Instantaneous Power and Phase Shifts at Piezoceramic Bars Forced Vibrations

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Abstract

This paper is devoted to analysis of the electric loading conditions problem for piezoceramic bars' forced vibrations. New simple experimental technique together with computing permits to investigate many resonators' parameters: admittance, impedance, phase shifts, power components etc for constant amplitude input voltage, constant amplitude sample voltage and constant amplitude sample current electric conditions based on experimental data for "as there is" regime. Such computer modeling makes possible to decrease of the experimental difficulties and to study in linear approximations the dependence of resonators’ parameters from loading conditions. The fundamental mode of vibrations of thin piezoelectric bar is given as example. It is established that high admittance nonlinearity in constant amplitude voltage regime and its absence for constant amplitude current case are created by different behavior of instantaneous power level. The obtained results are in good agreement with experimental data.

Keywords: Piezoceramic resonators; Electromechanical coupling factor; Thin piezoelectric bars; Instantaneous power components; 2000 MSC: 74-05; 74F15

Introduction

Piezoceramic constructive elements' vibrations characterize by great electromechanical coupling between electric fields and elastic displacements or stresses [1-5]. The internal physical processes nature in such bodies drives to the fact that mechanical displacements, strains and stresses, sample admittance, impedance or instantaneous power have both real and imaginary parts. Thus it is possible to calculate any amplitude with accounting the energy losses only. The analytic solutions for electro-elastic vibrations of simple geometric form bodies are used for determination the real parts of the dielectric, elastic and piezoelectric coefficients [6-8]. Imaginary parts usually are determined on maxima/minima admittance, first proposed by Martin [9]. Very important role in energy losses belongs to mechanic quality factor Q, which differs for resonance and anti-resonance [10].

Acoustic bulletin [11] was devoted to modeling of the loss-energy piezoceramic resonators by electric equivalent networks Van-Dyke-type with passive elements. It was shown that when piezoelectric sample is excited by constant voltage the instantaneous power in sample increases at resonance frequency in many times in respect to off-resonant case. And when sample is excited by constant current the instantaneous power in sample decreases at resonance frequency in that ratio.

Reports of NAS of Ukraine [12] on the example of a famous problem of thin piezoceramic full electrode disk radial vibration the expressions for admittance were derived and graphs of the admittance change near resonance/anti-resonance at constant voltage (with constant amplitude) or constant current (with constant amplitude) were plotted. Calculations were made in complex form with accounting of experimentally determined mechanic, dielectric and piezoelectric energy losses. Calculated results were compared and agreed with experiment data. It was shown that for constant voltage regime instantaneous power sharply increases near resonance but it decreases for constant current regime. It explains existence or nonexistence of nonlinearity which was discovered in loss determination methodology for a piezoelectric ceramic [2].

This paper is devoted to analysis of the electric loading conditions problem for thin piezoceramic bars' forced vibrations. An idea of the step-by-step voltage measuring in modern Mason's scheme [11,12] is continued and method of phase determination between admittance's or power's components with cosine law is used [12-14]. New simple experimental technique together with computing permits to plot many resonators' parameters: admittance, impedance, phase shifts, power components etc for constant input voltage, constant sample voltage, constant sample current and constant instantaneous power electric conditions based on experimental data for "as there is" regime. Regimes constant voltage, constant current or constant power means that their amplitudes are installed at experiment beginning and not changed for all studied frequency range. Computer modeling makes possible to decrease of the experimental difficulties and to study in linear approximations the dependence of resonators' parameters from loading conditions.

It was established that admittance, impedance, phase shifts are independent from loading conditions. High admittance nonlinearity in constant voltage regime and its absence for constant current case may be created by different behavior of instantaneous power. To modeling constant power regime it is necessary to increase input voltage and sample voltage near resonance on 30% to 40% and in several times at anti-resonance in respect to off-resonance case.

Calculated and measured instantaneous power's spectrum for constant current conditions has the same view as impedances spectrum while instantaneous power's spectrum for constant voltage has the same view as admittance's spectrum. Investigations show that constant current regime leads to decreasing resonant power and to increasing anti-resonant power, but constant voltage regime leads to increasing resonance power and to decreasing anti-resonant power.

Admittance, Impedance and Power Components for Thin Piezoceramic Bar

Piezoelectric bars with transversal polarization became already "touchstone" in many experimental researches because their vibrations

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are described with simple mathematical formulas, and the first overtone lies far on frequency from fundamental resonance [1-3,9,10,15]. The mechanical and electric values of these structures are coupled between the so-called transversal coefficient of electromechanical coupling (EMC) \( k_{31} \).

In Karlash, Shulga, and Uchino studies [11–14] it was shown that the piezoelectric resonator's admittance may be presented in calculations as imaginary conductivity of the inter-electrode sample capacity \( C_0 \) multiplied on anti-resonance \( \Delta_x(x) \) to resonance \( \Delta(x) \) determinants ratio:

\[
Y = j\omega C_0 \frac{\Delta_x(x)}{\Delta(x)}, \quad (1)
\]

Where \( x \) – is dimensionless frequency, which depends on geometric sample's form.

For thin bar with thickness polarization next formula was developed [16]

\[
Y_b = j\omega C_0 \left[ 1 - k_{31}^2 + \frac{k_{31}^2 \sin x}{\cos x} \right] = j\omega C_0 \frac{\Delta_x(x)}{\Delta(x)}, \quad (2)
\]

\[
\Delta(x) = \cos(x), \Delta_x(x) = (1 - k_{31}^2)\Delta(x) + k_{31}^2 \sin x / x.
\]

Here: \( j \) is an imaginary unit, \( \omega \) is an angular frequency, \( \omega_r \) – resonant angular frequency, \( k_{31} \) – transverse coupling coefficient.

All variables, functions and electro-elastic coefficients are complex [4,11,16–18]. Dimensionless frequency \( x \) is definite as:

\[
x = (\rho s_{33} f_m^2) / (2f_m) = 2(1 - j x_{11} / 2) = x_1 - j x_2,
\]

\[
(s_{11}^2 = s_{33}^2(1 - j x_{11})). \quad (3)
\]

Here: \( l \) is a bar’s length, \( x_1, x_2 \) are real and imaginary parts of a complex dimensionless frequency, \( x_{11} \) – complex elastic compliances, \( \rho \) is a density.

Admittance (or full conductivity) characterizes sample's possibility to conduct electric current and determines as sample current to sample voltage ratio. This parameter is convenient near piezoelectric sample resonance where it reaches maximum value. But for anti-resonant frequency region more convenient is impedance because it reaches maximum value on anti-resonance. Admittance \( Y \) and impedance \( Z \) are in inverse ratio and for impedance calculation we may use a simple relation

\[
Z = \frac{1}{Y}. \quad (4)
\]

There are three characteristic power's components in sinusoidal alternative current circuit: instantaneous power \( P \) in volt-ampere (VA), which is voltage drop on some circuit area \( U \) in some time moment multiplied on circuit's current \( I \) in the same moment, active power \( P_{\text{active}} \), in Watts (W), which is distinguished on active resistance and heats it and reactive power \( P_{\text{reactive}} \), in volt-ampere reactive (VAR), which is distinguished on reactive circuit's elements (inductances or capacitance) and creates electric or magnetic fields

\[
P = UI, P_{\text{active}} = UI \cos \alpha, P_{\text{reactive}} = UI \sin \alpha. \quad (5)
\]

When piezo resonator's voltage is \( U_1 \) and its current is \( I_1 \) we may write

\[
U_1 = I_1 / Y_1, I_1 = U_1 / Y_1 = I_1 / Y = U_1 / Y_{11}, \quad W_1 = \text{Re}(T) / \text{Im}(T),
\]

\[
\alpha = \text{arcot}(w), P_{\text{active}} = P \cos \alpha, P_{\text{reactive}} = P \sin \alpha. \quad (6)
\]

Real part of coupling coefficient \( k_{31} \) may be determined in experiments with using formula [4,10,16]

\[
\frac{k_{31}^2}{1 - k_{31}^2} = \frac{\pi f_n}{2f_m} \tan \left( \frac{f_m - f_n}{2f_m} \pi \right). \quad (7)
\]

Here: \( f_n \) and \( f_m \) are frequencies of minimum and maximum admittance respectively.

Real component of fundamental dimensionless resonance frequency for thin piezoceramic bar with thickness polarization is equal to \( \pi/2 \). Anti-resonance dimensionless frequency is dependent from coupling factor's value \( k_{31} \), which is determined as [9,16],

\[
k_{31}^2 = \frac{\kappa_{31}^2}{\epsilon_{33}^m} = \frac{\kappa_{31}^2}{\epsilon_{33}^m} (1 + j(k_{13} + \epsilon_{33} - 2d_{31})) = \frac{k_{31}^2}{\epsilon_{33}^m} (1 + j(k_{13} + \epsilon_{33} - 2d_{31})�).
\]

\[
(s_{11}^2 = s_{33}^2(1 - j x_{11})), c_{11}^2 = x_{11}(1 - j x_{11}), d_{11} = d_{11} - j x_{11}, d_{21} = d_{21} - 2j x_{11}.
\]

In our experiments in parallel to generator's output or coordinating divider output was included a series circuit consisting from piezoelectric Pe and loading resistors R [12,13]. We can measure for arbitrary chosen frequency range the voltages \( U_{\text{on}} \) on the sample, \( U_0 \) on loading resistor, input voltage \( U_0 \). An inter-electrode capacity \( C_0 \) and dielectric loss tangent \( \tan \theta \) are measured by alternative bridge at low frequency (1000 Hz). Voltage \( U_{\text{on}} \) is proportional to electrical current \( I_1 \) in resistor and sample.

\[
I_{pe} = \frac{U_0}{R}. \quad (9)
\]

The ratio of current to voltage is definite as admittance [6,13,17]

\[
Y_{pe} = \frac{I_{pe}}{U_{pe}} = \frac{U_0}{RU_{pe}}. \quad (10)
\]

Production of sample current on sample voltage is an instantaneous power

\[
P_{pe} = U_{pe} I_{pe} = \frac{U_0}{R} U_{pe}. \quad (11)
\]

Three measured voltages \( U_{pe} \), \( U_k \) and \( U_m \) created peculiar characteristic triangle and angles between its sides were calculated with using a cosine low [12,14]

\[
\cos \alpha = \frac{U_k^2 + U_m^2 - U_{pe}^2}{2U_k U_m}, \quad \cos \beta = \frac{U_k^2 + U_m^2 - U_{pe}^2}{2U_k U_m}, \quad \cos \gamma = \frac{U_k^2 + U_m^2 - U_{pe}^2}{2U_k U_m}. \quad (12)
\]

An angle \( \alpha \), formed sides \( U_k \) and \( U_m \), characterizes the change of phases between a current and voltage drop in piezoelement. An angle \( \beta \), formed sides \( U_k \) and \( U_{pe} \), answers a phase shift between output voltage of generator and consumable current. And angle \( \gamma \), formed sides \( U_{pe} \) and \( U_m \), characterizes the difference of phases between output voltage of generator and voltage drop on piezoelement.

Voltages \( U_k \), \( U_m \) and \( U_{pe} \) for “as there is” case together according frequencies were entered in PC and admittance's, impedance's, angle's and power's AFChs were plotted with formulae (4), (9) – (12) using. To model constant current, constant voltage or constant power loading regimes the next simple transition formulae were derived

\[
U_0 = U_{pe} \sin \gamma \sin \alpha = U_{pe} \sin \gamma \cos \alpha = U_{pe} \sin \gamma, \quad U_k = U_{pe} \cos \alpha = U_{pe} \cos \beta = U_{pe} \cos \gamma, \quad U_m = U_{pe} \cos \beta = U_{pe} \cos \gamma, \quad \cos \beta = \frac{U_k^2 + U_m^2 - U_{pe}^2}{2U_k U_m}.
\]

\[
P_0 = \frac{P_{pe} (1 - \cos \beta)}{\cos \beta} \sin \gamma, \quad \sin \gamma = \frac{U_k^2 + U_m^2 - U_{pe}^2}{2U_k U_m}.
\]

Here: \( U_{pe} \) are constant amplitude values which are taken for modelling while \( U_k \) and \( U_m \) for “as there is” regime.

Experimental-Calculation Methodology for Determination of the Coupling Factor and Loss Coefficients

It is necessary to know coupling and loss coefficients to calculate
any amplitude for piezoresonator’s vibrations. I used the simple experimental-analytical iterative process, which permits to obtain the refined values based on experimental data [11-13]. Elaborated by me iterative methodology is that.

At first the resonance/anti-resonance frequencies and admittances are measured for first vibration mode as well as static capacity $C_0$ and dielectric loss tangent $\tan \delta$. Values $s_{11m}$, $\kappa_{31}$, $d_{31m}$ enter to PC. Admittance AFCs in first resonance vicinity is plotted. A ratio maximum/minimum admittance’s frequency is compared with measured one and $k_{31}$ is correlated. Admittance AFC in first resonance vicinity is plotted again and $s_{11m}$ is correlated. When calculated values of $Y_m$ and $f_n/f_m$ coincide (or approach to) with measured ones it may be go to anti-resonant region and to find a piezoelectric loss tangent. Author’s experience shows that good results are obtaining with three or four iterative steps. For first step any hypothetic data may be taken of cause [18].

Determinations of transversal EMCC (electro-mechanic coupling coefficient) $k_{31}$, and tangents of mechanical $s_{11m}$ and piezoelectric $d_{31m}$ losses of energy were performed by iterative steps for basic longitudinal resonance of bar with sizes $33.4 \times 5.8 \times 1.25 \text{ mm}$ from piezoceramics TsTBS–3. It had $C_0 = 2.98 \text{ nF}$; $\tan \delta = 0.0637$; $Y_m = 11.6 \text{ mS}$; $Y_n = 0.0637 \text{ mS (Zn = 15.7 kOhm)}$; $f_n = 53.04 \text{ kHz}$; $f_m = 1.0398$; $a = 0.608 \text{ mS}$; $x_m = 1.571$. Multiplier $a$ serves to coordinate dimensionless and resonant frequencies and it is introducing as

$$\omega C_0 = 2\pi f_0 C_0 x / x_0 = a x_m$$

Where $x$ – running value of dimensionless complex frequency, $x_m$ – active component of dimensionless frequency, $f_0$ – measured frequency of admittance maximum.

The experimental measuring for thin piezoelectric bar fundamental mode of vibration was made with a loading resistor 229 Ohms.

Figure 1 illustrates three iterative steps (they were more in actual fact). For the sake of greater obviousness the plots of full conductivity are given to the first row, on the second row – entrance impedance. Plots for every step are similar and differ only with locations of a minimum of conductivity (or a maximum of impedance) on frequency. The voltage drops $U_{in}$ (solid lines) are given in the first column, $U_{in}$ (dashed curves) are resulted in a fourth column. Symbol “An” on the graphs means angle.

As a result of the first iteration which was made in the interval of dimensionless frequencies $1.5 \leq \times \leq 1.75$ at the next chosen values $k_{31}$ $s_{11m}$ $d_{31m}$ $\kappa_{31}$ $0.068 \text{ mS}$ such conductivities $Y_m = 7.8 \text{ mS}$; $Y_n = 0.112 \text{ mS}$ and frequencies $x_m = 1.64$; $x_m = 1.571$; $x_m/x_n = 1.0446$ were obtained (Figure 1a). It is need to diminish a ratio $x_m/x_n$, and it can be done only with diminishing of $k_{31}$ and for $Y_m$ increasing it is necessary to diminish $s_{11m}$.

Next iteration was provided in the same frequency range at other set of values $k_{31} = 0.09; s_{11m} = 0.006; \kappa_{31} = 0.0093; d_{31m} = 0.007; a = 0.608 \text{ mS}$. Such conductivities $Y_m = 11.7 \text{ mS}$; $Y_n = 0.0735 \text{ mS}$ and frequencies $x_m = 1.6321$; $x_n = 1.571$; $x_m/x_n = 1.0389$ were got (Figure 1b). Maximum of the complete conductivity and ratio of frequencies approach experimental values, and for diminishing of a minimum of conductivity it is needed to reduce the tangent of piezoelectric losses. Last iteration was conducted in a same frequency interval at $d_{31m} = 0.004$. It was got conductivities $Y_m = 11.7 \text{ mS}$; $Y_n = 0.0684 \text{ mS}$ and frequencies $x_m = 1.6321$; $x_n = 1.571$; $x_m/x_n = 1.0389$ (Figure 1c). Disagreement with an experiment makes for $Y_m = 0.86%$, $Y_n = 7.4%$, $f_n/f_m = 0.03%$.

Thus, as a result of iterative procedures it is possible to consider set for the studying bar the following information: $k_{31} = 0.09; s_{11m} = 0.006; \kappa_{31} = 0.0093$ and $d_{31m} = 0.004$. This information may be used for calculations of admittances, impedances, powers, displacements, strains or stresses in any point of thin piezoelectric bar.

Similar iterative technique was used [18] for accurate determination of real and imaginary parts of the piezoceramics coefficients.

**Modeling of an Electrical Loading Conditions of the Piezoelements**

To estimate influence of the chosen electric loading regime on piezoceramic bar with dimensions $33.4 \times 5.8 \times 1.25 \text{ mm}$ made of TsT-BC-3 ceramics forced vibrations amplitude-frequency-characteristics (AFCs) were plotted for the cases “as there is”, constant sample current, constant sample voltage and constant sample power (Figure 2). A transition from one type of loading conditions to other is done with the use of formula (13). There are plots in the first row “as there is”, the second row answers constant current permanent amplitude of 1mA, the third row brings results over for the case of a voltage on piezoelement 100 mV (such level was experimentally got on resonance) and fourth row represents a case of constant instantaneous power level 0.218 mVA. The voltage drops $U_{in}$ (solid lines) are given in the first column, $U_{in}$ (dashed curves) and $U_{in}$ (dotted lines). Second and third columns are accordingly built for AFCs of full conductivity and instantaneous power. AFCs of phase angles $\alpha$ (solid lines), $\beta$ (dotted lines) and $\gamma$ (dashed curves) are resulted in a fourth column. Symbol "An" on the graphs means angle.
The analysis of the graphs shows the next facts. The regime of the electric loading does not influence on AFChs of full conductivity and phase shifts – they remain without changes at the change of external electric conditions. At the same time, AFChs of instantaneous power and voltages strongly depend on the chosen loading regime. At approaching to resonance in the regime “as there is” a voltage \( U_0 \) goes down (due to shunting operating of measuring circuit on the output of generator or coordinating voltage divider). Sharp growth of loading resistor \( U_0 \) voltage takes a place and decline of voltage drops \( U_{\text{pe}} \) on piezoelement. And at nearing to anti-resonance the voltage drops on the loading resistor goes down and arrives at a minimum on certain frequency which is equated with anti-resonance [13,17,18].

An influence of electric loading conditions on piezoelectric ceramic sample vibrations’ parameters differs for voltage drops, instant powers and admittance/impedance ones. Although piezoceramic materials are known as nonlinear substance author's experience and literature data testify that they may be regarded as liner for electric field up to1000 V/m level range. All graphs in this paper were built for linear approximations. The experimental investigation for thin piezoceramic disk radial vibrations at constant input voltage, constant sample voltage and constant sample current corroborated such intention [12].

Results and Discussion

Graphs of input \( U_0 \) and sample \( U_{\text{pe}} \) voltages partly or fully coincide after transformations from "as there is" regime to constant current and constant power regimes. These curves do not be separated on black-white figs.

In regimes, constant sample current and constant sample voltage the frequency locations of instant power’s maxima coincide with frequency locations of input voltage maxima. In regimes "as there is" the "failure" at resonance is observed in AFCh of instant power that may be result of part power reduction by loading resistor. It is necessary to increase of the input voltage at anti-resonance to realize of the constant sample current regime and at resonance for realization of the constant sample voltage regime. Regimes of constant instantaneous power may be realized with simultaneous increasing both resonant and anti-resonant input voltage. The degree of such increasing depend upon of loading resistor value and consists from a number of tens percents near resonance to several times near anti-resonance in respect to off-resonance case. The phase shift between sample voltage and sample current (angle \( \alpha \)) reaches \( \pi \) radian at resonances and anti-resonances and it changes from \( \pi/2 \) to \( \pi \) in frequency range. The phase shift between output voltage of generator or voltage divider and consumable current (angle \( \beta \)) is equal to \( \pi/2 \) radian in frequency range [18]. It declines to zero at resonances and anti-resonances. And, difference of phases between output voltage of generator (voltage divider) and voltage drop on piezoelement (angle ) declines to zero at resonances and may reach \( \pi/2 \) radian level at off-resonance frequencies.

Figure 3 demonstrates the experimental and transformed data for sample admittance and instantaneous sample power, obtained on PZT-type piezoelectric plate \( 40 \times 16 \times 1 \) mm with thickness polarization. Admittance spectrum is plotted for constant sample power (Figure 3a), constant current (Figure 3b), constant sample voltage (Figure 3c), and constant input voltage (Figure 3d) at frequency range below and near strong lateral resonance. Sample admittance is not dependent from electrical regime.

Power spectrum for regimes "as there is" (Figure 4a), constant current (Figure 4b), constant sample voltage (Figure 4c), and constant input voltage (Figure 4d) was built for same frequency range (Figure 4).

Constant current regime leads to decreasing resonant power and to increasing anti-resonant power, constant voltage and “as there is” regimes lead to increasing resonance power and to decreasing anti-resonance power. Such is on my mind a reason of nonlinearity, obtained by authors [2,15].

Formulae (5) and (6) were used for calculations of instantaneous power and its real or imaginary parts of thin piezoelectric bar’s first longitudinal resonance. Calculations were made with next data \( k_2=0.09; s_{11m}=0.006; \varepsilon_{33m}=0.0093 \) and \( d_{31m}=0.004 \) which were obtained as a result of iterative process for \( 33.4 \times 5.8 \times 1.25 \) mm bar from TsTBS–3 piezoceramics.

Figure 5 illustrates power frequency spectrum in range \( 1.52 \leq x \leq 1.68 \) for constant current \( I_0 = 0.1 \) mA (a) and constant voltage \( U_0 = 0.1 \) V (b) loading conditions. The admittance for constant voltage (c) and impedance for constant current (d) AFChs are plotted for compare. Full values of instantaneous power, admittance and impedance are given with solid lines. Their real parts are depicted as dashed curves and imaginary components are shown with dotted lines.

It is easy to see that instantaneous power spectrum’s view for constant current conditions is the same as impedance's spectrum and

\[ \text{Figure 3: Transformed admittance spectrum for constant sample power (a), constant current (b), constant sample voltage (c), and constant input voltage (d) near strong lateral resonance.} \]

\[ \text{Figure 4: Transformed power spectrum for constant sample power (a), constant current (b), constant sample voltage (c), and constant input voltage (d) near strong lateral resonance.} \]

\[ \text{Figure 5: Calculated instantaneous power spectrum's view in comparison with admittance and impedance spectrums.} \]
Constant current regime leads to decreasing resonant power and to decreasing anti-resonant power. Iterative process and linear approximation were used by me for more complicated cases such as circular segments or thin bars with divided electrode coating [18]. Results of these investigations are similar to results for thin bar vibrations case.

**Conclusion**

Amplitude-frequency characteristics for piezoelectric bars, disks, short and high cylindrical rings which were received in Institute Mechanics Research Laboratory (Department of Electro-elasticiy) shown that electric loading regimes do not influence on admittance, impedance and phase angles. Independence these parameters from electrical loading regimes is explained simply – relations between voltages drops $U_w$, $U_r$ and $U_e$ are not changed. But voltage drops and instantaneous power are very sensitive to loading conditions.

Results may be explained in such a way that when piezoelectric sample is excited by constant voltage the instantaneous power in sample increases at resonance frequency in many times in respect to off-resonant case. And when sample is excited by constant current the instantaneous power in sample decreases at resonance frequency in that ratio. Thus, the reason of admittance curve nonlinearity at constant voltage and its absence at constant current is upper or lower level of an instantaneous power.

A linear approximation for transformation of measured data permits to study main features of the piezoelectric resonators’ vibrations without large mathematical and experimental difficulties. Such methodology gives possibility to make clear the general tendencies in piezoelectric sample behaviour for various electric loading conditions.

Instantaneous power spectrum’s view for constant current conditions is the same as impedance’s spectrum while instantaneous power spectrum’s view for constant voltage is the same as admittance’s spectrum. Calculations and experimental investigations show that constant current regime leads to decreasing resonant power and to increasing anti-resonant power, but constant voltage regime leads to increasing resonant power and to decreasing anti-resonant power.

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