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# THE APPLICATION OF PARALLEL OSCILLATORY CIRCUIT IN THE CIRCUITS WITH PIEZOELECTRIC TRANSFORMER

*The work is devoted to actual problems of the perfection of piezoelectric transformers. Changing of piezoelectric transformers characteristics is possible due to external circuit for piezoelectric element – electric, mechanical or acoustic one. The paper investigates the use of parallel oscillatory circuit in the schemes of piezoelectric transformers. Equivalent circuit modeling of piezoelectric transformers with parallel oscillatory circuit is made. The use of offered equivalent circuit allows with the application programs to assess characteristics, to predict the parameters and operation mode of piezoelectric transformers. The results of research are obtained by simulation and compared with real characteristics of experimental sample.*

***Key words:*** *piezoelectric transducer, transformer, parallel oscillatory circuit, amplitude-frequency response, equivalent circuit.*

Piezoelectric transducers are widely used in electroacoustics, hydroacoustics, in ultrasound, medical, measurement technique, in scanning probe nanomicroscopes, piezoengines and in other fields of science and technology [1-3].

Piezoelements are used for the manufacture of piezoelectric transducers in the form of piezoresonators and piezotransformers. The last, in some cases, can improve the transducers characteristics [2, 3].

Piezoelectric element is an electromechanical oscillatory system with sufficiently high quality factor. The parameters of such system can be changed by mechanical (acoustic) or electrical elements joining [4, 5].

In [4-6] the synthesis technologies of piezoelectric transducers are described. These technologies allow to create transducers with necessary characteristics.

Among the described technologies of special interest is the technology of additional elements, since in this case the change in characteristics of the transducer is due to external circuits of piezoelectric element. The essence of this technology is that additional oscillatory systems (electric, mechanical, electro-mechanical or acoustic systems) are attached to piezoelectric element [5].

The application of series oscillatory circuit in the circuits with piezoelectric transducers, having in a narrow band of frequencies near resonance relatively high conductivity, i.e. low resistance, is investigated in [4, 5]. But it is often necessary to use a resonant system having in a narrow band of frequencies relatively high resistance. Parallel resonant circuits possess this property [7].

The **purpose** of this work consists in the research of piezoelectric transformers with additional parallel oscillatory circuit.

As it is known, piezoelectric transformer is an electromechanical oscillatory system; its equivalent circuit diagram is shown in Fig. 1, ***a*** [1-3], where $L_d$, $C_d$, $R_d$ are dynamic inductance, capacitance and active losses in piezoelectric element.

Equivalent circuit (Fig. 1, *a*) can be simplified by reflecting secondary network to primary one (Fig. 1, *b*) [8].

The values of reflected resistance $R'_o$, reflected capacitance $C'_o$ and reflected output voltage $U'_{out}$ will be:

$$R'_o = \frac{R_o}{n^2}; \quad (1)$$

$$C'_o = n^2 \cdot C_o; \quad (2)$$

$$U'_{out} = \frac{U_{out}}{n^2}, \quad (3)$$

where $R_o$ is load resistance; $C_o$ is output capacitance; $U_{out}$ is output voltage; $n$ is ideal transformer transfer ratio.

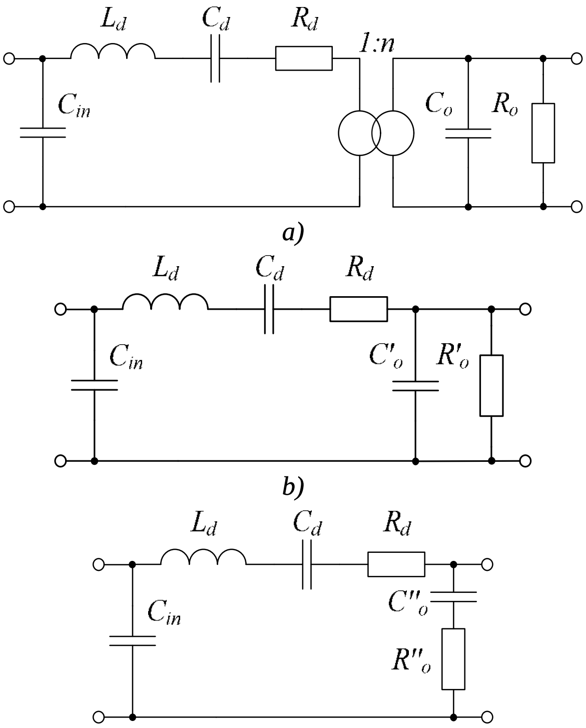



**Fig. 1. Equivalent circuits of piezoelectric transformer:** *a)* general model; *b)* reflected model; *c*) series model

Further simplification can be achieved by converting parallel network $R'_oC'_o$ to series network $R''_oC''_o$, in which series resistance $R''_o$ and series capacitance $C''_o$ are determined as:

$$R''_o = \frac{R'_o}{1+(wC'_o R'_o)^2}; \quad (4)$$

$$C''_o = C'_o \frac{1+(wC'_o R'_o)^2}{(wC'_o R'_o)^2}, \quad (5)$$

where $\omega$ is operating frequency.

Based on equations (4), (5), some general conclusions can already be drawn:

– maximum resistance $R''_{omax}$ is reached at $R'_{o\max} = \frac{1}{wC'_o}$;

– for a given reflected load $R'_o$ maximum output voltage will be obtained at resonant frequency $\omega_m$:

$$w_m = \frac{1}{\sqrt{L_d \tilde{N}_{eq}}}, \quad (6)$$

where $C_{eq}$ is series value of $C_d$ and $C''_o$ (Fig. 1):

$$\tilde{N}_{eq} = \frac{C_d C''_o}{C_d + C''_o}; \quad (7)$$

– for any given load $R_o$ output voltage can be controlled by shifting the frequency above or below $\omega_m$. This is, in fact, the method used in inverters and converters operating in frequency-shift control mode;

– for any given load $R_o$ the fraction of power transferred to the load at resonant frequency will depend on the ratio of $R''_o$ to $R_d$ (Fig. 1, *c*);

– maximum power will be delivered to the load when $R''_o = R_d$.

The efficiency of piezoelectric transformer can be found from [8]:

$$h = \frac{R''_o}{R''_o + R_d} = \frac{1}{1+\frac{R_d}{R''_o}}, \quad (8)$$

where $R''_o$ is reflected load resistance in equivalent series circuit $R''_oC''_o$ (Fig. 1, *c*).

When connecting parallel inductance $L_{ad}$ to piezoelectric transformer (PT) output (Fig. 2), this inductance and capacitance between the electrodes $C_o$ form parallel oscillatory circuit $L_{ad}C_o$, in which resonant frequency is determined as [7]:

$$f = \frac{1}{2p\sqrt{L_{ad}\tilde{N}_o}}. \quad (9)$$

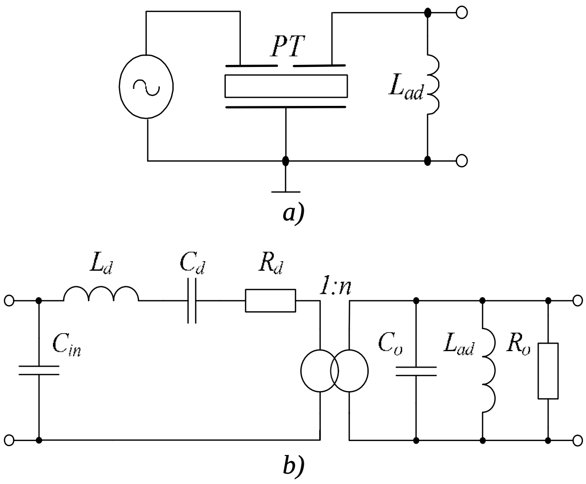



**Fig. 2. Piezoelectric transformer with parallel inductance:** *a)* connection diagram; *b)* equivalent circuit

Parallel inductance $L_{ad}$ is selected from equation (9):

$$L_{ad} = \frac{1}{w^2 \tilde{N}_o}, \qquad (10)$$

where $w = \frac{1}{\sqrt{L_d \tilde{N}_d}}$ is piezoelectric element own resonant frequency.

The application of parallel circuit allows to reach the improvement of piezoelectric transformer efficiency.

The losses in the resistance $R_d$ are lower in this case and therefore the efficiency of piezoelectric transformer will be higher. In such a case, equivalent resistances $R''_o$ and $R'_o$ (Fig. 1, *b*, *c*) have identical values and hence the equation (8) of piezoelectric transformer efficiency is reduced to the following form:

$$h_L = \frac{R'_o}{R'_o + R_d} = \frac{1}{1 + \frac{R_d}{R'_o}}. \qquad (11)$$

The ratio between efficiency values in two cases: without and with matching parallel inductance $L_{ad}$ is found from equations (11), (8) and (4):

$$\frac{h}{h_L} = \frac{1 + \frac{R_d}{R'_o}}{1 + \frac{R_d}{R"_o}} = \frac{1 + \frac{R_d}{R'_o}}{1 + \frac{R_d}{R'_o}\left[1 + (wC'_o R'_o)^2\right]}$$

or after converting [8]:

$$\frac{h}{h_L} = \frac{1}{1 + \frac{(wC'_o R'_o)^2}{1 + \frac{R'_o}{R_d}}}. \qquad (12)$$

The analysis of equation (12) shows, that in general $\eta < \eta_L$, but for small $\frac{R_d}{R'_o}$ and $wC'_o R'_o$ values, we find $\eta \approx \eta_L$.

Amplitude-frequency characteristics (AFC) of piezoelectric transformer based on bimorph element of the transducer ZP-19 and the transformer with parallel inductance are shown in Fig. 3.

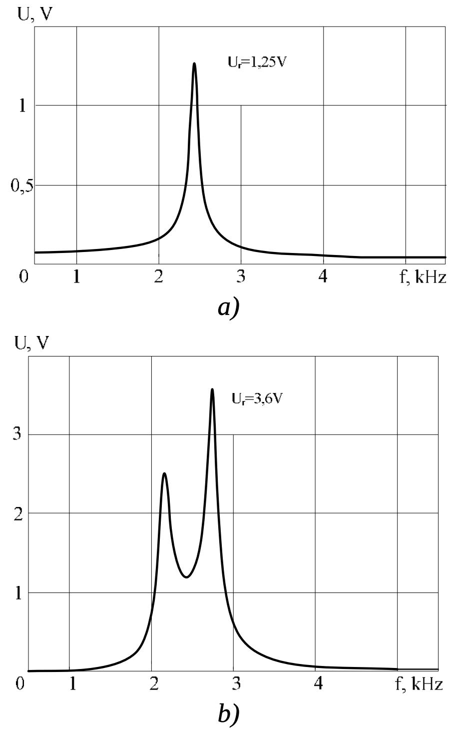
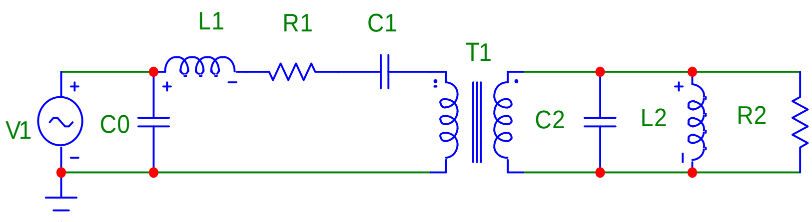



**Fig. 3. AFC of piezoelectric transformer without (*a*) and with parallel inductance (*b*)**

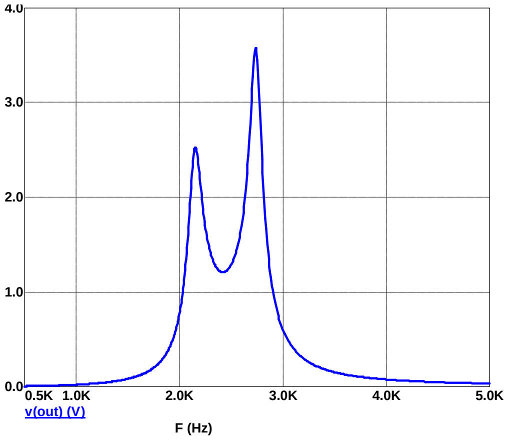
As can be seen from Fig. 3, the application of parallel inductance allows to raise output signal level and to expand a bandwidth.

Analytical expressions for amplitude-frequency characteristics (AFC) of such oscillatory systems are not available, so the determination of AFC is often carried out experimentally; it is not always convenient and increases the time of piezoelectric transducers designing. The use of models allows with application programs to assess characteristics, to predict the parameters and operation mode of piezoelectric transformers.

So for the transformer with additional parallel inductance (Fig. 2, *a*) schematic model (equivalent circuit) is built (Fig. 4, *a*) and its modeling is performed in Micro-Cap program Fig. 4, *b*).




*a)*




*b)*

**Fig. 4. Schematic model of piezoelectric transformer with parallel inductance (*a*) and AFC simulation results in Micro-Cap program (*b*)**

The resistances and voltages matrices for a given equivalent circuit (Fig. 4, *a*) can be written as:

$$A = \begin{pmatrix} 1 & -1 & 1 & 0 \\ 0 & 0 & \frac{1}{n} & -1 \\ R_g & X_{in} & 0 & 0 \\ 0 & X_{in} & Z_d & \frac{X_{out}}{n} \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ 0 \\ E \\ 0 \end{pmatrix}. \quad (13)$$

Piezoelectric transformer output voltage equals:

$$U_{out} = \frac{E \cdot X_{in} \cdot X_{out}}{n\left( (X_{in})^2 - (R_g + X_{in})\left( X_{in} + Z_d + X_{out}/n^2 \right) \right)}, \quad (14)$$

where

$$Z_d = jwL_d + \frac{1}{jwC_d} + R_d ; \; X_{in} = \frac{1}{jwC_{in}} ;$$

$$X_{out} = \frac{X_{Cout} \cdot X_{ad}}{X_{Cout} + X_{ad}} ; \; X_{Cout} = \frac{1}{jwC_{out}} ;$$

$$X_{ad} = jwL_{ad} ; \; w = 2p\, f \; ;$$

$L_d$, $C_d$, $R_d$ are piezoelectric transformer dynamic electrical parameters; $C_{in}$, $C_{out}$ are piezoelectric transformer input and output capacitances; $n$ is ideal transformer transfer ratio; $R_g$ is generator resistance.

Fig. 5 shows amplitude-frequency characteristic simulation of piezoelectric transformer with parallel inductance in Mathcad program according to equations (13, 14).

As can be seen from Fig. 3–5, amplitude-frequency characteristics of constructed model are practically the same with the characteristics of experimental sample.

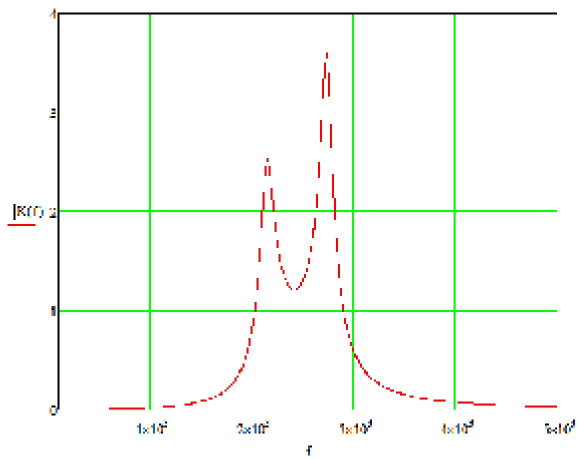



**Fig. 5. AFC simulation results in Mathcad program**

So, parallel oscillatory circuit can be used for more effective energy transfer from piezoelectric transformer to the load.

**Conclusions:**

1. The research of piezoelectric transformer with parallel oscillatory circuit is performed.

2. Equivalent circuit (schematic model) of piezoelectric transformer with parallel oscillatory circuit is constructed.

3. Offered equivalent circuit allows with application programs to assess characteristics, to predict the parameters and operation mode of piezoelectric transformers.

4. Parallel oscillatory circuit can be used for more effective energy transfer from piezoelectric transformer to the load.

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## ПРИМЕНЕНИЕ ПАРАЛЛЕЛЬНОГО КОЛЕБАТЕЛЬНОГО КОНТУРА В СХЕМАХ С ПЬЕЗОЭЛЕКТРИЧЕСКИМ ТРАНСФОРМАТОРОМ

*Работа посвящена актуальным вопросам совершенствования пьезоэлектрических трансформаторов. В статье исследовано применение параллельного колебательного контура в схемах с пьезоэлектрическими трансформаторами. Построена эквивалентная схема пьезоэлектрического трансформатора с параллельным колебательным контуром. Использование предложенной эквивалентной схемы позволяет с помощью прикладных программ проводить оценку характеристик, прогнозировать параметры и режим работы пьезоэлектрических трансформаторов. Представлены результаты сравнения характеристик экспериментального образца и эквивалентной схемы.*

***Ключевые слова:*** *пьезоэлектрический преобразователь, трансформатор, параллельный колебательный контур, амплитудно-частотная характеристика, эквивалентная схема.*