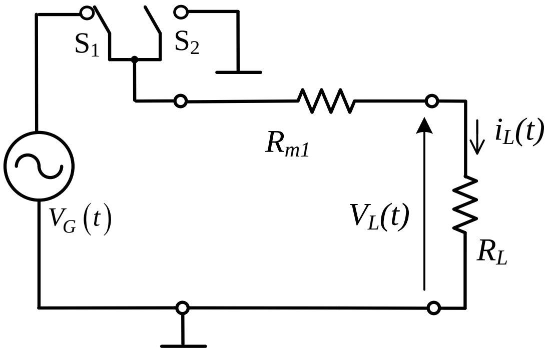


Fig. 4. Equivalent electrical circuit

From the obtained electrical circuit in fig. 4 the maximum value of the output current can be found.

$$I_{Lm} = \frac{V_{Gm}}{R_{m1} + R_L} \quad . \qquad (7)$$

The output current of the PT can also be expressed by the output voltage

$$I_{Lm} = \frac{V_{Lm}}{R_L} \quad . \qquad (8)$$

Thus from (7), (8) and (6) an expression is obtained, by means of which the first parameter of the mechanical part can be determined – the resistance, registering the mechanical losses in the PT

$$R_m = R_L \left(\frac{V_{Gm}}{V_{Lm}} - 1 \right) n_2^2 \quad . \qquad (\#9)$$

For defining the second parameter of the mechanical part L_m of the PT, the parameters of the dampening oscillatory process are taken into account after the contact S_2 has been turned on, and the two electrodes in the exciting section of the PT are connected to the mass – fig. 2. This transient process is registered by the oscilloscope and has a duration of Δt, whereas at its beginning the voltage in the piezoelectric receiver has a maximum value (the first amplitude) V_{Lm1}, fig. 5. Due to the inertness of the mechanical part of the PT, the electrical voltage $V_L(t)$ decreases by an exponential law for time Δt.

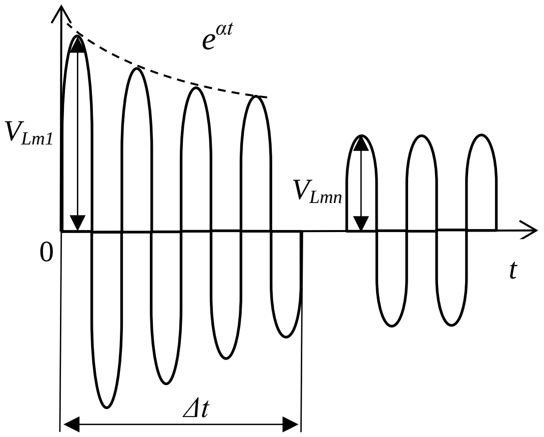


Fig. 5.

The amplitude of the voltage $V_L(t)$ at the end of the dampening process V_{Lmn} (for the *n*-th oscillation) can be determined by the first amplitude V_{Lm1},

$$V_{Lmn} = V_{Lm1}\, e^{\alpha \Delta t} \quad . \qquad (10)$$

After logarithming and certain transformations for the dampening coefficient of the mechanical waves α for time Δt it is obtained

$$\alpha = \frac{1}{\Delta t} \ln \frac{V_{Lmn}}{V_{Lm1}} \quad . \qquad (@11)$$

The dampening coefficient of the mechanical waves in this transient process can also be determined by means of the mechanical resistances of the PT [8]

$$\alpha = \frac{R_m}{2L_m} \quad . \qquad (12)$$

Hence an expression can be obtained for the mechanical inductance of the PT L_m, which is calculated by means of the earlier defined (9) and (11)

$$L_m = \frac{R_m}{2\alpha} \quad . \qquad (13)$$

The mechanical resistance, registering elasticity, is determined from the expression for the circular resonant frequency in stationary mode (2)

$$C_m = \frac{1}{\omega_0^2 L_m} \quad . \qquad (14)$$

4.Experimental studies

With the help of the experimental set in fig. 2 the dampening oscillatory process after turning the contact S_2 on is measured. Fig. 6 presents the voltage measured by the oscilloscope on the load $V_L(t)$,for the Rosen-type PT1 at amplitude $V_{Gm}=0,1$ V, together with the parameters of the dampening transient process, needed for determining the mechanical parameters of the PT.

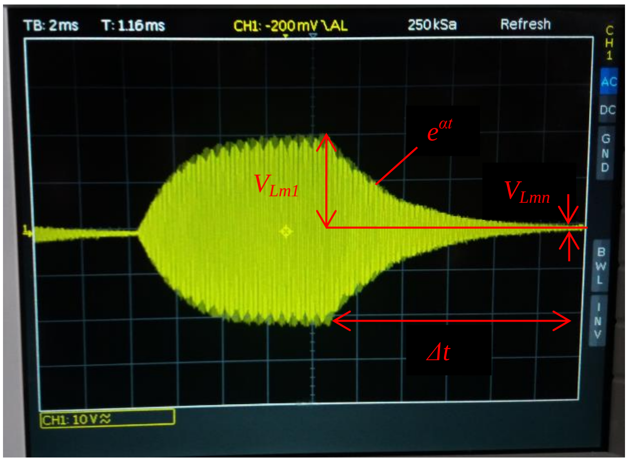
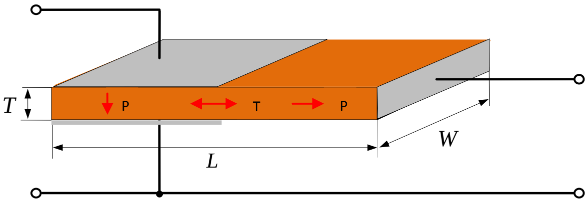


Fig. 6.

By the proposed methodology the mechanical parameters of the following three types of PTs are calculated: Rosen-type piezoelectric transformer - PT1; piezoelectric transformer with cross-cross polarization - PT2; and disk-type piezoelectric transformer - PT3, as presented in fig. 7, 8 and 9.



(P: polarization, T: stress)
Fig. 7. Rosen-type – PT1.

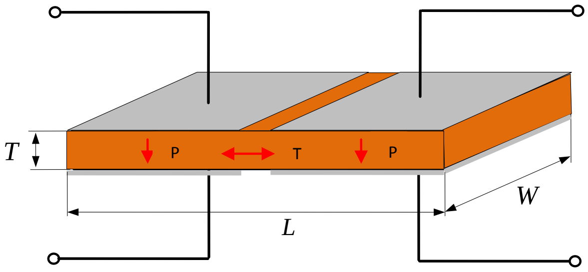


Fig. 8. Cross-cross polarization – PT2

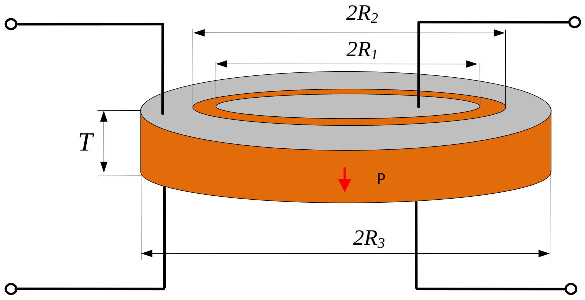


Fig. 9. Disk-type - PT3.

The three types of PTs are made of the piezoelectric ceramic material PZT4 with geometrical dimensions shown in Table 1 and electromechanical parameters presented in Table 2.

Table 1

	Type	*L*, mm	*W*, mm	*T*, mm	*2R*, mm
PT1	Rosen-type	40	20	1	-
PT2	Cross-cross polarized	50	20	1	
PT3	Disk-type	-	-	1	30

Table 2
Coefficients of piezoelectric ceramic material PZT4

Coefficient	**Value**	Дименсия
Density	$\rho=7600$	Kg/m^3
Mechanical Quality Factor	$Q_M=500$	
Piezoelectric Coefficient	$d_{31}=85.10^{-12}$ $d_{33}=225.10^{-12}$	C/N
Young`s Modulus	$Y_1=0,83.10^{11}$	N/m^2
Elastic Compliance	$S^E_{11}=11,7.10^{-12}$	m^2/N
Shear Frequency Constant	N=1600	m/s
Radial Frequency Constant	$N_p=1950$	m/s

The mechanical parameters of the studied three types of PTs are calculated not only by the proposed new methodology, denoted as “Meth”, but also by means of the following methodologies: by Y. Liu [6], denoted as “Liu”, by V. Lavrinenko [1], denoted as “Lavr”, and by M. Peerasaksophol [9], denoted as “Peer”, fig. 7-9.

The electromechanical parameters, the coefficient of ideal transformation and the circular resonant frequency of the PTs can be calculated by “Liu” methodology [6] in the following way:

$$L_m = \frac{LWT\rho}{8} \quad C_m = \frac{1}{\omega_0 L_m} \quad R_m = \frac{1}{Q_m}\sqrt{\frac{L_m}{C_m}}$$

$$n_1 = n_2 = \frac{d_{31}\, b}{S_{11}^E} \qquad \omega_0 = \frac{4\pi N}{l} \quad (15)$$

These electromechanical parameters, the coefficients of ideal transformation and the characteristic resistance, according to “Lavr” methodology [1] are equal to:

$$Z_0 = TW\sqrt{\rho Y_1^E} \quad n_1 = n_2 = bd_{31}Y_1$$

$$R_m = \frac{\pi Z_0}{4Q_M}; \quad L_m = \frac{\pi Z_0}{\omega_0}; \quad C_m = \frac{1}{\omega_0 \pi Z_0} \qquad (16)$$

The mechanical parameters of the disk-type PT are also calculated by “Peer” methodology as it follows [9]:

$$L_m = \frac{\rho S_{11}^E (1+n)T}{8\pi d_{31}^2} \qquad C_m = \frac{16 r^2 d_{31}^2}{\pi S_{11}^{E\,3}(1+n)T}$$

$$R_m = \frac{\sqrt{2\rho S_{11}^{E\,3}(1+n)T}}{16 r Q d_{31}^2} \qquad (17)$$

The obtained mechanical parameters, the coefficients of electromechanical transformation at the output *n₂* and the damping of the mechanical part *α*, measured by means of the four methodologies for the three types of PTs, are presented in Table 3.

The relative errors, comparing the four methodologies as a means of determining the three mechanical resistances, are shown in Table 4.

Table 3

		n_2	α, s^{-1}	R_m, Ω	L_m, mH	C_m nF
PT1	Lavr.	0,2		5,58	6,14	0,61
	Liu	0,1		6,11	6,22	0,67
	Meth.	0,2	-440,2	5,81	6,06	0,65
PT2	Lavr.	0,2		5,58	6,14	0,61
	Liu	0,2		6,11	6,22	0,67
	Meth.	0,2	-440,2	5,81	6,06	0,65
PT3	Peer.	0,37		3,91	4,53	1,25
	Liu	0,31		3,11	3,84	1,51
	Meth.	0,25	-424,8	3,22	3,79	1,56

Table 4

		δ_{max}, %		
		R_m	L_m	C_m
PT1	Lavr./ Meth.	3,96	1,32	6,25
	Liu/ Meth.	5,16	2,64	3,01
PT2	Lavr./ Meth.	3,96	1,32	6,25
	Liu/ Meth.	5,16	2,64	3,01
PT3	Peer/ Meth.	21,43	21,41	19,87
	Liu/ Meth.	3,41	3,42	2.56

5.Discussion

The voltage on the load $V_L(t)$, measured by the oscilloscope (fig. 6), is with the same time constants both for its increment at turning the switch S_1 on, and for the damping of the transient process at connecting the input of the PT to the mass by the switch S_2. In the proposed methodology only the dampening coefficient of the mechanical waves α, related to the time constant of the mechanical part, is used

$$\tau = \frac{1}{\alpha} = \frac{2L_m}{R_m}, \quad s \qquad . \qquad (15)$$

From the obtained mechanical parameters of the three types of PTs, calculated by means of the four methodologies and presented in Table 3, as well as from the relative errors shown in Table 4, it can be seen, that the methodologies “Lavr” and “Liu” give very close values to those, given by the proposed new methodology, whereas the relative errors are under 6,3%. When “Peer” methodology is compared to the newly proposed one as to the disk-type PTs, the errors are much higher and their maximum reaches up to 21,43%. When the new methodology is compared to “Liu” for the same type of PTs, it can be seen, that the calculated mechanical parameters are with very close values and the relative errors are under 3,5%. This confirms that the proposed methodology allows for determining relatively precisely the mechanical parameters of the three basic types of piezoelectric transformers, considered here. Thus, it is easy to obtain the electrical parameters of both stationary and transient processes in PTs by means of digital oscilloscopes, and calculate their mechanical parameters then. It is also possible to do that even when the piezoelectric material or its electrical and mechanical parameters are not known.

6.Conclusion

The proposed methodology allows for experimental determination of the mechanical parameters of the three main types of PTs, considered in this paper. The first parameter – the resistance, registering the mechanical losses in the PT - is obtained by means of the parameters of the measured stationary mode at parallel resonance in the output section of the PT. What is needed for finding out the second parameter – the resistance, registering the mass of the PT - are the parameters of the fading oscillatory process, controlled by the low-frequency switch, which turns a sinusoidal voltage source on and off to the PT. The third parameter – the mechanical resistance, registering elasticity - is defined from the expression for the circular resonant frequency.

By means of experimental studies and with the help of the proposed methodology the mechanical parameters of all three types of PTs have been calculated. Comparison between the results, obtained by means of the new and three more methodologies, has been drawn. It has been established that the proposed methodology allows for comparatively precise determination of the mechanical parameters of the three basic types of PTs, considered in this paper.

With the help of a digital oscilloscope it is easy to obtain the electrical parameters of the transient processes in a PT, from where their mechanical parameters can be easily calculated then. It can also be done even when neither the piezoelectric ceramic material nor its electrical or mechanical parameters are known.

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