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Methods for parameter estimation and frequency control of piezoelectric transducers

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1. Introduction

This chapter presents some considerations related to parameter identification and frequency control at piezoelectric transducers used in high power ultrasonic applications as: metal or plastic welding, ultrasonic cleaning and other. Piezoelectric transducers are used as actuators, which convert electric power in acoustic power at ultrasonic frequencies. In practical design it is important to have information about their equivalent electrical circuit: parameters and resonance frequency. The main purpose of research is to develop control systems for piezoelectric transducers with a higher efficiency of the energy conversion and greater frequency stability. In the world literature there are many publications treating the domain of transducer measurement and frequency control. Some of these references, related to the chapter theme, are presented as follows.

Piezoelectric transducers (Gallego-Juarez, 2009) 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 (Senchenkov, 1991), (Khemel & all, 2001) and many other. The high power ultrasonic piezoelectric transducers are analysed with complex structures by using equivalent circuits, starting from Mason's model, implemented on circuit analysis programs (Morris, 1986). Impedance measurement is done using different methods (Chen & all, 2008). The wave guides are analysed in the assemble of ultrasonic systems: transducer- wave guide - process (Mori, 1989). Books on ultrasonic are presenting modelling and design methods (Prokic, 2004), (Radmanovici & all, 2004). There are many technical solutions reported in practice, for example (Fuichi & Nose, 1981), (Khmelev & all, 2001), (Kirsh & Berens, 2006) or (Sullivan, 1983).

In the beginning of this chapter some general consideration related to the equivalent electrical circuit of the piezoelectric transducers and their characteristics useful in practice are presented. In the second paragraph a parameter estimation method based on the

transformation from the Nyquist hodograph from the frequency domain to a parameter model - the transfer function of the transducer's impedance, is presented. In the third paragraph a second parameter estimation method is based on an automatic measurement of piezoelectric transducer impedance using a deterministic convergence scheme with a gradient method with continuous adjustment. In the end the chapter provides a method for frequency control at ultrasonic high power piezoelectric transducers, using a feedback control systems based on the first derivative of the movement current.

2. Ultrasonic piezoelectric transducers

2.1 Constructive and functional characteristics

The ultrasonic piezoelectric transducers are made in a large domain of power from ten to thousand watts, in a frequency range of 20 kHz – 2 MHz. Example of characteristics of some commercial transducers are given in Tab. 1.

Transducer type	P [W]	f_s [KHz]	f_p [KHz]	m [Kg]	I [mA]	Constr. type	C_0 [nF]
TGUS 100-020-2	100	20±1	22±2	0,65	300	2	4,2±0,6
TGUS 100-025-2	100	25±1	27±2	0,6	300	2	4,2±0,6
TGUS 150-040-1	150	40±2	43±2	0,26	300	1, 2	4,1±0,6
TGUS 500-020-1	500	20±1	22±2	1,1	500	1	5,8±0,6

Table 1. Characteristics of some piezoelectric transducers made at I.F.T.M. Bucharest

The 1st type is for general applications and the 2nd type is for ultrasonic cleaning to be mounted on membranes. Two examples of piezoelectric transducers TGUS 150-040-1 and TGUS 500-25-1 are presented in Fig. 1.

Fig. 1. Piezoelectric transducer of 150 W at 40 kHz (left) and 500 W at 20 kHz (right)

They have small losses, a good coupling coefficient k_{ef} , a good quality mechanical coefficient Q_{m0} and a high efficiency η_0 :

$$k_{ef} = \sqrt{1 - \left(\frac{f_s}{f_p}\right)^2}, \quad Q_{m0} = \frac{f_p}{\Delta f_p}, \quad \eta_0 = 1 - \frac{2}{k_{ef}} \sqrt{\frac{tg\delta}{Q_{m0}}} \quad (1)$$

in normal operating conditions of temperature, humidity and atmospheric pressure.

3. Electrical characteristics

The high power ultrasonic installations have as components ultrasonic generator piezoelectric transducers, which are accomplish some technical conditions. They have the electrical equivalent circuit from Fig. 2.

Fig. 2. The simplified linear equivalent electrical circuit

Their magnitude-frequency characteristic is presented in Fig. 3.

Fig. 3. The impedance magnitude-frequency characteristic

We may notice on this characteristic a series resonant frequency f_s and a parallel resonant frequency f_p , placed at the right. The magnitude has the minimum value Z_m at the series frequency and the maximum value Z_M at the parallel resonant frequency, on bounded domain of frequencies. The piezoelectric transducer is used in the practical applications working at the series resonant frequency.

The most important aspect of this magnitude characteristic is the fact that the frequency characteristic is modifying permanently in the transient regimes, being affected by the load applied to the transducer, in the following manner: the minimum impedance Z_m is increasing, the maximum impedance Z_M is decreasing and also the frequency bandwidth $[f_s, f_p]$ is modifying in specific ways according to the load types. So, when at the transducer a

concentrator is coupled, as in Fig. 4, the frequency bandwidth $[f_s, f_p]$ became very narrow, as $f_p - f_s \approx 1-2$ Hz.

Fig. 4. A transducer 1 with a concentrator 2 and a welding tool 3

This is a great impediment because in this case a very precise and stable frequency control circuit is necessary at the electronic ultrasonic power generator for the feeding voltage of the transducer.

When at the transducer a horn or a membrane is mounted, as in Fig. 5, the frequency bandwidth $[f_s, f_p]$ increases for 10 times, $f_p - f_s \approx n$ kHz.

Fig. 5. A transducer with a horn and a membrane

The resonance frequencies are also modifying by the coupling of a concentrator on the transducer. In this case, to obtain the initial resonance frequency of the transducer the user must adjust mechanically the concentrator at the transducer own resonance frequency. At the ultrasonic blocks with three components (Fig. 4) a transducer 1, a mechanical concentrator 2 and a processing tool 3, the resonance frequency is given by the entire assembled block (1, 2, 3) and in the ultimate instance by the processing tool 3. At cleaning equipments the series resonance frequency is decreasing with 3÷4 KHz.

The transducers are characterised by a Nyquist hodograph of the impedance present in Fig. 6, which has the theoretical form of a circle. In reality, due to the non-linear character of the transducer, especially at high power, this circle is deformed.

The movement current i_m of piezoelectric transducer is important information related to the maximum power conversion efficiency at resonance frequency. It is the current passing through the equivalent RLC series circuit, which represents the mechanical branch of the equivalent circuit. It is obtained as the difference:

$$i_m = i - i_{C0} \quad (2)$$

An example of the measured movement current is presented in Fig. 7.

Fig. 6. Impedance hodograph around the resonant frequency

Fig. 7. Movement current frequency characteristic

4. Identification with frequency characteristics

4.1 Generalities

A good design of ultrasonic equipment requests a good knowledge of the equivalent models of ultrasonic components, when the primary piece is the transducer, as an electromechanical power generator of mechanical oscillations of ultrasonic frequency. The model is theoretical demonstrated and practical estimated with a relative accuracy. In practice the estimation consists in the selection of a model that assures a behaviour simulation most closed to the real effective measurements. The identification is taking in consideration some aspects as: model type, test signal type and the evaluation criterion of the error between the model and the studied transducer. Starting from a desired model we are adjusting the parameters until the difference between the behaviour of the transducer and the model is minimized. For the transducer its structure is presumed known, and it is the equivalent circuit from Fig. 2. The purpose of the identification is to find the equivalent parameters of this electrical circuit. The model is estimated from experimental data. One of the parametric models is the complex impedance of the transducer, given in a Laplace transformation. Other model, but in the frequency domain, is the Nyquist hodograph of impedance from Fig. 6. The frequency

model is given by a finite set of measured independent values. For the piezoelectric transducer a method that converts the frequency model into a parameter model – the complex impedance, is recommended (Tertisco & Stoica, 1980). A major disadvantage of this method is that the requests for complex estimation equipment and we must know the transducer model – the complex impedance of the equivalent electrical circuit. The frequency characteristic may be determinate easily testing the transducer with sinusoidal test signal with variable frequency. The passing from a frequency model to the parameter model is reduced to the determination of the parameters of the transfer impedance. The steps in such identification procedure are: organization and obtaining of experimental data on the transducer, interpretation of measured data, model deduction with its structure definition and model validation.

4.2 Identification method

Frequency representation of a transducer was presented before. The frequency characteristics may be obtained applying a sinusoidal test voltage signal to the transducer and obtaining a current with the same frequency, but with other magnitude and phase, variables with the applied frequency. The theoretic complex impedance is:

$$Z(j\omega) = |Z(j\omega)|e^{j\varphi(\omega)} = \text{Re}\{Z(j\omega)\} + j\text{Im}\{Z(j\omega)\} \quad (3)$$

Its parameter representation is:

$$Z(s) = \frac{B(s)}{A(s)} = \frac{\sum_{i=0}^m b_i s^i}{1 + \sum_{i=1}^n a_i s^i} = \frac{b_0 + b_1 s + b_2 s^2 + \dots + b_m s^m}{1 + a_1 s + a_2 s^2 + \dots + a_n s^n} \quad (4)$$

A general dimensional structure for identification with the orders $\{n, m\}$ is considered, where n and m follow to be estimated.

The model that must be obtained by identification is given by:

$$Z_M(j\omega_k) = \frac{b_0 + b_1(j\omega_k) + \dots + b_m(j\omega_k)^m}{1 + a_1(j\omega_k) + \dots + a_n(j\omega_k)^n} = \frac{\alpha + j\omega_k\beta}{\delta + j\omega_k\gamma} = \frac{B(j\omega_k)}{A(j\omega_k)} \quad (5)$$

We presume the existence of the experimental frequency characteristic, as samples:

$$\begin{aligned} Z_e(j\omega_k) &= \text{Re}\{Z_e(j\omega_k)\} + j\text{Im}\{Z_e(j\omega_k)\} \\ R_k &= \text{Re}\{Z_e(j\omega_k)\} \\ I_k &= \text{Im}\{Z_e(j\omega_k)\}, \quad k = 1, 2, 3, \dots, n_p \end{aligned} \quad (6)$$

For any particular value ω_k the error $\varepsilon(\omega_k)$ is defined as:

$$\varepsilon(\omega_k) = |Z_e(j\omega_k) - Z_M(j\omega_k)| = \left| Z_e(j\omega_k) - \frac{B(j\omega_k)}{A(j\omega_k)} \right| \quad (7)$$

The error criterion is defined as:

$$E = \sum_{k=0}^{n_p} |\varepsilon(\omega_k)|^2 \quad (8)$$

The estimation of orders $\{n, m\}$ and parameters is formulated as a parametric optimisation:

$$p = [a_0 \ a_1 \ \dots \ a_n \ b_1 \ b_2 \ \dots \ b_m] = \arg \min_p \sum_{k=0}^{n_p} |\varepsilon(\omega_k)|^2 \quad (9)$$

The error criterion is non-linear in parameters and the direct has practical difficulties: a huge computational effort, local minima, instability and so on. To simplify the algorithm, the error $\varepsilon(\omega_k)$ is weighted with $A(j\omega_k)$. A new error function is obtain:

$$B(j\omega_k)\varepsilon(j\omega_k) = A(j\omega_k).Z(j\omega_k) - B(j\omega_k) = X(\omega_k) + jY(\omega_k) \quad (10)$$

The weighted error function $e(\omega_k)$ is given by

$$e(\omega_k) = A(j\omega_k).\varepsilon(j\omega_k) \quad (11)$$

The new approximation error, corresponding to the weighted error is:

$$E = \sum_{k=1}^{n_p} |e(\omega_k)|^2 = \sum_{k=1}^{n_p} |A(j\omega_k).\varepsilon(j\omega_k)|^2 = \sum_{k=1}^{n_p} [X^2(\omega_k) + Y^2(\omega_k)] \quad (12)$$

The minimization of E is done based on the weighted least squares criterion, in which the weighting function $[A(j\omega_k)]^2$ was chosen so E to be square in model parameters:

$$p = \arg \min_p \sum_{k=1}^{n_p} |e(\omega_k)|^2 \quad (13)$$

$$E^i = \sum_{k=1}^{n_p} \left| \frac{A_i(j\omega_k)}{A_{i-1}(j\omega_k)} \right| \varepsilon_i^2(\omega_k) \quad (14)$$

But, also this method is not good in practice. The frequency characteristic must be approximated on the all frequency domain. The low frequencies are not good weighted, so the circuit gain will be wrong approximated. To eliminate this disadvantage the criterion is modified in the following way:

$$p^i = \arg \min_p \sum_{k=1}^{n_p} \left| \frac{A_i(j\omega_k)}{A_{i-1}(j\omega_k)} \right|^2 \varepsilon_i^2(\omega_k) \quad (15)$$

where i represents the iteration number, p^i is the vector of the parameters at the iteration i . The error $\varepsilon_i(\omega_k)$ is given by:

$$\varepsilon_i(\omega_k) = \left| Z_e(j\omega_k) - \frac{B_i(j\omega_k)}{A_i(j\omega_k)} \right| \quad (16)$$

At the algorithm initiation:

$$B_0(j\omega_k) = 1 \quad (17)$$

The criterion is quadratic in p^i , so the parameter vector at the iteration i may be analytically determinate.

In the same time the method converges, because there is the condition:

$$\lim_{i \rightarrow \infty} \frac{A_i(j\omega_k)}{A_{i-1}(j\omega_k)} = 1 \quad (18)$$

The estimation accuracy will have the same value on the entire frequency spectre.

The procedure is an iterative variant of the least weighted squares method. At each iteration the criterion is minimized and the linear equation system is obtained:

$$\begin{aligned} \left(\frac{\partial E_i}{\partial a_k} \right)_i &= 0 \\ \left(\frac{\partial E_i}{\partial b_k} \right)_i &= 0 \end{aligned} \quad (19)$$

To obtain an explicit relation for p_i we notice that:

$$\begin{aligned} \operatorname{Re}\{A_i(j\omega_k)\} &= \sum_{i=0}^{r_1} (-1)^i a_{2i} \omega_k^{2i} \\ \operatorname{Im}\{A_i(j\omega_k)\} &= \sum_{i=0}^{r_2} (-1)^i a_{2i+1} \omega_k^{2i+1} \end{aligned} \quad (20)$$

where $r_1 = n/2$ and $r_2 = n/2 - 1$, if n is odd and $r_1 = (n-1)/2$ și $r_2 = (n-1)/2$, if n is even. By analogy $\operatorname{Re}\{B(j\omega_k)\}$ and $\operatorname{Im}\{B(j\omega_k)\}$ may be represented in the same way, for r_3 and r_4 , function of m .

From the linear relations the following linear system is obtained:

$$E \times p_i = F \quad (21)$$

where the matrix E , p_i , F are given by the relations (24), in which k takes the values from 1, 0, 0 and 0 until $r_{1,2,3,4}$ for rows, from up to down, and j takes values from 1, 0, 0 and 0 until $r_{1,2,3,4}$ for columns from the left to the right.

$$E = \begin{bmatrix} (-1)^{j+1} \Gamma_{2(j+k)} & 0 & (-1)^j \Delta_{2(j+k)} & (-1)^j \Phi_{2(j+k)+1} \\ 0 & (-1)^j U_{2(j+k+1)} & (-1)^j \Phi_{2(j+k)+1} & (-1)^{j+1} \Delta_{2(j+k+1)} \\ (-1)^{j+1} \Delta_{2(j+k)} & (-1)^j \Phi_{2(j+k)+1} & (-1)^j \Pi_{2(j+k)+1} & 0 \\ (-1)^{j+1} \Phi_{2(j+k)+1} & (-1)^{j+1} \Delta_{2(j+k+1)} & 0 & (-1)^j \Gamma_{2(j+k+1)} \end{bmatrix} \quad (22)$$

$$p_i = \begin{bmatrix} \hat{a}_2 & \dots & \hat{a}_{2r_1} & \hat{a}_1 & \dots & \hat{a}_{2r_2+1} & \hat{b}_0 & \dots & \hat{b}_{2r_3} & \hat{b}_1 & \dots & \hat{b}_{2r_4+1} \end{bmatrix}^T \quad (23)$$

$$F = [\Gamma_2 \quad \dots \quad \Gamma_{2r_1} \quad 0 \quad \Delta_0 \quad \dots \quad \Delta_{2r_3} \quad \Phi_1 \quad \dots \quad \Phi_{2r_4+1}]^T$$

$$\Gamma_i = \sum_{k=1}^{n_p} \frac{(R_k^2 + I_k^2) \omega_k^i}{|A(j\omega_k)|_{i-1}^2}, \quad \Delta_i = \sum_{k=1}^{n_p} \frac{R_k \cdot \omega_k^i}{|A(j\omega_k)|_{i-1}^2}, \quad (24)$$

$$\Phi_i = \sum_{k=1}^{n_p} \frac{I_k \cdot \omega_k^i}{|A(j\omega_k)|_{i-1}^2}, \quad \Pi_i = \sum_{k=1}^{n_p} \frac{\omega_k^i}{|A(j\omega_k)|_{i-1}^2} \quad (25)$$

The values of n and m are determinate after iterative modifications and iterative estimations.

The block diagram of the estimation procedure is given in Fig. 8.

Fig. 8. Estimation equipment

The frequency characteristic of the piezoelectric transducer E is measured with a digital impedance meter IMP. An estimation program on a personal computer PC processes measured data. In practical application estimated parameter are obtain with a relative tolerance of 10 %.

5. Automatic parameter estimation

The method estimates the parameters of the equivalent circuit from Fig. 2: the mechanical inductance L_m , the mechanical capacitor C_m , the resistance corresponding to acoustic dissipation R_m , the input capacitor C_0 and other characteristics as: the mechanical resonance frequency f_m , the movement current i_m or the efficiency η . The estimation is done in a unitary and complete manner, for the functioning of the transducer loaded and unloaded, mounted on different equipments. By reducing the ultrasonic process at the transducer we may determine by the above parameters and variables the global characteristics of the ultrasonic assembling block transducer-process.

The identification is made based on a method of automatic measuring of complex impedances from the theory of system identification (Eyikoff, 1974), by implementation of the generalized model of piezoelectric transducer, and the instantaneous minimization of an imposed error criterion, with a gradient method – the deepest descent method.

In the structure of industrial ultrasonic equipments there are used piezoelectric transducers, placed between the electronic generators and the adapter mechanical elements. Over the transducer a lot of forces of electrical and mechanical origin are working and stressing. The knowledge of electrical characteristics is important to assure a good process control and to increase the efficiency of ultrasonic process.

Based on the equivalent circuit, considered as a physical model for the transducer, we may determine a mathematic model, the integral-differential equation:

$$L_m \frac{di}{dt} + R_m i + \frac{1}{C_m} \int i dt = L_m C_0 \frac{d^2 u}{dt^2} + L_m C_0 \frac{R_m}{R_p} \frac{du}{dt} + \frac{R_m}{R_0} u + \frac{1}{C_m R_0} \int u dt \quad (26)$$

This model represents a relation between the voltage u applied at the input, as an acting force and the current i through transducer. The model is in continuous time. We do not know the parameters and the state variables of the model. This model assures a good representation. A complex one will make a heavier identification. The classical theory of identification is using different methods as: frequency methods, stochastic methods and other. This method has the disadvantage that it determines only the global transfer function.

Starting from equation (28) we obtain the linear equation in parameters:

$$\sum_0^2 \alpha_i i_i + \sum_0^3 \beta_i u_i = 0 \quad (27)$$

$$i_0 = i, i_1 = di/dt, i_2 = \int i dt,$$

$$u_0 = -u, u_1 = -du/dt, u_2 = -d^2u/dt^2, u_3 = -\int u dt \quad (28)$$

$$\alpha_0 = R_m, \alpha_1 = L_m, \alpha_2 = 1/C_m,$$

$$\beta_0 = R_m/R_0, \beta_1 = L_m/R_d + C_0 R_m, \beta_2 = L_m C_0, \beta_3 = 1/(C_m R_0) \quad (29)$$

The relation gives the transducer generalized model, with the generalized error:

$$e = \sum_0^2 \alpha_i i_i + \sum_0^3 \beta_i u_i \quad (32)$$

The estimation is doing using a signal continuous in time, sampled, sinusoidal, with variable frequency. For an accurate determination of parameters there are necessary the following knowledge: the magnitude order of the parameters and some known values of them.

The error criterion is imposed as a quadratic one:

$$E = e^2 \quad (30)$$

which influences in a positive sense at negative and positive variations of error. To minimize this error criterion we may adopt, for example a gradient method in a scheme of continuous adjustment of parameters, with the deepest descent method. In this case the model is driven to a tangential trajectory, what for a certain adjusted speed it gives the fastest error decreasing. The trajectory is normally to the curves with $E=ct$. The parameters are adjusted with the relation:

$$\begin{bmatrix} \dot{\alpha}_i \\ \dot{\beta}_i \end{bmatrix} = -\Gamma \begin{bmatrix} -\frac{\partial E}{\partial \alpha_i} \\ -\frac{\partial E}{\partial \beta_i} \end{bmatrix} = -\Gamma \begin{bmatrix} 2e \frac{\partial e}{\partial \alpha_i} \\ 2e \frac{\partial e}{\partial \beta_i} \end{bmatrix} = -2\Gamma \begin{bmatrix} i_i \\ u_i \end{bmatrix} \quad (31)$$

where Γ is a constant matrix, which together with the partial derivatives determines parameter variation speed. Derivative measuring is not instantaneously, so a variation speed limitation must be maintained. To determine the constant Γ we may apply Lyapunov stability method. Based on the generalized model and of equation (34) the estimation algorithm may be implemented digitally. The block diagram of the estimator is presented in Fig. 9.

Fig. 9. The block diagram of parameter estimator

Shannon condition must be accomplished in sampling. We may notice some identical blocks from the diagram are repeating themselves, so they may be implemented using the same procedures. Based on differential equation:

$$u = L_m \frac{di_m}{dt} + R_m i_m + \frac{1}{C_m} \int i_m dt = \alpha_1 i_1 + \alpha_2 i_2 + \alpha_0 i_0$$

(32)

which is characterising the mechanical branch of transducer with the parameters obtained with the above scheme, we may determine the movement current with the principle block diagram from Fig. 10.

Fig. 10. The block diagram of movement current estimation

The variation of the error criterion *E* in practical tests is presented in Fig. 11, for 1000 samples.

Fig. 11. Error criterion variation

Using the model parameters we may compute the mechanical resonance frequency with the relation:

$$f_m = \frac{1}{2\pi\sqrt{L_m C_m}} \quad (33)$$

The efficiency of conversion as a rapport from the acoustic power P_m and total power P_t is

$$\eta = \frac{P_m}{P_t} \quad (34)$$

where P_m is the power on the resistance R_m :

$$P_m = I_m^2 R_m \quad (35)$$

and the total power is the power consumed from the source:

$$P_t = P_m + P_0 \quad (36)$$

where P_0 is the power consumed by the unloaded transducer:

$$P_0 = I_{m0}^2 R_p \quad (37)$$

where I_{m0} is the movement current through the unloaded transducer and R_p is the resistance corresponding to mechanical circuit unloaded.

Using the estimator from Fig. 9 and 10 we may do an identification of mechanical adapters. A mechanical adaptor coupled to the transducer influences the equivalent electrical circuit, modifying the equivalent parameters, the resonance frequency and the movement current. We may do the same measuring several times over the unloaded and then over the loaded transducer. Knowing the characteristics of the unloaded transducer we may find the way how the adapter influences the equivalent circuit. So, we may determine the parameters of the assemble transducer – adapter, reduced to the transducer: resonance frequency, movement current and efficiency. To determine efficiency we must take in consideration the power of the unloaded transducer and the power of the unloaded adapter.

Also, the process may be identified using the same estimator. Considering the transducer coupled with an adapter and introduced into a ultrasonic process, as welding, cleaning and other, we may determine by an identification for the loaded functioning the way that the process influences the equivalent parameters. We may determine the resonant frequency of the

ultrasonic process and the global acoustic efficiency of ultrasonic system transducer-adaptor-process. We may determine the mechanical resonant frequency of the entire assemble, which is the frequency at what the electronic power generator must functioning to obtain maximum efficiency, the movement current of the loaded transducer and total efficiency, including the power given to the ultrasonic process.

This estimation method has the following advantages: easy to be treated mathematically; easy to implement; generally applicable to all the transducers which have the same equivalent circuit; it assures an optimal estimation with a know error; it offers a good convergence speed,

The method may be implemented digitally, on DSPs, or on PCs, for example using Simulink and dSpace, or using LabView. We present an example of a simple virtual instrument in Fig. capable to be developed to implement the block diagram from Fig. 12.

Fig. 12. Example of a front panel for a virtual instrument

The instantaneous variation of parameters and variables of the equivalent circuit may be presented on waveform graphs, data values may be introduced using input controllers. Behind the panel a LabView block diagram similar may be developed using existent virtual instruments from the LabView toolboxes.

6. Frequency control

6.1 Control principle

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 present method is based on a feedback made using the estimated movement current from the transducer. The following presentation has at its basic the paper (Volosencu, 2008).

In the general case the ultrasonic piezoelectric transducers have a non-linear equivalent electric circuit from Fig. 13.

Fig. 13. The non-linear equivalent circuit

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 non-linear, depending on transducer load. The current through mechanical part i_m is the movement current. The input capacitor C_0 of the transducer is considered as a constant parameter. The equations (14) are describing the time variation of the signals and the mechanical parameters, where ϕ is the magnetic flux through the mechanical inductance L_m and q is the electric load over the mechanical capacitor C_m :

$$\begin{aligned}
 u_{Lm} &= \frac{d\phi_{Lm}}{dt} = \frac{dL_m}{dt} i_m + L_m \frac{di_m}{dt} \\
 i_{Cm} &= \frac{dq_{Cm}}{dt} = \frac{dC_m}{dt} u_{Cm} + C_m \frac{du_{Cm}}{dt} \\
 R_m &= \frac{du_{Rm}}{di_m} \\
 i &= i_0 + i_m \\
 u &= u_{Lm} + u_{Cm} + u_{Rm} \\
 C_0 \frac{du}{dt} &= i_{C0}
 \end{aligned} \tag{38}$$

The piezoelectric transducer has a frequency characteristic of its impedance Z with a series and a parallel resonance, as it is presented in Fig. 14. The movement current i_m has the frequency characteristic from Fig. 15.

Fig. 14. The magnitude-frequency characteristic of transducer impedance

Fig. 15. The frequency characteristic of the transducer movement current

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 movement current derivative $\dot{i}_m$ is zero:

$$\dot{i}_m(t) = \frac{di_m}{dt} = 0 \quad (39)$$

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

6.2 Control system

The block diagram of the frequency control system based on the above assumption is presented in Fig. 16.

Fig. 16. The block diagram of the frequency control system

A power amplifier AP, working in commutation, at high frequency, 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 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 frequency control system from Fig. 16 is based on the derivative movement current error e_{dim} as the difference between the reference value $\text{dim}^*=0$ and the computed value of the derivative dim :

$$e_{\text{dim}} = \text{dim}^* - \text{dim} \quad (40)$$

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

$$u_f^*(s) = K_R \left(1 + \frac{1}{T_R s} \right) e_{\text{dim}}(s) \quad (41)$$

The frequency controller is working after the error of the derivative of the movement current e_{dim} . The derivative of the movement current dim is computed using a circuit CC_DCM, based on the following relation with Laplace transformations:

$$\text{dim}(s) = s[i(s) - sC_0 u(s)] \quad (42)$$

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.

6.3 Modelling and simulation

Two models for the transducer and for the block diagram from Fig. 16 were developed to test the control principle by simulation. In the first model the parameters of the mechanical part are considered with a fix static value and a dynamical variation. In the second model the electromechanical transducer is considered coupled with a mechanical concentrator and the equivalent circuits are coupled in series. Approximating the relations (41), the following relations are used to model the behaviour of the piezoelectric transducer:

$$\begin{aligned} u_{Lm}(s) &= sL_m(s)i_m(s) + sL_m(s)i_m(s) \\ i_{Cm}(s) &= sC_m(s)u_{Cm}(s) + sC_m(s)u_{Cm}(s) \\ u_{Rm}(s) &= \frac{1}{s} R_m[si_m(s)] \\ u(s) &= u_{Lm}(s) + u_{Cm}(s) + u_{Rm}(s) \end{aligned} \quad (43)$$

The mechanic parameters from the above relations have the following variations, in the vicinity of the stationary points R_{m0} , L_{m0} and C_{m0} :

$$R_m = R_{m0} + \Delta R_m, \quad L_m = L_{m0} + \Delta L_m, \quad C_m = C_{m0} + \Delta C_m \quad (44)$$

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

$$i_m(s) = \frac{1}{s} \left[\frac{1}{L_m} \times \left(u(s) - \frac{1}{s} \cdot \frac{1}{C_m} \times i_m(s) - R_m \times i_m(s) \right) \right] \quad (45)$$

The block diagram of the movement current model is presented in Fig. 17.

Fig. 17. Simulation model for mechanical part

A second model is taken in consideration. The transducer is considered coupled with the concentrator and the equivalent circuit is presented in Fig. 18.

Fig. 18. Equivalent circuit of the transducer with concentrator

In this model there is a series RLC circuit 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 control system is presented in Fig. 19.

Fig. 19. Transient characteristic for the error, 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.

6.4 Implementation and test results

The frequency control system is developed to be implemented using analogue, high and low power circuits, for general usage. The power amplifier AP is built using four power IGBT transistors, in a complete bridge, working in commutation at high frequency. The electric circuit of the power inverter is presented in Fig. 20.

Fig. 20. The power inverter

The four IGBT transistors V1÷4 have the voltage and current protection circuits. The power transistors are commanded with 4 circuits Cmd. The Power inverter is fed from the power system with a rectifier and a filter. The command circuits are receiving the command voltage u_c from the VC_FG circuit. The voltage controlled frequency generator GF_CT is made 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, working at high frequency. The electronic generator is presented in Fig. 21.

Fig. 21. The electronic generator

Some transient signal variations are presented as follows. The pulse train of the command voltage u_c is presented in Fig. 22.

Fig. 22. Examples of sensor impulse trains.

The output voltage of the power amplifier is presented in Fig. 23.

Fig. 23. The output voltage

The voltage u over the piezoelectric transducer is presented in Fig. 24.

Fig. 24. The transducer voltage

The measured movement current i_m is presented in Fig. 25.

Fig. 25. The movement current

The control system was developed for a plastic welding machine in the range of 3000 W at 40 kHz.

7. Conclusion

This chapter presented two methods for parameter identification at the piezoelectric transducers used in high power ultrasonic applications as welding, cleaning and other. The methods are offering information about the equivalent electrical circuit: parameters and resonance frequency, efficiency and other. The first parameter estimation method is using the transformation from non-parameter model – the Nyquist hodograph – to a parameter model – the transfer function of the transducer's impedance, testing the piezoelectric transducers with a sinusoidal signal with variable frequency. The second parameter estimation method is based on an automatic measurement of piezoelectric transducer impedance using a deterministic convergence scheme with a gradient method with continuous adjustment – the method of deepest descent with a maximum slope. Some practical results are given. Some indications to implement the method using LabView are given. In the end, the paper provides a method for frequency control at 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 control principle is implanted on a power electronic generator. Some transient characteristics are presented. 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.

8. References

- Bose, B.K., (2000). Energy, Environment and Advances in Power Electronics, *IEEE Transactions on Power Electronics*, vol. 15, no. 4, July, 2000, pag. 688-701.
- Chen, Y. C., Hung, L. C., Chaol, S.H. & Chien, T. H. (2008). PC-base impedance measurement system for piezoelectric transducers and its implementation on elements values extraction of lump circuit model, *WSEAS Transactions on Systems*, Volume 7, Issue 5, May 2008. Pages 521-526.
- Eykhoff, P. (1974). *System Identification*, John Wiley and Sons, Chicester, U.K., 1974.
- Furuichi, S. & Nose, T., (1981). Driving system for an ultrasonic piezoelectric transducer, *U.S. patent 4271371*.
- Gallego-Juarez, J. A. (2009). Macrosonics: Sound as a Source of Energy, In: *Recent Advances in Acoustic and Music, Theory and Applications, Proceedings of the 10th WSEAS International Conference on Acoustics & Music Theory & Applications*, pag. 11-12, ISBN: 978-960-474-061-1, ISSN 1790-5095, Prague, Czech Rep., March 23-25, 2009.
- Hulst, A.P., (1972). Macrosonics in industry 2. Ultrasonic welding of metals, *Ultrasonics*, Nov., 1972.
- Khmelev, V.N., Barsukov, R.V., Barsukov, V., Slivin, A.N. and Tchyganok, S.N., (2001). System of phase-locked-loop frequency control of ultrasonic generators, *Proceedings of the 2nd Annual Siberian Russian Student Workshop on Electron Devices and Materials*, 2001. pag. 56-57.
- Kirsch, M. & Berens, F., (2006). Automatic frequency control circuit, *U. S. Patent 6571088*.
- Marchesoni, M., (1992). High-Performance Current Control Techniques for Applications to Multilevel High-Power Voltage Source Inverters, In *IEEE Trans. on Power Electronics*, Jan.
- Mori, E., 1989. High Power Ultrasonic Wave Transmission System, In *J. Inst. Electron. Inf. Commun. Eng.*, vol. 72, no. 4, April.
- Morris, A.S., (1986). Implementation of Mason's model on circuit analysis programs, In *IEEE Transactions on ultrasonics, ferroelectric and frequency control*, vol. UFFC-33, no. 3.
- Neppiras, E.A., (1972). Macrosonics in industry, 1. Introduction. *Ultrasonics*, Jan., 1972.
- Prokic, M., (2004). *Piezoelectric Converters Modelling and Characterization*, MPI Interconsulting, Le Locle, Switzerland.
- Radmanovic, M. D. & Mancic, D. D., (2004). *Design and Modelling of Power Ultrasonic Transducers*, University of Nis, 2004, MPI Interconsulting.
- Senchenkov, I.K., (1991). Resonance vibrations of an electromechanical rod system with automatic frequency control, *International Applied Mechanics*, Vol. 27, No. 9, Sept., Springer, N. Y.
- Sullivan, R.A. (1983). Power supply having automatic frequency control for ultrasonic bonding, *U. S. Patent 4389601*.
- Tertisco, M. & Stoica, P. (1980), *Identificarea si estimarea parametrilor sistemelor*, Editura Academiei Romaniei, Bucuresti, 1980.

Volosencu, C. (2008). Frequency Control of the Piezoelectric Transducers, Based on the Movement Current, *Proceedings of ICINCO 2008 – Fifth International Conference on Informatics in Control, Automation and Robotics*, ISBN 978-989-8111-35-7, Funchal, Madeira, Portugal, May 11-15, 2008.

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The present edited book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of automation and control. The volume is organized in four parts according to the main subjects, regarding the recent advances in this field of engineering. The first thematic part of the book is devoted to automation. This includes solving of assembly line balancing problem and design of software architecture for cognitive assembling in production systems. The second part of the book concerns different aspects of modelling and control. This includes a study on modelling pollutant emission of diesel engine, development of a PLC program obtained from DEVS model, control networks for digital home, automatic control of temperature and flow in heat exchanger, and non-linear analysis and design of phase locked loops. The third part addresses issues of parameter estimation and filter design, including methods for parameters estimation, control and design of the wave digital filters. The fourth part presents new results in the intelligent control. This includes building a neural PDF strategy for hydroelectric saturation simulator, intelligent network system for process control, neural generalized predictive control for industrial processes, intelligent system for forecasting, diagnosis and decision making based on neural networks and self-organizing maps, development of a smart semantic middleware for the Internet, development of appropriate AI methods in fault-tolerant control, building expert system in rotary railcar dumpers, expert system for plant asset management, and building of a image retrieval system in heterogeneous database. The content of this thematic book admirably reflects the complementary aspects of theory and practice which have taken place in the last years. Certainly, the content of this book will serve as a valuable overview of theoretical and practical methods in control and automation to those who deal with engineering and research in this field of activities.

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