Analysis of the design of ultrasonic electronic generators

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Abstract. The design and operation of electronic generators for ultrasonic intensification of processes in gaseous and liquid media will be considered. General requirements and new approaches to electronic generators have been developed based on the analysis of the characteristics of modern piezoelectric vibration systems that perform large amplitude oscillations (quality factor, multi-frequency, multilayer piezoelectric elements). Continuous monitoring of system parameters and setting of optimal operating modes of the electronic generator were studied.

1. Introduction

The industrial application of high intensity ultrasonic vibrations began about 60 years ago. Nevertheless, in such a short period of time, ultrasonic technologies have proven their high efficiency, especially in the processes of extraction, dispersion, emulsion production, drying, impregnation of porous materials, production or coagulation of aerosols, welding of polymers and metals. To intensify technological processes under the influence of high-intensity ultrasonic vibrations, special devices are used - ultrasonic technological devices (UTA). An ultrasonic technological apparatus consists of a technological volume (or technological equipment), an ultrasonic oscillatory system (UOS), which converts electrical vibrations of ultrasonic frequency into elastic mechanical vibrations, transforms them and enters into the processed medium, and an electronic generator that converts the energy of the electrical network into the energy of electrical oscillations of ultrasonic frequency, designed to power the ultrasonic vibrating system [1].

Currently, due to the development and application of new types of ultrasonic generators [2], the technology of activation of processes occurring in the gaseous environment is experiencing a rebirth. Among such technologies, the coagulation of natural and man-made dispersions in the air is of great interest [3].

Ultrasonic equipment (ultrasound apparatus) used to enhance processes in a gaseous environment consists of two main elements that complement each other.

The main element of the equipment is an ultrasonic vibration system consisting of a piezoelectric converter that converts the energy of electrical vibrations from an electronic generator, a wave-water amplifier structure and a transmitter that converts ultrasonic vibrations into a gaseous medium under the influence of ultrasound.

2. Features of ultrasonic electronic generators

Currently, both in our country and abroad, a system of resonant piezoelectric vibration-wave type, powered by a transistor electronic generator operating in switching mode, is being built according to
the standard scheme of ultrasonic technological devices of different capacities and technological purposes. [2, 3]. Ultrasonic oscillatory systems, made according to a half-wave design scheme, using modern piezoelectric materials, have an efficiency, up to 80% [4]. Transistor generators operating in the key mode are also characterized by high efficiency: 92–97% (theoretically achievable - almost 100%). Obviously, the theoretically achievable overall efficiency energy conversion in an ultrasonic technological apparatus is approximately 100 \cdot (0.95 \cdot 0.8) = 76\% [5]. Unfortunately, this is not implemented in practice, especially under conditions when the properties of the processed media in the technological process are continuously changing. The reason for the decrease in overall efficiency, ultrasonic technological devices is the inefficient transfer of energy from the electronic generator to the ultrasonic vibrating system and from the ultrasonic vibrating system to the processed medium, that is, the conditions for optimal acoustic and electrical matching are not met. Optimal acoustic matching is understood as such a mode of interaction of an ultrasonic oscillatory system with a processed medium, in which the value of its acoustic impedance is minimal and is a real value [1, 4, 5]. Obviously, in order to fulfill the condition of acoustic matching of the ultrasonic oscillatory system with the processed medium, it is sufficient to ensure the equality of the frequency of its mechanical resonance and the frequency of the supply voltage. Under the electrical matching of an electronic generator (operating in a key mode) and an ultrasonic oscillatory system is understood such a mode of their interaction, in which the following conditions are met [2, 6, 7]:

1. The current flowing through the ultrasonic oscillatory system is harmonic.
2. Switching of the output transistors of the generator occurs at zero current.
3. Generator load power factor is one.

Fulfillment of the listed conditions allows to transfer energy from the electronic generator to the ultrasonic vibrating system with the least losses. As is known, when connecting a piezoelectric oscillatory system to an electronic generator, this condition is not met. This necessitates the inclusion of special electrical matching circuits between the output of the electronic generator and the input of the ultrasonic vibrating system, which are reactive quadripoles [1, 6]. Under the conditions of changes in the parameters of the processed media and the presence of other destabilizing factors, the modes of acoustic and electrical matching during the operation of the UTA change. Therefore, to maintain optimal matching modes, automatic regulation of some parameters of the ultrasonic technological apparatus is required in accordance with changes in the properties of the processed medium. The problem of optimizing the acoustic matching of an ultrasonic oscillatory system with the processed medium under conditions of changing the parameters of the latter is solved by automatically adjusting the output frequency of the generator in accordance with all possible changes in the frequency of the oscillating system [2, 8]. More difficult to solve is the problem of electrical matching. To date, there are no practical methods and means for implementing automatic control of the electrical matching circuit. At the same time, all known UTA designs are equipped with electrical matching circuits, the parameters of which are fixed and selected in such a way as to ensure maximum operating efficiency in only one technological mode in a narrow range of changes in the properties of the processed medium [1, 4]. In the case of changing the properties of the medium and the parameters of the technological process in a wider range, the optimal electrical matching cannot be achieved.

3. Frequency of ultrasonic vibration system

To establish the relationship between the acoustic characteristics of the processed medium and the input electrical resistance of the ultrasonic vibrating system, the method of electromechanical analogies proposed by W. Mason [9] is used. This method makes it possible to represent mechanical quantities by their electrical equivalents and to consider ultrasonic vibrating systems as an electrical load. In the case under consideration, the piezoelectric ultrasonic oscillatory system is represented by an equivalent electrical equivalent circuit, which makes it possible to relate its acoustic and electrical parameters. One of the options for such an equivalent circuit is shown in Fig. 2.
The curves shown were obtained using an equivalent electrical model of an ultrasonic transducer (Figure 3) with a resonant frequency of 25.0 kHz. To show the effect of the electrical capacitance of piezoceramic elements on the frequency dependence of the phase shift between current and voltage in irradiated piezoelectric elements, these dependencies are given as an example (curves 2).

From the presented dependencies, it can be seen that the change in electrical power of the piezoceramic elements as a result of overheating during the emitter operation causes the frequency response system of the existing ultrasonic generators to direct the phase shift between current and voltage. the emitter elements are zero, which causes the ultrasonic electron generator to operate at a frequency that does not correspond to the resonant frequency of the ultrasonic vibration system, but slightly exceeds it (the curves in Figure 1 are a maximum of 3 relative to the curve). the corresponding point on the right).

![Figure 1](image.png)

**Figure 1.** Amplitude-frequency and phase-frequency characteristics of piezoceramic elements depending on the change in electrical capacitance.

As we have noted, the operation of an ultrasonic vibration system in a gaseous environment is accompanied by a strong heating of its elements, a decrease in the resonant frequency and an increase in the electrical power of the piezoelectric elements. With a high quality factor of the system, the intensity of the ultrasonic effect and the efficiency of the processes performed are reduced due to errors in the operation of the AFC system (due to the capacitive effect of piezoceramic elements).

To eliminate the effect of the capacitance of the piezoelectric elements on the frequency matching of the generator with the ultrasonic vibration system, a scheme of current reception of the mechanical network was proposed. As a mechanical vibration system, the phase-frequency characteristic of the emitter does not depend on the electrical power of the piezoceramic elements of the emitter.

Figure 2 shows the equivalent electrical circuit of an ultrasonic emitter, operating close to a mechanical resonance frequency [2].
Figure 2. Equivalent circuit of an ultrasonic emitter with a piezoelectric transducer.

In this circuit, inductance \( L_M \) is equivalent to the oscillating mass of the system, capacitance \( C_M \) is the elasticity of the system material; active resistance \( R_{\text{mech}} \) - resistance to mechanical losses, \( C_k \) - electrical capacitance of piezoceramic elements, \( R_d \) - dielectric losses. Elements \( L_M, C_M, R_{\text{mech}} \) form the so-called mechanical branch of the equivalent electrical circuit of a piezoelectric oscillatory system with a complex resistance \( Z_{\text{mech}} \).

The current flowing through the \( L_M, C_M, R_{\text{mech}} \) elements is the current of the mechanical branch, the frequency characteristic of which (amplitude and phase) completely repeats the frequency response of the ultrasonic emitter, if it is considered as a mechanical oscillatory system. Thus, a new criterion for tuning the electronic generator to the resonant frequency of the oscillatory system is the tendency to zero phase shift between the voltage on the piezoceramic elements of the emitter and the current of its mechanical branch.

The most significant and dynamic changes in the process of UTA operation are subject to elements determined by the processed environment. When ultrasonic vibrations are emitted into a liquid medium, the inertial resistance prevails over the elastic one, and the medium behaves like a mass attached to the emitter. In this regard, the UOS can be excluded from the calculation.

\[
\omega = \frac{1}{\sqrt{C_k L_M}}
\]  

(1)

To determine the real values of the variable values when operating under conditions of an unmatched load, experimental studies were carried out and the dependences of the power losses in the output transistors and efficiency were obtained. Output stage on the phase angle between current and voltage at the output of the generator. The research results are presented in the form of graphs in fig. 3. The same graphs show the theoretical approximation defined by the expression 1.

Figure 3. Graphs of the dependence of power losses (a) and efficiency (b) on the phase angle
between current and voltage at the output of the generator. Triangular markers correspond to theoretical data, round markers correspond to experimental data.

Under the influence of ultrasound on a gaseous medium, the parameters of the emitters such as Q-factor, resonant frequency and vibration amplitude do not change, for example, in a liquid medium where the wave impedance varies in magnitude. When high-intensity ultrasonic fields are used, this leads to a dynamic change in the emitter parameters. The only factor that determines the change in the resonant frequency of a generator operating in a gaseous environment is the heating of its structure. The rate of change of the resonant frequency of the emitter is about 5.2 Gts / s. In this case, the speed requirements of the AFC generator system can be significantly reduced.

The proposed new technical solutions were implemented in the creation of electronic generators operating as part of ultrasonic installations designed to create powerful acoustic fields in gaseous media.

With an ultrasonic generator power of 300,01 W and a radiating disk diameter of 35 sm, ultrasonic vibrations were obtained with an intensity of up to 164 dB. The level of amplitude modulation of the current in the power supply circuit of the emitter does not exceed 5,0%, while when operating existing AFC systems (when working with emitters, the Q factor of which reaches 1000), the level of amplitude modulation reaches 70,0%.

Practical results on coagulation of fogs, solid particles in the air, fire-extinguishing foam in the process of beer filling, drying of products [8, 9] have confirmed the high efficiency of the developed electronic generators.

4. Conclusion

The conducted studies allowed laying the foundation for solving the problem of coordination and obtaining the following practical results.

1. It has been established that the decrease in the efficiency of ultrasonic technological devices during technological processes is due to the electrical mismatch between the electronic generator and the ultrasonic oscillatory system.

2. It is shown that the cause of the mismatch is a change in the electrical parameters of the oscillatory system, due to a change in the properties of the processed media during the technological process.

3. The features of the construction of tunable electrical matching circuits are analyzed and the requirements for equipment providing the optimal electrical matching mode are formulated.

4. The limits of the necessary restructuring of the parameters of the electrical matching circuits are determined and the need for their automatic regulation during the operation of the ultrasonic technological apparatus is shown.

5. A method for automatic control of electrical matching was proposed and its practical implementation was developed, which made it possible to ensure the maximum efficiency of the operation of the ultrasonic technological apparatus with any changes in the parameters of media and oscillatory systems.

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