

# FREQUENCY CONTROL FOR ULTRASONIC PIEZOELECTRIC TRANSDUCERS, BASED ON THE MOVEMENT CURRENT

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**Abstract:** This paper provides a method for frequency control at the ultrasonic high power piezoelectric transducers, using a feedback control systems based on the first derivative of the movement current. This method assures a higher efficiency of the energy conversion and greater frequency stability. A simulation for two kinds of transducer model is made. The method is implanted on a power electronic generator. Some transient characteristics are presented.

## 1 INTRODUCTION

Piezoelectric transducers (Gallego-Juarez, 1989) have proved their huge viability in the high power ultrasonic applications as cleaning, welding, chemical or biological activations and other for many years (Hulst, 1972), (Neppiras, 1972). And these applications continue to be of a large necessity.

The power ultrasonic transducers are fed with power inverters, using transistors working in commutation at high frequency (Bose, 1992). A large scale of electronic equipments, based on analogue or digital technology, is used for control in the practical applications (Marchesoni, 1992.).

A good efficiency of the energy conversion in the power ultrasonic equipments is very important to be assured. Different control methods are used in practice to control the signal frequency in the power inverters (Ramos, et. all., 1985), (Fabianski and Palczynski, 1989).

The high power ultrasonic piezoelectric transducers are analysed with complex structures by using equivalent circuits (Lazaro et. all. 1989), starting from Mason's model, implemented on circuit analysis programs (Morris, 1986).

Many frequency control methods, structures and devices, on this field of interest, are patented.

This paper presents a method to control the frequency of the feeding voltage for the piezoelectric transducer. A power amplifier working in commutation at high frequency generates the feeding voltage. The control system is based on a PI

controller, which keep at zero the derivative of the movement current. This control assures the maximum of the mechanic power generated by the transducer.

## 2 RELATED WORK

To perform an effective function of an ultrasonic device for intensification of different technological processes a generator should have a system for an automatic frequency searching and tuning in terms of changes of the oscillation system resonance frequency. The article (Khmelev, et all., 2001) presents a system of phase-locked-loop frequency control of ultrasonic generators with automatic resonance frequency searching in the given band of frequencies.

In (Furuichi and Nose, 1981) a driving circuit for ultrasonic tools which uses a piezoelectric transducer to convert ultrasonic electric signals into ultrasonic mechanical vibrations includes a voltage-controlled oscillator which produces an output signal at a frequency that is proportional to an input voltage, a power amplifier stage having its input coupled to the output of the voltage-controlled oscillator.

In (Hasegawa, 2003) an automatic frequency control (AFC) circuit is based on a frequency offset estimating circuit produces a lock signal if a calculated frequency error becomes smaller than a predetermined value.

The dynamic characteristics of a fixed measuring transducer are defined not only by the parameters of its mechanical system and the ability to convert mechanical into electrical energy but also by the properties of the object on which the transducer is mounted and by the mounting rigidity. In the paper (Senchenkov, 1991) the block diagram is discussed of a system that will detect and evaluate the faults in measuring transducers by comparing the amplitude-frequency characteristic obtained by applying electric pulses to the piezoelement of the transducer with the amplitude-frequency characteristics obtained for the transducer in its natural state and at the moment after it has been mounted on an object.

In (Sullivan, 1983) a power supply is provided for an electromechanical device of the type employing ultrasonic frequency vibratory energy for bonding materials. An automatic frequency control varies the output frequency of the power supply until the ratio of the maximum to minimum amplitudes of a standing wave produced in the mechanical vibratory member falls below a pre-set maximum. The power supply frequency is automatically varied to maintain the standing wave ratio below a pre-set value which is deemed to be an acceptable value for efficient transfer of power.

### 3 CONTROL PRINCIPLE

#### 3.1 The Equivalent Circuit of the Piezoelectric Transducer

The electrical energy of ultrasonic frequency in the bandwidth of 20-80 kHz is converted in mechanical energy using piezoelectric transducers. A kind of piezoelectric transducer of 100 W is presented in figure 1,a. In practice the transducer (1) is mechanical coupled with an energy concentrator (2), as is presented in figure 1,b).

The ultrasonic piezoelectric transducers have the equivalent electric circuit from figure 2. In this circuit there is emphasized the mechanical part, seen as a series RLC circuit, with the equivalent parameters  $R_m$ ,  $L_m$  and  $C_m$ , which are nonlinear, depending on the transducer load.

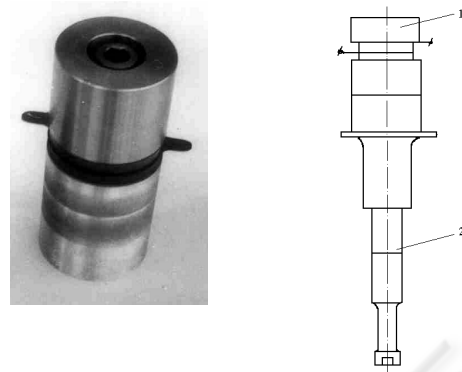


Figure 1 a): A piezoelectric transducer.

Figure 1 b): Piezoelectric transducer coupled with an energy concentrator.

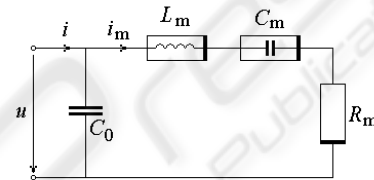


Figure 2: The equivalent circuit of the piezoelectric transducer.

The current through the mechanical part  $i_m$  is the movement current. The input capacitor  $C_0$  of the transducer is considered as a constant parameter.

The equations (1) are describing the time variation of the signals and the mechanical parameters.

$$\begin{aligned}
 u_{L_m} &= \frac{d\phi_{L_m}}{dt} = \frac{dL_m}{dt} i_m + L_m \frac{di_m}{dt} \\
 i_{C_m} &= \frac{dq_{C_m}}{dt} = \frac{dC_m}{dt} u_{C_m} + C_m \frac{du_{C_m}}{dt} \\
 i_{C_m} &= \frac{dq_{C_m}}{dt} = \frac{dC_m}{dt} u_{C_m} + C_m \frac{du_{C_m}}{dt} \quad (1) \\
 R_m &= \frac{du_{R_m}}{di_m} \\
 i &= i_0 + i_m \\
 u &= u_{L_m} + u_{C_m} + u_{R_m} \\
 C_0 \frac{du}{dt} &= i_{C_0}
 \end{aligned}$$

where  $\phi$  is the magnetic flux through the mechanical inductance  $L_m$  and  $q$  is the electric load over the mechanical capacitor  $C_m$ .

The piezoelectric transducer has a frequency characteristic of its impedance  $Z$  with a series and a parallel resonance, as it is presented in figure 3.

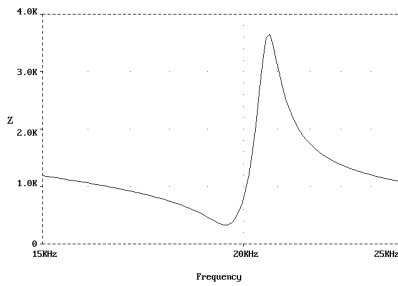


Figure 3: The frequency characteristic of the transducer impedance.

The movement current  $i_m$  has the frequency characteristics from figure 4.

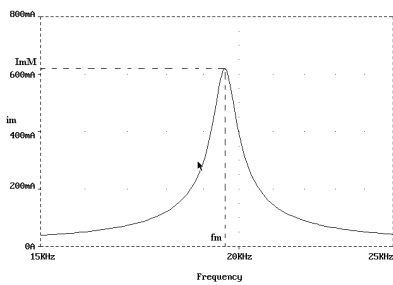


Figure 4: The frequency characteristic of the transducer impedance.

The maximum mechanical power developed by the transducer is obtained when it is fed at the frequency  $f_m$ , where the maximum movement current  $i_m = I_{mM}$  is obtained. Of course, the maximum of the movement current  $i_m$  is obtained when the derivative of the absolute value of the movement current  $dim$  is zero:

$$dim(t) = \frac{d|i_m|}{dt} = 0 \quad (2)$$

So, a frequency control system, functioning after the error of the derivative movement current may be developed, is using a PI frequency controller, to assure a zero value for this error in the permanent regime.

### 3.2 The Frequency Control System

The block diagram of the frequency control system based on the above assumption is presented in figure 5.

A power amplifier AP, working in commutation, at high frequencies, feeds a piezoelectric transducer E, with a rectangular high voltage  $u$ , with the frequency  $f$ . An output transformer T assures the high voltage  $u$  for the ultrasonic transducer E. A command circuit CC assures the needed command signals for the power amplifier AP. The command signal  $u_c$  is a rectangular signal, generated by a voltage controlled frequency generator GF\_CT. The rectangular command signal  $u_c$  has the frequency  $f$  and equal durations of the pulses. The frequency of the signal  $u_c$  is controlled with the voltage  $u_f^*$ . The signal  $u_f^*$  to control the frequency  $f$  of the transducer is provided by the frequency controller RG-f.

The frequency control system from figure 4 is based on the derivative movement current error  $e_{dim}$ :

$$e_{dim} = dim^* - dim \quad (3)$$

as the difference between the reference value  $dim^* = 0$  and the computed value of the derivative  $dim$ .

A PI controller is used to control the frequency, with the following transfer function:

$$u_f^*(s) = K_R \left( 1 + \frac{1}{T_R s} \right) e_{dim}(s) \quad (4)$$

The frequency controller is working after the error of the derivative of the movement current  $e_{dim}$ .

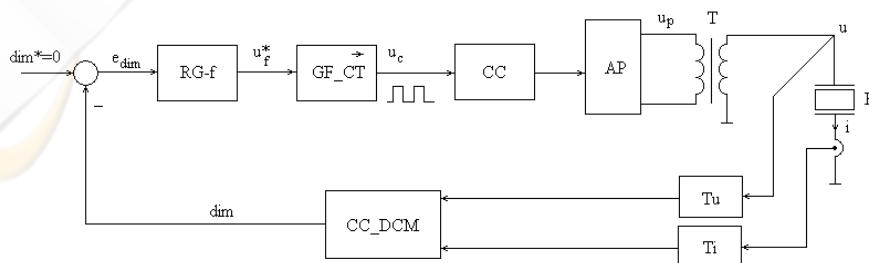


Figure 5: The block diagram of the frequency control system.

The derivative of the movement current  $dim$  is computed using a circuit CC\_DCM, where  $C_0$  is the known constant value of the capacitor from transducer input and  $u$  and  $i$  are the measured values of the transducer voltage and current.

The voltage upon the transducer  $u$  and the current  $i$  through the transducer are measured using a voltage sensor Tu and respectively a current sensor Ti.

#### 4 MODELING AND SIMULATION

Some models for different parts of the block diagram from figure 5 were developed to test the control principle by simulation.

Two models are tested for the transducer. In the first model the parameters of the mechanical part are considered with a static value and a dynamical variation. In the second model the electromechanical transducer is considered coupled with a mechanical concentrator.

Approximating the relations (1), the following relations are used to model the behaviour of the piezoelectric transducer:

$$\begin{aligned} u_{Lm}(s) &= sL_m(s)i_m(s) + sL_m(s)i_m(s) \\ i_{Cm}(s) &= sC_m(s)u_{Cm}(s) + sC_m(s)u_{Cm}(s) \\ u_{Rm}(s) &= \frac{1}{s}R_m[s\dot{i}_m(s)] \\ u(s) &= u_{Lm}(s) + u_{Cm}(s) + u_{Rm}(s) \end{aligned} \quad (5)$$

The movement current  $i_m(s)$  is modelled, based on the above relations, with the following relation:

$$i_m(s) = \frac{1}{s} \left[ \frac{1}{L_m} \times \left( u(s) - \frac{1}{s} \cdot \frac{1}{C_m} \times i_m(s) - R_m \times i_m(s) \right) \right] \quad (6)$$

The block diagram of the movement current model is presented in figure 6.

The mechanic parameters from the above relations have the variations given by relations (7), in the vicinity of the stationary points  $R_{m0}$ ,  $L_{m0}$  and  $C_{m0}$ .

$$\begin{aligned} R_m &= R_{m0} + \Delta R_m \\ L_m &= L_{m0} + \Delta L_m \\ C_m &= C_{m0} + \Delta C_m \end{aligned} \quad (7)$$

A second model is taken in consideration. The transducer is considered coupled with the concentrator and the equivalent circuit is presented in figure 7.

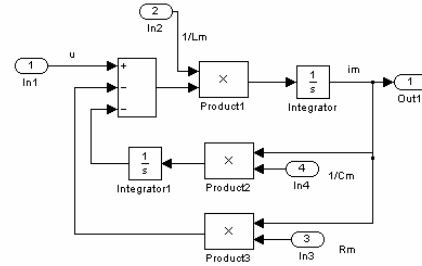


Figure 6: The block diagram, model for the mechanical part of the piezoelectric transducer.

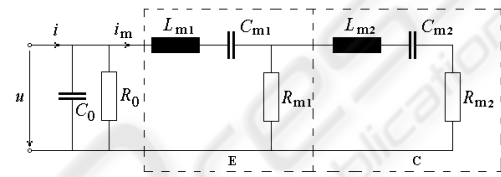


Figure 7: Equivalent circuit of the transducer with concentrator.

In this model there is a series RLC with the parameters  $L_{m1}$ ,  $C_{m1}$  and  $R_{m1}$  for the transducer T and a series RLC circuit with the parameters  $L_{m2}$ ,  $C_{m2}$  and  $R_{m2}$  for the concentrator C, coupled in cascade.

The parts of the control block diagram are modelled using Simulink blocks. A transient characteristic of the frequency error  $e_{dim}$  from the control system is presented in figure 8.

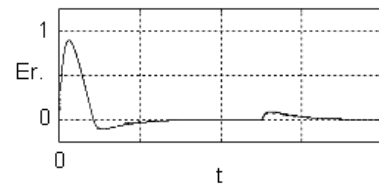


Figure 8: Transient characteristic for the frequency control system, obtained by simulation.

The simulation is made considering for the first model the variation with 10 % at the transducer parameters. The deviation in frequency is eliminated fast. The frequency response has a small overshoot.

## 5 IMPLEMENTATION AND TEST RESULTS

The frequency control system is developed to be implemented using analog, high and low power, circuits, for general usage. The power amplifier AP is realized using four power MOSFET transistors, in a full bridge, working in commutation at high frequency. The voltage controlled frequency generator GF\_CT is realized using a phase lock loop PLL circuit and a comparator. The computing circuit CC\_DCM, which implements the relations and the frequency controller RG-f are realized using analogue operational amplifiers. The transformer T is realized using ferrite cores.

The electronic generator is presented in figure 9.

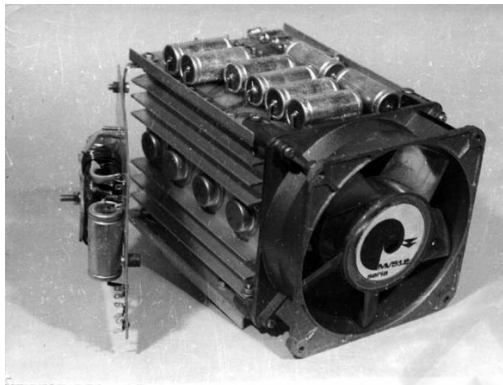


Figure 9: The electronic generator.

In the following figures some transient signal variations of the control system are presented.

The pulse train of the command voltage  $u_c$  is presented in figure 10.

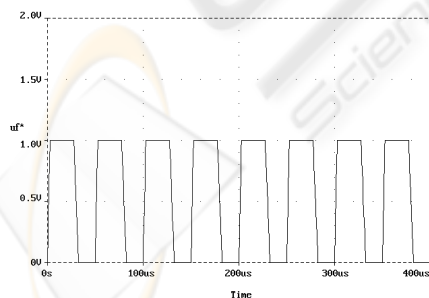


Figure 10: Examples of sensor impulse trains.

The output voltage of the power amplifier is presented in figure 11.

The voltage  $u$  over the piezoelectric transducer is presented in figure 12.

The measured movement current  $i_m$  is presented in figure 13.

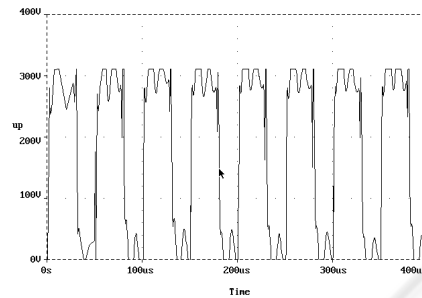


Figure 11: The output voltage.

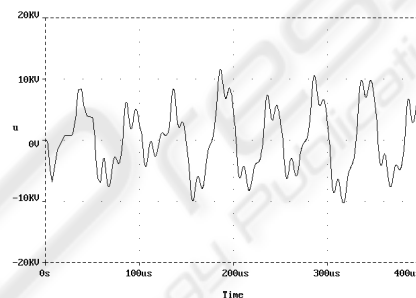


Figure 12: The transducer voltage.

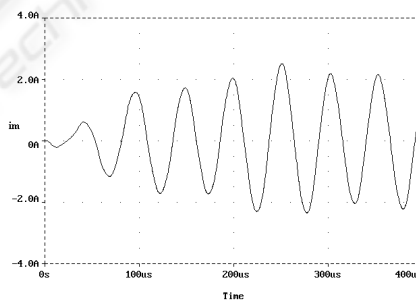


Figure 13: The movement current.

## 6 CONCLUSIONS

In this paper a method to control the frequency of the piezoelectric ultrasonic transducers based on the movement current through the mechanical part of the equivalent circuit of the transducer is presented. The principle of this method is to assure the maximum mechanical power developed by the transducer, based on the measured transducer's voltage and current, controlling the feeding voltage frequency, as the derivative of the movement current to be zero.



The frequency control system was modelled and simulated using Matlab and Simulink. Two models for the mechanical part of the transducer are chosen. Two different regimes for the time variations of the mechanical parameters of the transducer was chosen and tested. A Simulink model and a simulation result are presented. The simulation results have proven that the control principle developed in this paper gives good quality criteria for the output frequency control.

The control system is implemented using a power inverter with transistors working in commutation at high frequencies and analogue circuits for command. Transient characteristics of the control systems are presented.

The frequency control system may be developed for piezoelectric transducers in a large scale of constructive types, powers and frequencies, using general usage analogue components, at a low price, with good control criteria.

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