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Genetic identification of parameters the piezoelectric transducers for digital model of power converter in ultrasonic systems

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1. Introduction

This chapter is dedicated to ultrasonic piezoelectric ceramic power transducers. These elements are now the most popular source of high power ultrasound and is used in many industrial applications. High power ultrasonic waves are generally used in such industrial processes as welding, acceleration of chemical reactions, scavenging in gas medium, echo sounding and underwater communication (sonar systems), picture transmission, and, above all, ultrasonic cleaning. In practice is now the most widely used the sandwich type power transducers.

Stage design power converters high power ultrasonic devices usually preceded by computer analysis of currents and voltages waveforms the elements of the system, particularly in semiconductor instruments of power. Competent representation requires the use of these waveforms of electrical models of piezoelectric ceramic transducers under the parameters of line with reality and allows to calculate the electrical operating parameters used in the layout of semiconductor switches, capacitors and reactors. The proposed method in the chapter to identify the parameters using a genetic algorithm is one of many possible methods to use here, but has the advantage that it can be implemented automatically.

For example the standard ultrasonic system for cleaning technology (Fig.1.1) includes:

1. ultrasonic generator,
2. transducer or set of transducers,
3. cleaning tank.

Piezoelectric ceramic transducers placed in the tub generate ultrasonic waves that pass through the liquid and reach the element immersed in the tank. As a result, created in the liquid, with very high frequency, alternating areas of high and low pressure. In areas, where low pressure is forming millions of bubbles of vacuum. When the pressure in the alveoli increases and is high enough, bubbles implode, releasing enormous energy at the same time. This phenomenon is called cavitation. Emerging implosions work as a whole series of small cleaning brush. The phenomenon is spreading in all directions and causes intense but controlled detachment of particles of pollutants on the entire surface of cleaning detail. Washed away dirt particles collect on the surface of the cleaning solution from where they are blown into a nearby basin, and then be filtered and recycled.

Ultrasonic cleaning is more effective in cleaning hard materials, than the cleaning of soft or porous materials. It was found that, the harder the surface, including the operation of ultrasound is more efficient. Hence, metals, glass, hard plastics well led by ultrasound and are ideally suited for ultrasonic cleaning.

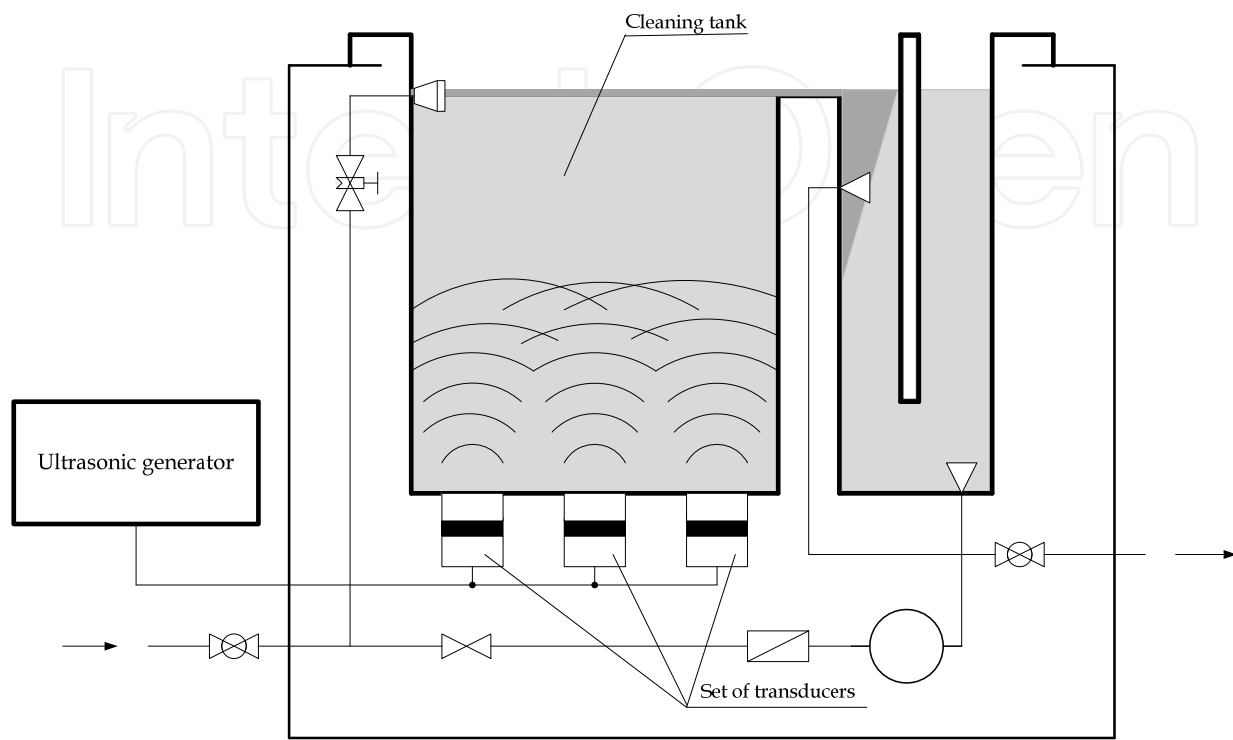


Fig. 1.1 Ultrasonic cleaning system

The quality of ultrasonic cleaning can be improved:

- increasing the ultrasonic power density (cavitation stronger, better cleaning effect),
- reducing the frequency of the generated ultrasound (a stronger phenomenon of cavitations),
- maintaining optimal cleaning bath temperature, the temperature range from 40 °C to 50 °C (cavitation effect is strongest).

By increasing the temperature of the cleaning bath can get more cleaning, but for temperatures ranging from 70 °C to 80 °C, the cleaning effect will be weaker now.

Block diagram and the main circuit of the ultrasonic generator (Fig. 1.2) consists of:

- converter AC/DC,
- full-bridge inverter FBI (T_1 - T_4 , D_1 - D_4),
- isolating transformer T,
- special filter F (L_w , C_w),
- sandwich type transducer PT,
- sensor of vibrations S (optional),
- control unit CU.

The control unit consists of two parts. The first part, in FBI inverter, is the frequency feed-back control loop and the second part in AC/DC converter is the amplitude feed-back control loop.

Two coupling loop works independently. In the case of overload inverter system of current limiter disconnect supply of AC/DC converter. Signal f_{set} make possible to set up manually frequency switching inverter FBI and signal A_{set} establish amplitude ultrasonic oscillation.

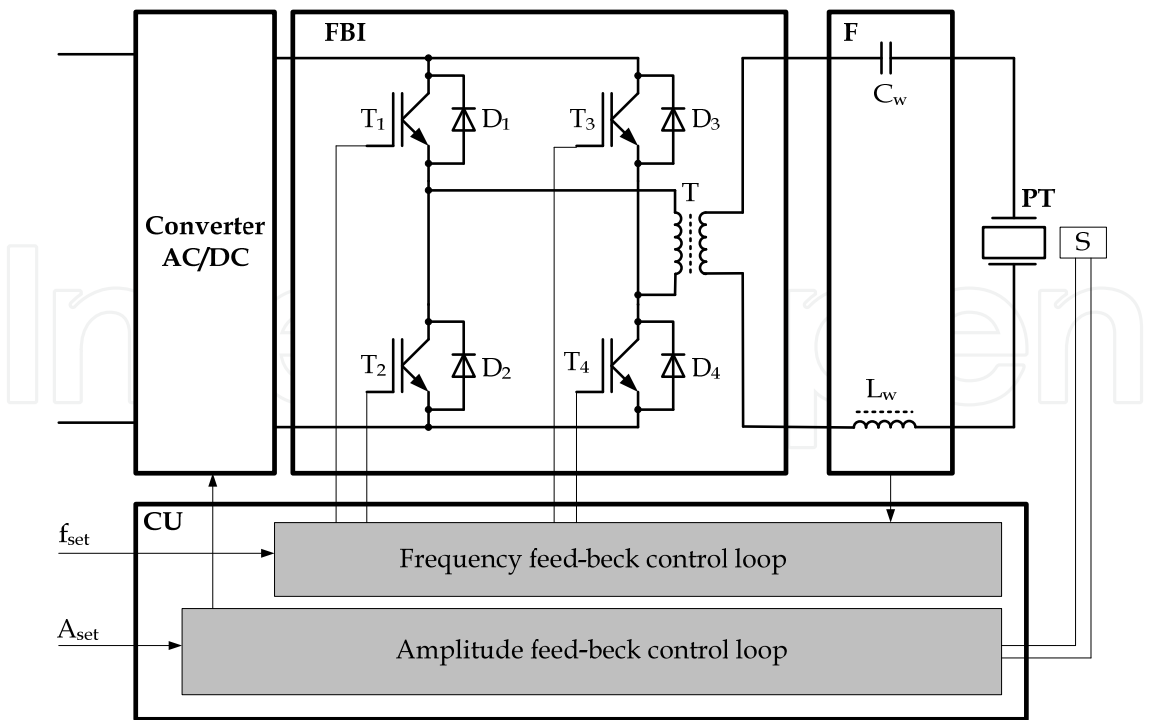


Fig. 1.2 Ultrasonic generator

In most applications, the stabilization of the amplitude of vibration is carried out by other means and do not apply vibration sensor S and the feedback loop. In simple systems, without the exact amplitude of vibration stability, instead of inverter-controlled AC/DC system used free-fall small bridge rectifier.

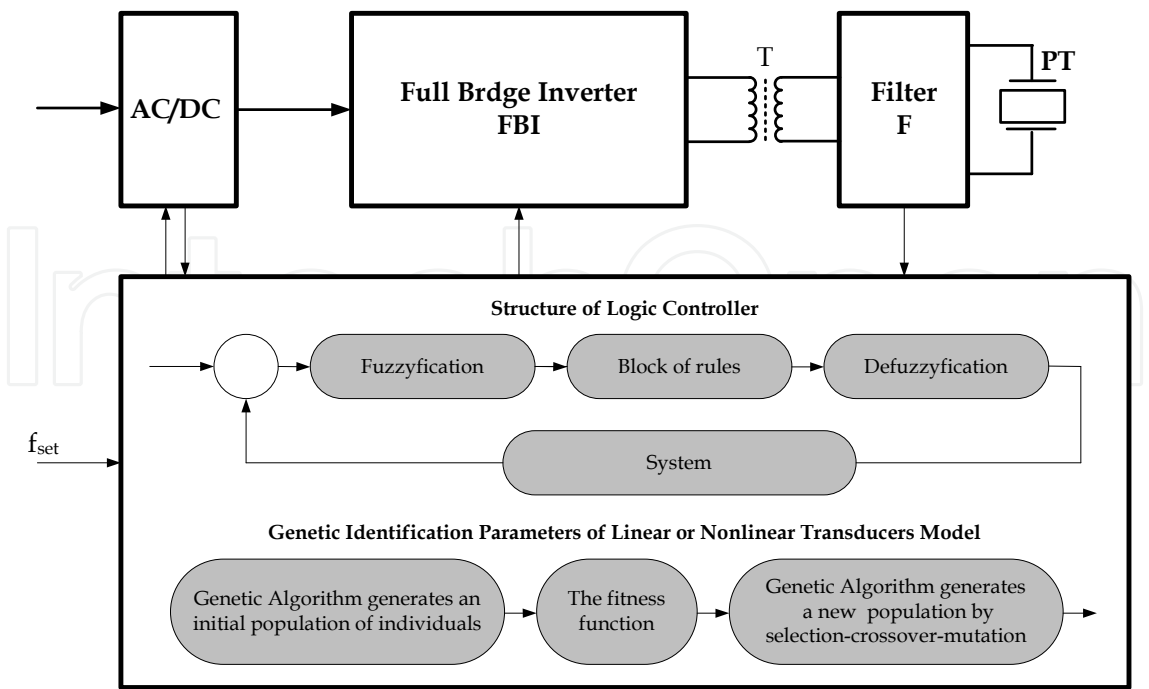


Fig. 1.3 Example of adaptive control system with an ultrasonic generator parameter identification of the transducer member

Tuning the frequency of the inverter output voltage to the FBI, the mechanical resonance of the transducer PT is also implemented in different ways. In large power systems apply adaptive systems, such as fuzzy logic systems, as shown in Figure 1.3.

In the case of untuning, the frequency feed-back control system of the converter change the output voltage frequency and untuning the generator to the mechanical resonance frequency of transducers. The output voltage frequency of converter most by equals the mechanical resonance frequency of the transducers and most by tuning with high precise.

In real circuit the mechanical resonant frequency is function of many parameters of piezoelectric material, among others, the most important are temperature, time, and for industrial cleaning systems the column of cleaning factor, and the surface of the cleaned elements. The frequency feed-back control system for the short power most by very simple, and for the high power very complicated.

The precise microprocessor control systems with an observer often requires knowledge of the electrical model of the replacement of the converter, especially for frequencies near the mechanical resonance. To identification this parameters is used genetic algorithm.

2. Sandwich type ultrasonic transducer

2.1 Construction

The view and construction of ultrasonic transducer by sandwich type is shown in Figure 2.1. This element is made of piezoelectric ceramics PZT and are for example a combination of steel-ceramics-aluminum blocks connected by one or several screws. The transmitter is constructed of two metal blocks between which are clamped piezoelectric ceramic plate (Fig.2.1.b).

This transducer design has much less to its resonant frequency compared to the same frequency of the vibration plate and more importantly allows you to generate ultrasound with high power ratings.

Change torsional screw adjusts the ratio of mechanical stiffness (elasticity), and reduces the weight of the mechanical resonance frequency of the entire transducer. Minor changes to the degree twist allows fine tuning of the resonance frequency transducer to the required value.

Piezoelectric ceramic plates squeeze between two metal blocks also has practical significance. Piezoelectric ceramic material from which the rings are made of a material that is very hard, but unfortunately also fragile. By increasing the stiffness of the mechanical transducer is thus protects the vibrating piezoelectric ceramic rings before cracking and crushing.

As mentioned above, the elements likely to attract the vibrations of sandwich transducers are piezoelectric ceramic plate. On the surface of the contact blocks and metal plates shall be a partial reflection of ultrasonic wave generated in the transducer. The energy associated with this wave is lost as heat and causes a reduction in efficiency of the converter and increasing its temperature. Any change in temperature alters the mechanical stresses occurring in the piezoelectric ceramic plates and changing the mechanical resonance frequency. Losses can be minimized if the acoustic impedance of the metal from which the blocks are made of has a value close to the acoustic impedance of piezoelectric ceramic material.

The sandwich transducers employed environmental overlays hydroacoustic metal blocks should be small as possible acoustic impedance, acoustic impedance similar to water. Types of materials used and construction of the transmitter determines, therefore, two contradictory requirements, forcing the designer to compromise. In addition to the tiered sandwich transducers are often used pickups, flat and tubular bimorph.

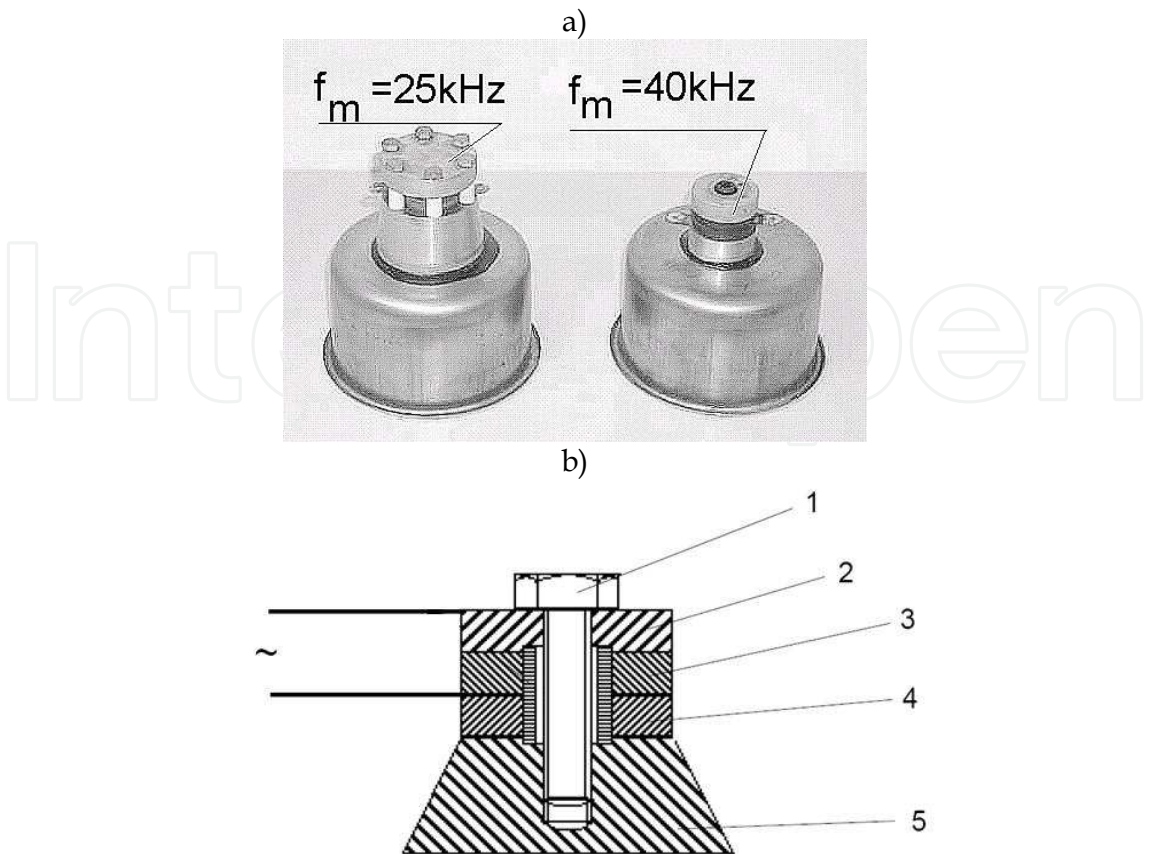


Fig. 2.1 Sandwich type piezoelectric ceramic transducers,
a) view (the resonant frequency about 25 kHz, 40 kHz)
b) construction 1 – screw or pin settings (gripping), transmitter
2.5 – blocks of metal (eg. aluminum, iron, brass)
3.4 – piezoelectric ceramic plates (cylindrical, annular)

2.2 Electric Model

Most assumed that the equivalent electrical circuit of piezoelectric ceramic transducers about the resonant frequency of mechanical vibration consist of connection in parallel resistance R_e , capacity C_e and dynamic RLC elements.

This model is shown in Figure 2.2., where

- R_e = resistance of the piezoelectric ceramic plates,
- C_e – static, electric capacity of the transducer,
- C - equivalent mechanical capacity,
- L - equivalent mechanical inductance,
- R - equivalent resistance,
- $R = R_m + R_a$

where: R_m - equivalent mechanical loss resistance, R_a - equivalent acoustic resistance.

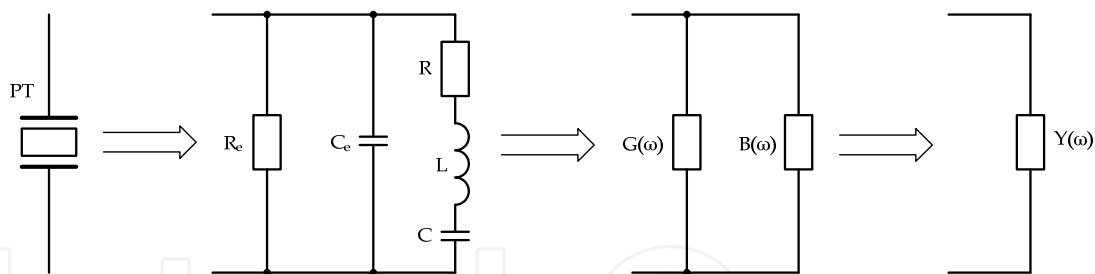


Fig. 2.2 The equivalent circuit of piezoelectric ceramic transducer about the resonant frequency of mechanical vibration

This model must be linear and nonlinear. If the resistance R_m changes as a function of pulsation untuning resonant converter model is nonlinear. Mostly for small untuning assumed that at constant load resistance R_m is constant and the model of transducer is linear. For linear model the susceptance B , conductance G , admittance Y of the transducers in frequency ω function may be expressed by the following equations:

$$B(\omega) = \text{Im } Y(\omega) = \omega C_e + \frac{\omega C(1 - \omega^2 LC)}{\omega^2 C^2 R^2 + (1 - \omega^2 LC)^2} \tag{2.1}$$

$$G(\omega) = \text{Re } Y(\omega) = G_e + \frac{\omega^2 C^2 R}{\omega^2 C^2 R^2 + (1 - \omega^2 LC)^2} \tag{2.2}$$

$$Y(\omega) = \sqrt{G^2 + B^2} \tag{2.3}$$

where $G_e = \frac{1}{R_e}$, $\omega = 2\pi f$.

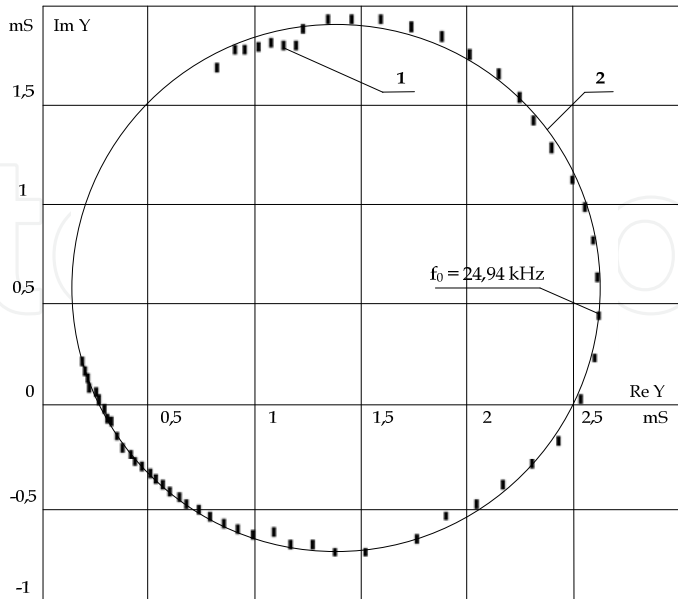


Fig. 2.3 Exemplary admittance characteristics of sandwich type transducers
1. Real characteristic,
2. Equivalent characteristic

The frequency f_0 of mechanical vibration may be calculated by known equation:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

(2.4)

Using this model we can simulate and monitor the operation of the sandwich type transducer. The building is distinguished by its two components: a electrical branch, which includes R_e and C_e , and dynamic branch, which consists of R , C , L elements. The values R_e , C_e , C , L , R must be calculated from admittance characteristic of transducers (Fig. 2.3), for the off-load and on-load conditions ($R_a = \text{var}$).

3. Application of genetic algorithm
to identify the parameters of the transducer

The electrical characteristics of ceramic transducer resistance R_e and electrical capacitance C_e can be determined with high accuracy on the basis of electrical measurement. Changes in these parameters while the transducer can be considered to be negligible because of the transmitter power is assumed that the C_e and R_e are fixed. Parameters of dynamic branch R , L , C of power piezoelectric ceramic transducer model electric are not physically measurable. We can only designate empirically. Identification algorithm is therefore based on numerical calculations. Input parameter for these calculations is the image of the actual characteristics of the transducer admittance.

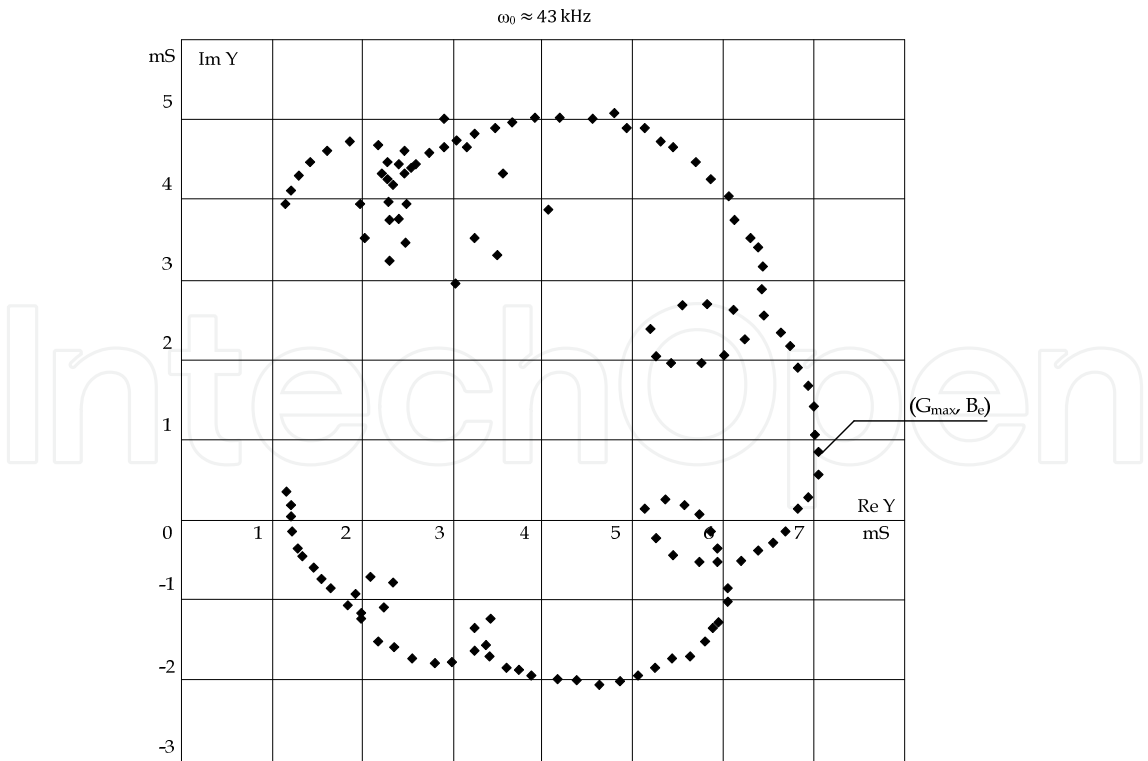


Fig. 3.1. Real admittance characteristics of the piezoelectric ceramic transducer

An example measurements of results for the transducer mechanical resonance frequency equal to about 43 kHz is locate in appendix in Table 1 and one-to-one correspondence real admittance characteristics of this transducer is shown in Fig.3.1. The graph consists of points whose coordinates correspond to the conductance $G = \text{Re}(Y)$ and susceptance $B = \text{Im}(Y)$ of the converter, measured at a certain frequency.

Analysing the shape of this characteristic can be clearly observed that with increasing frequency (Figure accordance with the frequency increasing clockwise), outlines the main loop of the graph. In the general case, the image of the curve is an ellipse. This ellipse is interpolated electrical admittance characteristics of an ideal replacement transducer schedule shown in Fig.3.1. It may be noted that the actual characteristics, in addition to the main loop also includes many smaller "loops" that testify to the presence of additional resonances in the transducer side. These resonances, however, will not occur in the adopted system replacement transmitter.

After eliminating these "loops" with the actual picture of the actual characteristics of the admittance characteristics of the transducer will be the figure presented in Fig. 3.2.

In Table 1 are marked in bold points, which missed the chart.

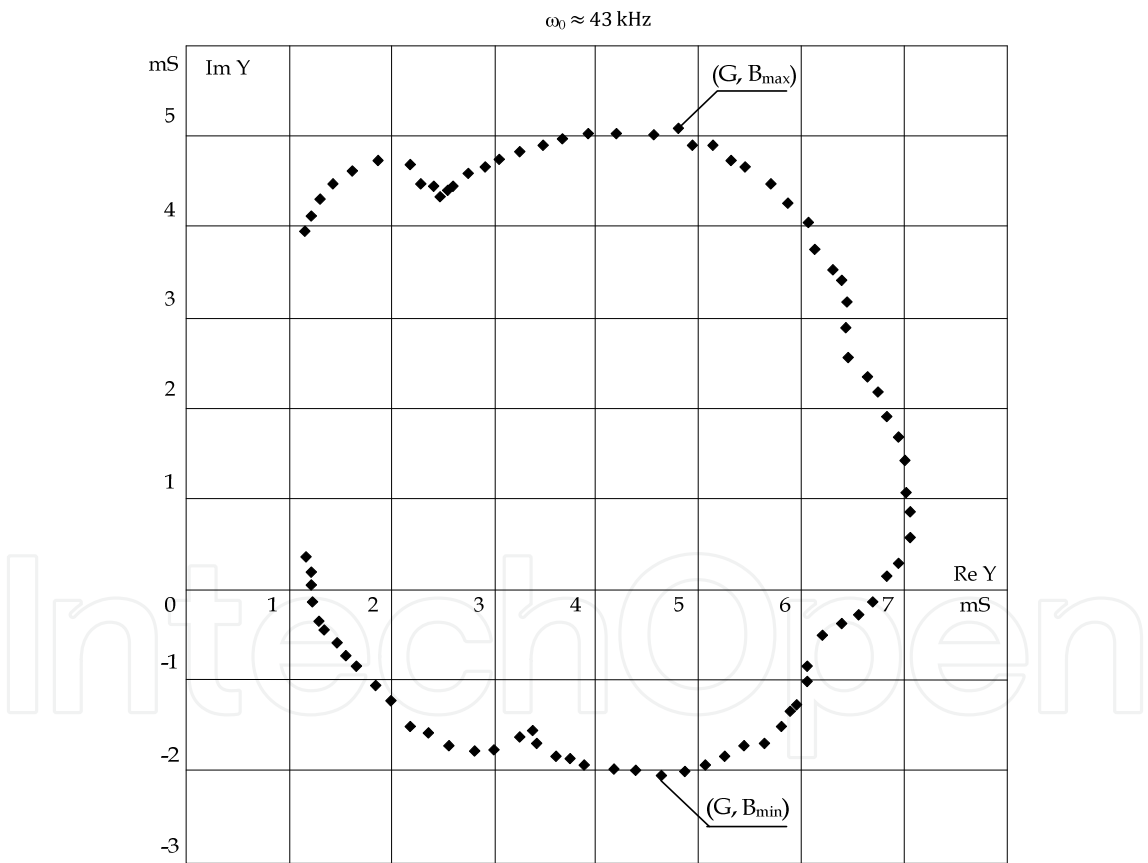


Fig. 3.2 The actual characteristics of the transducer after eliminating resonances fringe

The set of coordinates of the actual approximation characteristics transducer (Fig. 3.2) is a database for further calculations.

3.1 Calculation algorithm

Designation of alternative modes of dynamic parameters of the transmitter requires the implementation of numerical calculations and find such a set of R, L, C parameters, which in a given error will allow mapping of the main loop, the actual characteristics of the transducer admittance presented Fig.3.2.

One element of the identification of these parameters is a genetic algorithm.. Generally one can say that the genetic algorithm is a regula - system learner who makes a certain number of iteration steps. It is a group of strict security procedures that are based on the fundamental mechanisms of biological evolution such as natural selection and inheritance. It works interactively with the environment in discrete time. The algorithm of this type of reproduction may take place subject to the diversity of the population:

- model with preload,
- measures niche

A special feature of this type is that the algorithm is not seeking a single optimal solution, but a group of cooperating the best solutions. At any time, the algorithm works evolutionary principle of survival, which is always available some of the best solutions at the moment. As the proceedings algorithm solution to optimize and adapt to the conditions in which the algorithm works. For further calculations is always the best solutions are selected and rejected solutions are worse. Here there is a process of succession. In order to obtain optimal solutions group for further reproduction of the best solutions are selected at the time of the algorithm. It is a natural selection process occurs in nature. It is known that the probability of obtaining better result is greater if we use it to generate the best available solution than the use of inferior results. According to the law of nature and genetics "survive" the best and strongest.

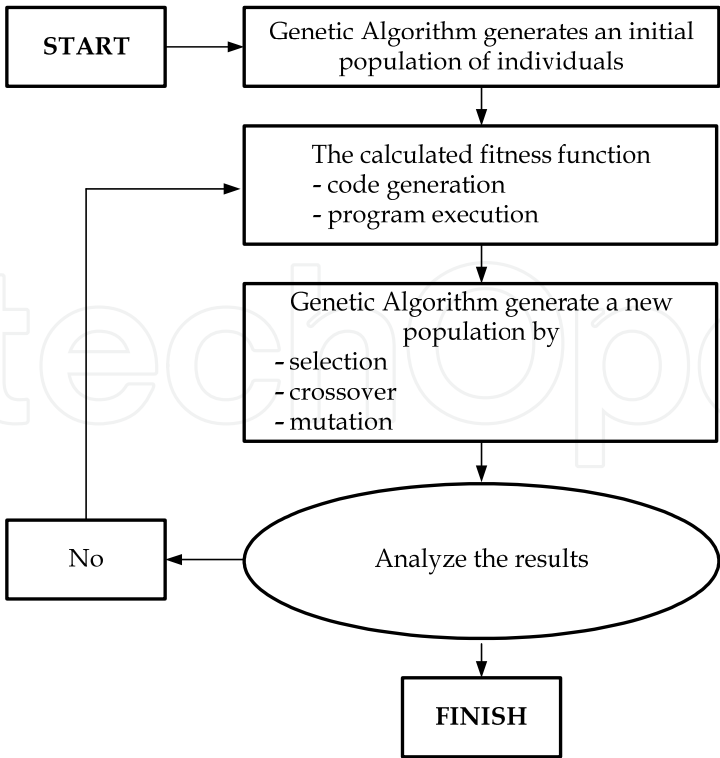


Fig. 3.3 Simply genetic algorithm

The genetic algorithms is a natural process of mating genes. It is no different genetic algorithm. There also are choosing the best "genes" of each solution and verify their combinations. Alongside the cross as a natural evolution is mutation, a random change in the gene. Both these processes are the values of the genetic operator. Using the genetic algorithm, remember to keep the best balance between the transfer of genes to the next generation, and a draw solution space. Too broad conditions imposed solutions may give erroneous results in spite of every generation the best available solution at the moment. Genetic algorithm is an excellent tool to monitor and maintain the balance between these two dependencies. The overall pattern of genetic algorithm is illustrated in Fig. 3.3. Using a genetic algorithm to identify the parameters of dynamic model of the electrical branch of the transducer sandwich working near mechanical resonance is shown in Fig. 3.4.

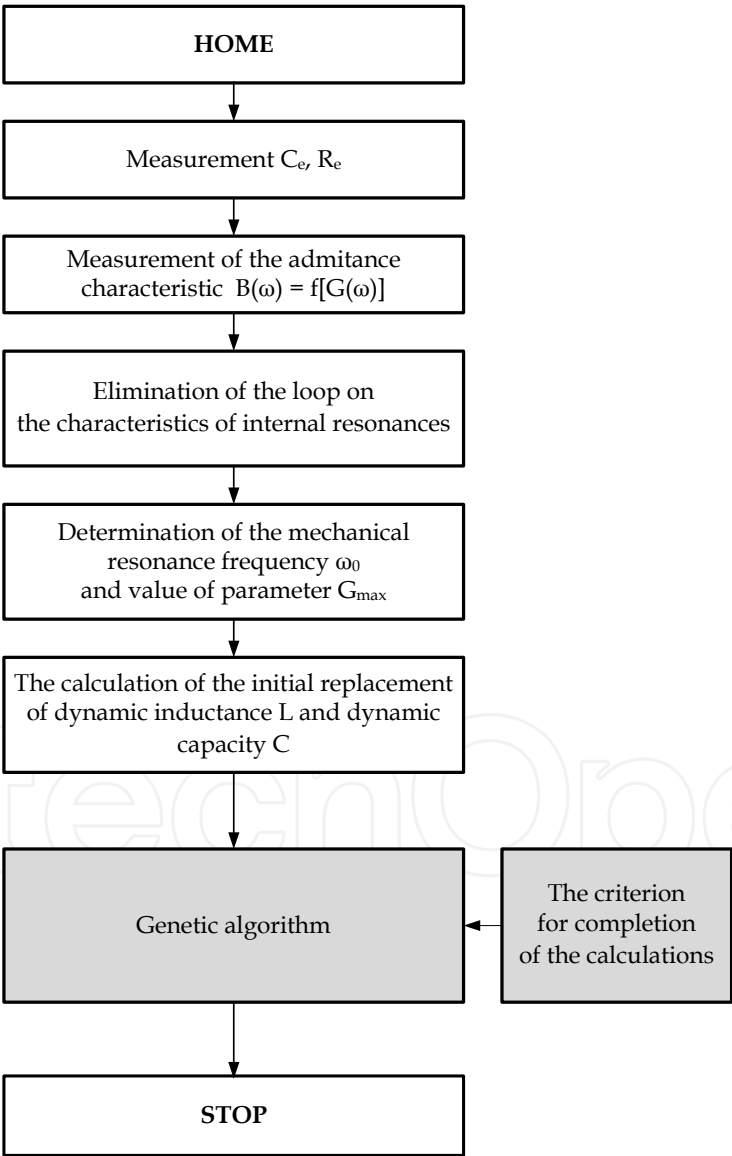


Fig. 3.4 Algorithm for parameter identification of dynamic model of the branch of electrical power ultrasonic transducer

The initial value of the dynamic resistance R is calculated by selecting the characteristics shown in Fig.3.1 point with coordinates (G_{\max}, B_e) . In this point there is a mechanical resonance of the transducer and is a good approximation condition.

$$\omega_0^2 LC - 1 = 0 \quad (3.1)$$

The dependence (2.2) shows that the resonance:

$$G_{\max}(\omega_0) = G_e + \frac{1}{R} \quad (3.2)$$

Therefore:

$$R = \frac{1}{G_{\max}(\omega_0) - G_e} \quad (3.3)$$

Choosing the actual characteristics of the admittance of any two points with coordinates (G_1, B_1) , (G_2, B_2) , which lie beyond the point of mechanical resonance ($\omega_1 \neq \omega_0$, $\omega_2 \neq \omega_0$) can calculate the initial value of the replacement of mechanical capacity C .

Transforming the system of equations:

$$\begin{aligned} G_1 - G_e &= \frac{\omega_1^2 C^2 R}{(1 - \omega_1^2 LC)^2 + \omega_1^2 R^2 C^2} \\ G_2 - G_e &= \frac{\omega_2^2 C^2 R}{(1 - \omega_2^2 LC)^2 + \omega_2^2 R^2 C^2} \end{aligned} \quad (3.4)$$

and taking into account that for G_{\max} is equal to the pulsation vibrations ω_0 approximate value of C is described by the formula:

$$C' = \frac{1 - \frac{\omega_1^2}{\omega_0^2}}{\omega_1} \sqrt{\frac{(G_1 - G_e)[(G_{\max}(\omega_0) - G_e)]}{1 - \frac{(G_1 - G_e)}{G_{\max}(\omega_0) - G_e}}} \quad (3.5)$$

$$C'' = \frac{1 - \frac{\omega_2^2}{\omega_0^2}}{\omega_2} \sqrt{\frac{(G_2 - G_e)[(G_{\max}(\omega_0) - G_e)]}{1 - \frac{(G_2 - G_e)}{G_{\max}(\omega_0) - G_e}}} \quad (3.6)$$

$$C = \frac{C' + C''}{2} \quad (3.7)$$

The initial value of the replacement of mechanical inductance L determined from the relationship:

$$L = \frac{1}{\omega_0^2 C} \quad (3.8)$$

After substituting the calculated value of the R, L, C and the measurement R_e, C_e the relationship (2.1) and (2.2) is determined by numerical coordinates of the points of the electrical characteristics of the admittance model for the same pulse, for which measurements of actual performance. If the error resulting from a comparison of the approximation characteristic with real characteristic (Fig.3.2) is greater than the accepted values, generate a new population of R_e, C_e, R, L, C parameters, repeat the calculation of coordinates of the electrical characteristics of the model and then analyze the resulting error. Calculations should be continued until the error resulting from a comparison of the characteristics shown in Fig.3.2 with the characteristics of the accepted model of the electrical transducer is smaller than the set value. Measurement error should be performed in the pulsation ω changing between points B_{max} and B_{min} (Fig.3.2).

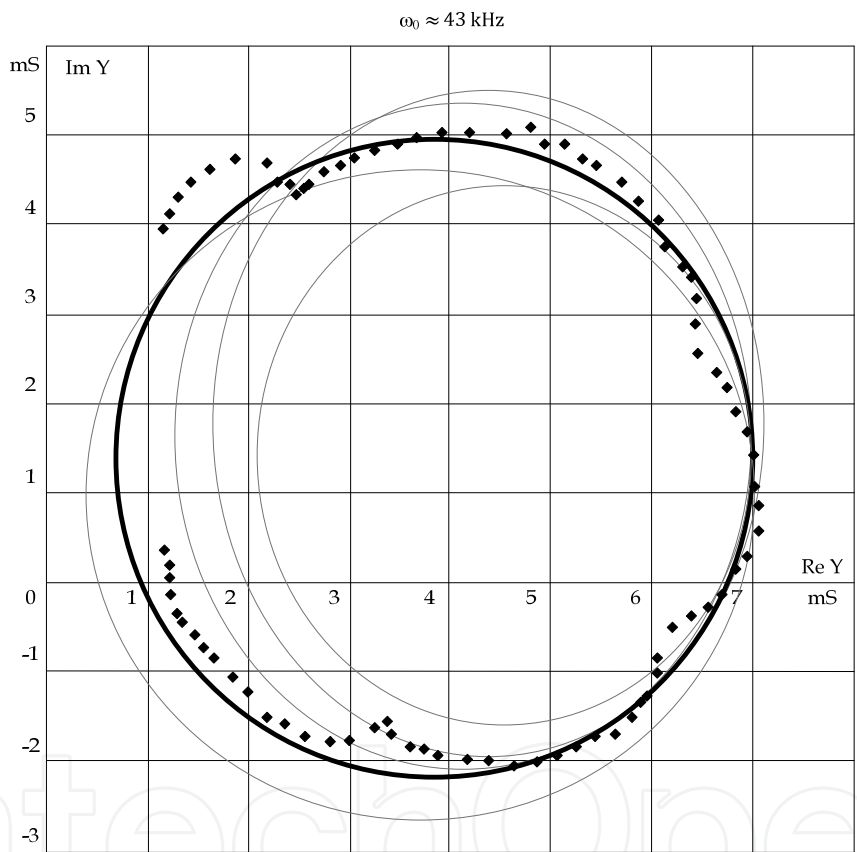


Fig. 3.5 Iterative improvement of the results obtained in numerical calculations and a computer simulation electric model of an sandwich type transducers

Procedure described above can be used and introduces the appropriate algorithm in the DSP program simulation.

```
//Program piezoelectric ceramic transducer
input {Circuit parameters [ $R_e, C_e, R, L, C, u(t)$ ];
      Simulation parameters ( $t_p, t_k, \Delta, v(0)$ );
      Evolution parameters (Num,Size, NumM,Initial,NumG,stop);}
```

```
Output (t, u; tp; uo=u(o));  
  
for (t, tk, t++) {New function form;  
    start initial population;}  
for (integer i=1, Num, i++) {New population,  
    Select the best}
```

where:
Genotype dimension: Num,
Size of the generation created by mutation: Size,
Number of the best selected genotypes for mutation: NumM,
Number of the best selected genotypes for crossing: NumC,
initial parameter mutation range: Initial

Examples of results obtained in subsequent iterative steps for the transducer mechanical resonance frequency of 42.9 kHz is shown in Fig.3.5.
When the next iterative step will be the condition for the completion of the calculations should be considered that the characteristics of the model shown in Fig. 2.2 parameters R_e, C_e, R, L, C generated in the genetic algorithm in the last population of values, coincides with the actual characteristics of the interpolated transducer. The shape of this characteristic is shown in Fig. 3.6.

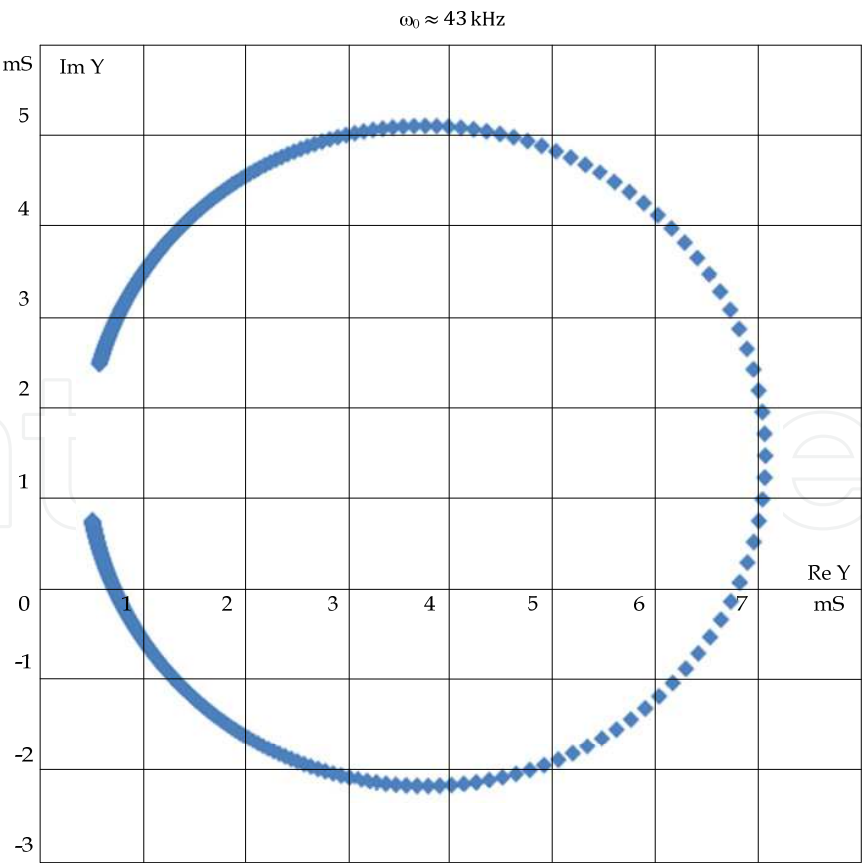


Fig. 3.6 Circle admittance obtained using genetic algorithm

3.2 Effect of the electrical equivalent circuit parameters on the shape characteristics of the transducer admittance

Location of figures which creates a characteristic admittance of the transducer coordinate system $B(\omega) = f [G(\omega)]$ can be determined by changing the value of capacity C_e and the loss of electrical resistance of ceramics R_e . The higher value of R_e the greater displacement figures to the right people along the conductance $G(\omega)$. If you forget in the pattern of replacement sensor resistance R_e ($R_e \rightarrow \infty$) will move to the left approximation of the characteristics. In this case, the graph will be almost tangential to the axis $B(\omega)$. Reduction in the capacity of C_e will move down the sheet, along the axis $B(\omega)$. Conductance G_{max} value determines the width of the main loop of the graph. From relation (3.2) shows that the value of G_{max} decreases when the resistance R increases.

The impact of dynamic capacity C can analyze the shape characteristics of saving the relationship (2.1) in the form

$$B(\omega) \approx \frac{\omega C (1 - \frac{\omega^2}{\omega_0^2})}{\omega^2 C^2 R^2 + (1 - \frac{\omega^2}{\omega_0^2})^2} \tag{3.9}$$

For small, $\pm 2\%$ of the pulsation untuning mechanical resonance, it can be assumed that:

$$B(\omega) \approx \frac{1 - \frac{\omega^2}{\omega_0^2}}{\omega C R^2} \tag{3.10}$$

From relation (3.10) shows that reducing the value of the dynamic capacity C will increase susceptance system. This also applies to the maximum B_{max} and minimum B_{min} . In this case, it means that the values of B_{max} and $|B_{min}|$ increased. The difference $B_{max} - B_{min}$ is equal to the amount of main loop of the graph.

These rule changes in the electrical equivalent circuit parameters of the transducer should be used during the generation of successive populations of a set of values of R_e , C_e , R , L , C genetic algorithm.

4. Conclusion

The actual characteristics of the admittance is a source of transparent, condensed information about the properties and parameters of the piezoelectric ceramic transducer stimulated by the mechanical vibrations. Used to identify the dynamic parameters of R , L , C , and optimization of electrical parameters R_e , C_e occurring electric transducer model, genetic algorithm uses these data and represents one of many possible methods to use here. It has the advantage that it can be realized in automatic cycle.

Based on preliminary data obtained experimentally from measurements of electrical parameters (R_e , C_e) and measurements of voltage and current waveforms created image of the actual transducer admittance characteristics of $B(\omega) = f [G(\omega)]$. Genetic algorithm can find the optimal approximation of the characteristics, correction of the value of R_e , and C_e and calculation of parameters R , L , C model of the electrical industry dynamic.

An important part of the described method is the proper preparation of input data. They should be given in the form of an ordered table of coordinates of points lying on the actual characteristics of the transducer according to those points that do not belong to the main loop of the graph. The process of eliminating points of the loop parasitic resonances can be implemented step by step analysis of the data included in the table of measurement results or by analyzing the image created by a set of characteristic points of $B(\omega) = f[G(\omega)]$.

Attempts to identify the parameters of a single transducer mechanical resonance frequency of 23.8 kHz and 43.2 kHz have confirmed the effectiveness of the genetic algorithm. Identification algorithm described above can be particularly useful in studies of larger groups of ultrasound transducers in high-power washing.

By introducing the necessary modifications can also be used to identify the parameters of transducers working in real conditions and to implement control systems that track the frequency of mechanical resonance.

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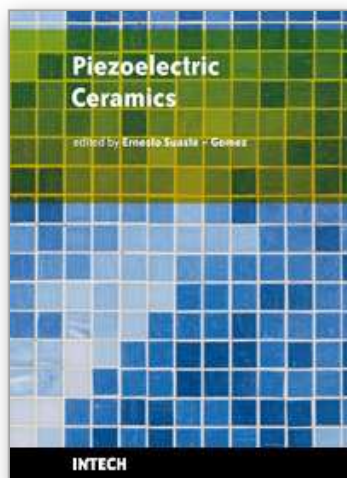
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6. Appendix

Table 1 shows selected results of detailed studies of the piezoelectric ceramic transducer mechanical resonance frequency of 42.9 kHz. Measurements were performed impedance meter HP 4192 type IMPEDANCE Analyzer. Indicated in bold letter omitted in the genetic algorithm performance admittance points beyond the main loop of the graph. The contents of Table 1 refers to Fig. 3.1, and Fig. 3.2.

f kHz	R kΩ	X kΩ	tg(φ)	φ rad	cos φ	sin φ	G mS	B mS
42,00	0,0721	-0,2338	3,2426	1,27166	0,2947	0,9556	1,204320	4,650189
42,04	0,0674	-0,2132	3,1659	1,26485	0,3012	0,9536	1,346922	4,223453
42,08	0,0703	-0,1925	2,7371	1,22052	0,3432	0,9393	1,674703	4,456680
42,12	0,0841	-0,1745	2,0750	1,12171	0,4341	0,9008	2,241050	4,963926
42,16	0,1006	-0,1809	1,7988	1,06342	0,4859	0,8740	2,347906	4,296001
42,20	0,0921	-0,1763	1,9138	1,08930	0,4631	0,8863	2,328693	3,289479
42,24	0,0888	-0,1483	1,6705	1,03138	0,5136	0,8580	2,971594	3,192256
42,28	0,1148	-0,1358	1,1834	0,86919	0,6454	0,7638	3,630303	3,907909
42,32	0,1515	-0,1403	0,9255	0,74675	0,7339	0,6793	3,554097	3,487659
42,36	0,1501	-0,2015	1,3423	0,93051	0,5974	0,8019	2,378189	3,725892
42,40	0,1047	-0,2014	1,9231	1,09127	0,4614	0,8872	2,032128	3,739428
42,44	0,1432	-0,1502	1,0492	0,80942	0,6899	0,7239	3,323991	4,162891
42,48	0,1212	-0,1918	1,5831	1,00742	0,5340	0,8455	2,353507	4,431376
42,52	0,1227	-0,1868	1,5228	0,98973	0,5489	0,8359	2,455637	4,700036
42,56	0,1041	-0,1800	1,7284	1,04629	0,5008	0,8656	2,408478	4,873619
42,60	0,0992	-0,1666	1,6791	1,03365	0,5117	0,8592	2,639118	4,997220
42,64	0,0980	-0,1478	1,5079	0,98522	0,5527	0,8334	3,116930	4,959969
42,68	0,0973	-0,1351	1,3884	0,94660	0,5844	0,8114	3,510281	4,685777
42,72	0,0974	-0,1229	1,2610	0,90034	0,6213	0,7835	3,962806	4,035905
42,76	0,1005	-0,1081	1,0752	0,82162	0,6810	0,7322	4,613098	2,849480
42,80	0,1057	-0,0924	0,8738	0,71814	0,7530	0,6580	5,362597	1,944590
42,84	0,1139	-0,0752	0,6599	0,58331	0,8346	0,5508	6,115813	2,348010
42,88	0,1295	-0,0571	0,4408	0,41517	0,9150	0,4033	6,464511	2,602020
42,92	0,1542	-0,0514	0,3331	0,32152	0,9488	0,3160	5,838341	1,397040
42,96	0,1582	-0,0704	0,4451	0,41880	0,9136	0,4067	5,274907	-0,305750
43,00	0,1374	-0,0578	0,4207	0,39819	0,9218	0,3878	6,185462	-0,238180
43,04	0,1365	-0,0271	0,1982	0,19569	0,9809	0,1944	7,047725	-0,525000
43,08	0,1509	0,0070	-0,0463	-0,04622	0,9989	-0,0462	6,610636	-1,104520
43,12	0,1880	0,0084	-0,0449	-0,04483	0,9990	-0,0448	5,309238	-1,992950
43,15	0,1585	0,0133	-0,0838	-0,08362	0,9965	-0,0835	6,263456	-1,955190
43,17	0,1577	0,0283	-0,1798	-0,17789	0,9842	-0,1770	6,143423	-1,362000
43,20	0,1697	0,0661	-0,3894	-0,37135	0,9318	-0,3629	5,117705	-1,591100
43,24	0,2042	0,1018	-0,4985	-0,46245	0,8950	-0,4461	3,922151	-1,756280
43,28	0,2579	0,1058	-0,4104	-0,38940	0,9251	-0,3796	3,319092	-1,271460
43,32	0,2395	0,1108	-0,4627	-0,43339	0,9075	-0,4200	3,438489	-0,718400
43,36	0,2638	0,1777	-0,6736	-0,59280	0,8294	-0,5587	2,607243	4,650189
43,40	0,3530	0,2199	-0,6231	-0,55720	0,8487	-0,5288	2,040678	4,223453

Table 1. Results of laboratory tests by the ultrasonic transducer sandwich of the resonance frequency around 43 kHz



Piezoelectric Ceramics

Edited by Ernesto Suaste-Gomez

ISBN 978-953-307-122-0

Hard cover, 294 pages

Publisher Sciyo

Published online 05, October, 2010

Published in print edition October, 2010

This book reviews a big window of opportunity for piezoelectric ceramics, such as new materials, material combinations, structures, damages and porosity effects. In addition, applications of sensors, actuators, transducers for ultrasonic imaging, positioning systems, energy harvesting, biomedical and microelectronic devices are described. The book consists of fourteen chapters. The genetic algorithm is used for identification of RLC parameters in the equivalent electrical circuit of piezoelectric transducers. Concept and development perspectives for piezoelectric energy harvesting are described. The characterization of principal properties and advantages of a novel device called ceramic-controlled piezoelectric with a Pt wire implant is included. Bio-compatibility studies between piezoelectric ceramic material and biological cell suspension are exposed. Thus, piezoelectric ceramics have been a very favorable solution as a consequence of its high energy density and the variety of fabrication techniques to obtain bulk or thin films devices. Finally, the readers will perceive a trend analysis and examine recent developments in different fields of applications of piezoelectric ceramics.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Pawel Fabijanski and Ryszard Łagoda (2010). Genetic Identification of Parameters the Piezoelectric Transducers for Digital Model of Power Converter in Ultrasonic Systems, Piezoelectric Ceramics, Ernesto Suaste-Gomez (Ed.), ISBN: 978-953-307-122-0, InTech, Available from:
<http://www.intechopen.com/books/piezoelectric-ceramics/genetic-identification-of-parameters-the-piezoelectric-transducers-for-digital-model-of-power-conver>

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