Piezoelectric Device with Volume Elastic Wave for Ultrasonic Pulses Generating

MARIAN PEARSICĂ
"Henri Coanda” Air Force Academy
Mihai Viteazu St. 160, 2200, Brasov, ROMANIA
marianpearsica@yahoo.com  http://www.afahc.ro

CIPRIAN RĂCUCIU, NICOLAE JULA, DAN RĂDUCANU
Military Technical Academy
George Coşbuc Blvd. 81-83, Sector 5, Bucharest, ROMANIA
ciprian.racuciu@gmail.com, nicolae.jula@gmail.com, dan.raducanu@gmail.com

Abstract: - The device constitutes a specific application of piezoelectric transducers, which allows the generation of impulses series with constant or pseudo-aleatory frequency, and constant or variable pause. The device work is based on the process of achieving inverse piezoelectric effect, meaning the deformation of the crystalline network of the piezoelectric device caused by an external electrical field. The equipment was physically realized and it constituted the object of a research contract of the Optical-Electronic Institute of Bucharest. In this paper is also presented a PSpice simulation of the projected equipment.

Key-Words: - piezoelectric transducer, generator, acoustic power, electrical field, ultrasonic signals, pseudo-aleatory frequency

1 Introduction

In the industrial applications, besides defect detection, ultrasound can also be used to determine significant materials characteristics such as density, thickness, mechanical properties, level sensing, and more. By propagating a wave in a given medium, useful information about the medium can be generated by analyzing the transmitted or reflected signals.

The piezoelectric transducers present the advantages: high positioning accuracy with a resolution of 0.005μm/V, high stiffness, fast response, high efficiency. Ultrasound is applicable to all states of matter, with the exception of plasma and vacuum. Propagation of ultrasound in a material is not affected by its transparency or opacity.

Possible applications: optical systems and measurement technology, laser tuning, fiber positioning, microelectronics, micro-lithography, acoustic propagation system, precision mechanics and mechanical engineering.

Ultrasonic signals generating device, based on piezoelectric crystals, is used to obtain ultrasonic signals with fixing frequency between 20÷120kHz. The device could also generate packets of ultrasonic signals with constant or pseudo-aleatory frequency, and constant and variable pause [6]. It is a specific application of the piezoelectric crystals, which allow the obtaining ultrasonic signals, based on unconventional method. Its work is based on the inverse piezoelectric effect, obtained by the deformation of the crystalline network of the piezoelectric device under the action of an external electric field.

The generator is a piezoelectric transducer, which belong to the series of piezoelectric devices with elastic wave of volume. The configuration of the electro-elastic piezoelectric transducer is presented in Figure 1.

![Fig.1 Configuration of the electro-elastic piezoelectric transducer](image1)

For certain values of frequency, the equivalent electro-elastic diagram could be represented as a circuit with discreet elements (Fig.2).

![Fig.2 Equivalent diagram of piezoelectric transducer](image2)
The elements of equivalent scheme have the following expressions and significations [2]:

\[
C_o^s = \frac{1}{2\pi f} \Im \left\{ \frac{1}{Z_{eo}} \right\}
\]

(1)

\[
R_e = \frac{Q_e}{2\pi f C_o^s}
\]

(2)

\[
L = \frac{Z_{om}}{8\pi^2 f_i^2 \nu_f} = Z_{om} \frac{\lambda}{16\pi f_i n^2}
\]

(3)

\[
C = \frac{4n^2}{\pi^2 f_i Z_{om}}
\]

(4)

\[
R = \frac{\pi Z_{om}}{8Q_m n^2}
\]

(5)

where: \( F \) is the representative in simplified complex of elastic force at mechanical gate; \( V \) – the representative in simplified complex of vibration speed at mechanical gate; \( U_s, I \) – the representatives in simplified complex of voltage and electrical current at electrical gate; \( n \) – the transformation ratio of ideal electro-elastic transformer; \( f \) – the oscillation frequency of electrical applied field; \( \lambda \) – the wave length of the gradual elastic wave; \( Z_{om} \) – the characteristic elastic impedance of the transducer; \( Q_m, Q_e \) – the qualitative mechanical and electrical factors of the transducer; \( f_i \) – the value of the frequency for which the constant phase of the transducer has the particular characteristic value at the mechanical resonance; \( \nu_f \) – the propagation speed of the elastic wave in the piezoelectric transducer; \( Z_e, Z_i \) – the complex electromotive voltage and the internal complex impedance of the supply source for the piezoelectric transducer; \( Z_s \) – the complex load impedance.

Concrete values of elements in equivalent diagram are determined by material parameters corresponding to transducer configuration and constructive sizes.

In both the direct and inverse piezoelectric effects, the strain and stress are related to the electrical parameters by the piezoelectric constants, \( d_{ij}, g_{ij}, h_{ij} \) and \( e_{ij} \), which are different values for different directions in the material. The most commonly measured of these constants is the piezoelectric strain constant \( d_{ij} \). In the longitudinal mode of X-cut crystal, the applicable value is \( d_{11} \). For an applied voltage, \( U_{in}, d_{11} \) will determine the resultant thickness change, \( \Delta l_{out} \), respectively:

\[
\Delta l_{out} = d_{11} \cdot U_{in}
\]

(6)

To determine the resultant voltage for the direct piezoelectric effect two different constants are used. The piezoelectric deformation constant \( h_{ij} \) is used to relate the resultant voltage to a given deformation. In this case the thickness change, \( \Delta l_{in} \), produces an output voltage, \( U_{out} \), according to:

\[
U_{out} = h_{ij} \cdot \Delta l_{in}
\]

(7)

A second constant, the piezoelectric pressure constant, \( g_{ij} \) is used to relate the resultant voltage to a given applied pressure, \( P \). The resultant voltage, \( U_{out} \), is given by:

\[
U_{out} = g_{ij} \cdot P
\]

(8)

For many applications the material constant of interest is the electro-mechanical coupling factor, \( k_{ij} \), which is a measure of the piezoelectric material’s ratio of output energy to input energy or efficiency:

\[
k_{ij} = \frac{U_{out}}{U_{in}} \cdot \frac{\Delta l_{out}}{\Delta l_{in}} = h_{ij} \cdot d_{ij}
\]

(9)

The coupling factor is electrically determined using the resonance frequency data [1].

The wavelength of the ultrasound used has a significant effect on the probability of detecting a discontinuity.

In ultrasonic testing, the shorter wavelength resulting from an increase in frequency will usually provide for the detection of smaller discontinuities. Changing the frequency when the sound velocity is fixed will result in a change in the wavelength of the sound.

The general relationship between the speed of sound in a solid and its density and elastic constants is given by the following equation:

\[
V = \sqrt{\frac{c_{ij}}{\rho}}
\]

(10)

Where \( V \) is the speed of sound, \( c_{ij} \) is the elastic constant, and \( \rho \) is the material density.

This equation may take a number of different forms depending on the type of wave (longitudinal or shear) and which of the elastic constant that are used.

2 Equipment block diagram. Principle of operation.

The emitter section of the ultrasonic emitter-receiver generates short, large amplitude electric pulses of controlled energy, which are converted into ultrasonic pulses when applied to ultrasonic transducers. Most emitter sections have very low impedance outputs to better drive transducers. Control functions associated with the emitter circuit include:

- Pulse length or damping (The amount of time the pulse is applied to the transducer.)
- Pulse energy (The voltage applied to the transducer.)

In the receiver section the voltage signals produced by the transducer, which represent the received ultrasonic pulses, are amplified. The amplified signal is available as an output for display or capture for signal processing.

The equipment consists in a piezoelectric generator and a command and supply system. Under the action of the oscillating electrical field produced by the excitation source, the piezoelectric generator will pulse with the frequency of the command impulses (will expand and respectively contract). If the frequency of the AC field corresponds with the frequency where the thickness of the crystal represents half a wavelength, the amplitude of the crystal vibration will be much greater. This is called the crystal’s fundamental resonance frequency.

The power module is achieved using Power MOSFET transistors, which are connected in derivation. The high-voltage transformer ensures the necessary voltage for the supply of the piezoelectric device and also the adaptation to the load. A specific computer program is used to generate the series of datum impulses. The block diagram of ultrasonic signals generating set, which is presented in Figure 3, has two components: a surface equipment (A) and an equipment inside a stainless steel cylinder (b), which functions at 300m depth.

Technical conditions for input and output were the following: the equipment supply was realized from the supply network – 220±15%V AC, f = 50Hz; operating regime – a) generation of pulses trains with pseudo-aleatory frequency (20÷120kHz), and constant and variable pause, b) generation of pulses trains with constant frequency (established by the user between 20 and 120kHz), and constant and variable pause; maximal voltage on piezoelectric device, \( U_{\text{max}} = 1kV \); efficiency of excitation electronic source, \( \eta \geq 80\% \); the supply and command of the piezoelectric device were realized at maximum depth of 300m; electrical resistance of supply cable, \( R_c = 80\Omega/km \); imposed acoustic power, \( P_a = 250W \); the programmable time of pulses train between 0÷35ms, and pause between pulses trains, 0÷75ms; variation of excitation voltage value will determine the variation of acoustic output power value; protection against overload, supra-voltage, electrocution, radio-electronic interferences in/from network; the electronic source and piezoelectric device were introduced into a stainless steel cylinder with inside diameter – 105mm, outside diameter – 110mm and maximal height – 0.5m.

Considering the input and imposed output conditions were established functional units, which compose the generating equipment.

The functional units of the surface equipment (A) are the following: protective unit against radio-electronic interferences in/from network (A1); rectify and filtering unit for supply voltage (A2); auxiliary power supply for lifting motor (A3); auxiliary power supply of \( \pm 18 \) V (A4); computer with keyboard (A5); display (A6); interface and command unit (A7).

The equipment (B) has the following functional unit: steady voltage of \( \pm 29 \) V for lifting motor supply (B1); steady voltage of \( \pm 15 \) V (B2); low-pass filter (B3); circuit for amplitude discrimination of command pulses (B4); circuit for width discrimination of command pulses (B5); command circuit of power module (B6); filter for radio-electronic interferences (B7); condensers battery (B8); high-voltage transformer (B9); power module (B10); protection overload unit (B11); reaction circuit (B12); supra-voltage protection unit (B13); piezoelectric generator (B14).

The switching element of power module is realized by Power MOSFET transistors, connected in derivation, that allow obtaining an electrical power of 600W [3, 4]. Input and output parameters are presented on display, and working conditions are established with keyboard computer.
The interface and command unit realizes the interface between PC and functional unit (B), processes input and output data, and establishes working conditions. The command circuit \((B_6)\) realizes charge and discharge the gate-drain capacitance of Power MOSFET transistors, determining saturation or blocking them \([4]\).

Because the command pulses are conducted through a 300m long cable, it was necessary to utilize some receiving circuits for command pulses, like: low-pass filter, pulse height discriminator realized with a Smith trigger, circuit for time discrimination, circuit for reject the spikes and unlike interferences. High-voltage transformer delivers necessary voltage to supply piezoelectric generator; also, it realized the load matching. The transfer of energy is made sin-phase.

Piezoelectric device consists in one piezoelectric radial polarized transducer, which pulses with frequency of the command pulses. The acoustic power of piezoelectric transducer is approximately 250W.

### 3 Designing elements. Obtained Results.

Many of today’s applications of piezoelectricity use polycrystalline ceramics instead of natural crystals. Piezoelectric ceramic materials can be manufactured in almost any shape or size, and the mechanical and electrical axes of the material can be oriented in relation to the shape of the material. The orientation of the DC poling field determines the orientation of the mechanical and electrical axes.

The active element is the heart of the transducer as it converts the electrical energy to acoustic energy and vice versa. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular structure of the material. This alignment of molecules will cause the material to change dimensions.

The piezoelectric transducers are made of ceramic materials as PZT (titanium, zirconium, lead) and the research was realized using a material as \(\text{Pb(Zr}_{0.53}\text{Ti}_{0.47})\text{O}_3\) doped with \(\text{Nb}_2\text{O}_5\), \(\text{Bi}_2\text{O}_3\) and \(\text{MnO}\) \([5]\). The dimensions and the composition of the piezoelectric transducers were determined considering the frequency band \((20-120 \text{ kHz})\) of the ultrasonic signals and the imposed acoustic power \((250W)\).

After the performed experiments at Optical Electronic Institute of Bucharest, it resulted that the piezoelectric generator represents a preponderant capacitive load with a capacitance around 10nF. For an electrical power of 600W and a frequency of 120kHz, the electrical stored energy in piezoelectric crystal capacitance is around 5mJ. It results the relation for excitation voltage of piezoelectric crystal:

\[
U_a = \frac{2E}{C} \Rightarrow U_a \approx 1kV
\]

For a conduction time of 4\(\mu\)s and a required power of 600W, the electrical voltage on piezoelectric crystal increases to maximum 1000V.

An important parameter that we must consider for piezoelectric crystal designing is maximum pulsing frequency. Considering relaxation time of crystal around 4.2\(\mu\)s, it results the maximum working frequency around 120kHz. Another requirement for piezoelectric crystal is its output impedance to be better matching to radiation impedance of environment. So, the oscillatory circuit represented by piezoelectric crystal must have its own damping, and its impedance must varies linear in frequency band (doesn’t have poles).

The piezoelectric generator is formed by a cylindrical piezoelectric piece, radial polarized, with dimensions: \(\phi_{\text{out}} = 50\text{mm}, \phi_{\text{int}} = 38\text{mm}, h = 6\text{mm}\). Piezoelectric generator assembly is show in Figure 4, and it is composed by the following elements: cylindrical stainless steel tube (1), terminal for high-voltage supply (2), metallic reflector (3), non-conductive metallic axle (4), insulated piece (5), piezoelectric crystal (6), silicone oil (7), mixture of resin and wolfram powder (8), sealing piece (9).

![Fig.4 Piezoelectric generator assembly](image)
piezoelectric generator works into a silicone oil medium, which allows acoustic propagation. The oscillatory circuit realized by the secondary inductance of high-voltage transformer and by the piezoelectric generator capacitance is strongly damped because the medium radiation impedance, where the generator is situated.

By PSpice simulation was tested in time and frequency domains the excitation source of piezoelectric device. In order to simplify the analysis and to reduce simulation time, from projected source was considered only the power module. The excitation source is in essence a closed loop regulating system (Fig.5), and it must be analyzed its stability.

The converter output-control transfer function is determinate by mediation method [7], doing Forward converter – Buck converter equivalence. It is given by the following equation:

\[
T_C(s) = \frac{U_O(s)}{U_C(s)} = K \cdot \frac{1 + \frac{s}{s_1}}{s^2 + \frac{s}{\omega_o \cdot Q} + 1}
\]

(12)

Where:

\[
K = \frac{n \cdot D}{2} \cdot U_{in}, \quad \omega_o = \frac{1}{\sqrt{L_o \cdot C_o}}, \quad \omega_o \cdot Q = \frac{R_s}{L_o}, \quad s_1 = \frac{1}{r_c \cdot C_o}, \quad r_c - \text{series equivalent resistance of transducer capacitance, } C_o.
\]

The transfer function of the closed loop regulating system may be expressed by the equation [4]:

\[
F(s) = \frac{U_o(s)}{U_{ref}(s)} = \frac{T_R(s) \cdot T_M(s) \cdot T_C(s)}{1 + T_D(s) \cdot T_R(s) \cdot T_M(s) \cdot T_C(s)} \Rightarrow F(s) = \frac{S(s)}{1 + T_D(s) \cdot S(s)}
\]

(13)

Where: \(T_M(s)\) represents the PWM chopper transfer function, \(T_R(s)\) is the PI controller transfer function; \(T_D(s)\) is the division circuit transfer function; \(S(s)\) = \(T_R(s) \cdot T_M(s) \cdot T_C(s)\) represents the open loop gain; \(T_D(s) \cdot S(s)\) is the open loop transfer function.

By resolving \(1 + T_D(s) \cdot S(s) = 0\) equation, are determined the closed loop transfer function poles.

The waveforms for: grid current, drain current, drain-source voltage, and excitation voltage of piezoelectric device are presented in Figure 6.

Fig.5 Excitation source as a closed loop regulating system

The frequency attenuation characteristics and phase responses, for PI chopper, and converter are presented in Figures 7, and 8.

Fig.6 Electrical quantities waveforms for analyzed circuit

Fig.7 Chopper waveforms in frequency domain
The frequency attenuation characteristic and envelope-delay characteristic (phase response), for excitation source, are presented in Figure 9.

The open loop transfer function of the system, \(T_D(s)\), has a pole in fixed point, which is introduced by the controller, a double pole introduced by the converter, and two zero, one introduced by the controller and the other one introduced by the converter. The presence of pole in fixed point ensures a high gain at low frequencies. The zero introduced by the controller is placed near the double pole introduced by the converter, so that the passing through \(f_{\text{cross}}\) is realized with 20dB/dec. It results \(f_{\text{cross}} = 4.2\text{kHz}\). The phase edge is positive and has the value equal to 49.2°.

Considering the results of performed analyze it is allowed to affirm that the open loop transfer function of the system ensures its stability.

4 Conclusions

The presented equipment is a complex system, purposed to generate ultrasonic signals by an unconventional method, using piezoelectric transducers.

The piezoelectric generator is composed of a piezoelectric crystal supplied by impulses and it pulses with the command impulses frequency.

Many factors, including material, mechanical and electrical construction, and external mechanical and electrical load conditions, influence the behavior of a transducer. One of the essential features of ultrasonic measurements is mechanical coupling between the transducer and the solid whose structure or properties are to be studied.

The geometric conformation and the structure of the piezoelectric piece were established considering first maximal work frequency and the imposed acoustic power.

The excitation source works in switching and allows obtaining an electrical power of 600W. The piezoelectric generator works also as a storage condenser and the transfer of energy is made in-phase.

As a consequence of the performed PSpice analysis, it results that the evolutions in time of the electrical quantities and also the obtained signal levels have a good concordance with calculated values.

References: