Ultrasonic Signal Generator with digital feedback

T Muksunov, I Kuzmenko, K Zavyalova
Tomsk State University, Tomsk, Russia
E-mail: zkv@mail.tsu.ru

Abstract. It is proposed generator of power ultrasonic signal with digital feedback and digital control of generating signal. Such approach will allow for the implementation of a rather complex control algorithm that is not feasible by circuit engineering means. A functional diagram of the layout of the control unit and generating a powerful ultrasonic signal has been developed. The digital microcontroller generates periodic pulses that trigger the generator at an appropriate frequency and controls the voltage at the output of the regulated power supply. The voltage level of the power source is set according to required power of the generated signal. The algorithm and software for the control of the signal generator with digital feedback has been developed.

1. Introduction
Generators of powerful ultrasonic signals are widely used in cutting, coagulation and processing of various materials. One of the broad applications of powerful ultrasonic vibrations is surgery [1–3]. To generate a powerful ultrasonic signal with an amplitude of hundreds of volts with a supply voltage less than 30 volts and a power up to 200 watts, is preferable to use the resonance effect. At resonance, there is an accumulation of energy in the oscillatory system and an increase in the amplitude of oscillations. As a result, the generator must adjust its frequency to the resonant frequency of the controlled system. The resonant frequency will depend on the mechanical properties of the ultrasonic instrument, the electrical properties of the piezoelectric element and the matching electrical components of the generator circuit. It is extremely difficult to take into account all these factors with sufficient accuracy in advance. Analytical solutions and numerical simulations can approximately estimate the spectrum of resonant frequencies, however, such estimates will not exactly match the characteristics of the real device. It is necessary to provide a feedback system and generator frequency control. It is proposed to carry out digital feedback and digital control of the generator, which will allow for the implementation of a rather complex control algorithm that cannot be implemented by circuit engineering tools.

The development was accompanied by numerical simulation of various variations of the circuit in the NI Multisim software package, which made it possible to select the parameters of the electrical components to maximize the amplitude of the output signal.

2. Development of the layout of the control unit and generating a powerful ultrasonic signal
There are already quite developed analog technologies for generating high-power ultrasonic signals [4–6]. Generators with an auto-tuning of the resonant frequency based on the inclusion of a piezoelectric transducer in the feedback circuit already exist. In this case, the voltage switches, usually on field-effect transistors, are controlled by an electrical signal from the oscillating system being excited. The system has the maximum response at its resonant frequency, and therefore the control
signal through the feedback acquires the resonance frequency. A similar scheme was assembled and studied. It was possible to observe the effects of cavitation in the water bath when connecting the piezoelectric element. However, this circuit does not have digital or analog external control, and we cannot control the transition to the optimal resonant frequency. As a rule, there are several resonances, and there is no guarantee that this system will adjust to the optimal frequency.

Next, a push-pull excitation circuit of the piezoelectric element on transistors IRF640, controlled by an IR2153 chip, specifying a sequence of command pulses, was assembled. The frequency was changed manually using a trimming resistor in the control circuit IR2153. Manual tuning of the frequency made it possible to investigate the operation of the generator at different frequencies. Further, by adjusting the resistor, an increase in the power consumption at the resonant frequencies was detected. It was found that it is advisable to replace the transistors with more powerful IRFZ44N, and, in addition, transistors need radiators. Also, experimental studies of the generator were carried out on the more powerful transistors IRFP4229. It is necessary to apply a shielding metal case into which the generator should be placed, and the signal lines from the controlling microcontroller should be shielded by using a coaxial cable to establish electromagnetic compatibility.

Also, it was found that due to the effect of unilateral saturation of the transformer, there is a loss of control over the operation of the piezoelectric element and the exit of the system from the operating mode. To eliminate the effects of this effect, it is necessary to complicate the control algorithm and digital feedback.

3. Development control unit and powerful ultrasonic signal generator

A functional diagram of the layout of the control unit and the generation of a powerful ultrasonic signal, shown in Figure 1 is proposed. The digital microcontroller generates periodic pulses that trigger the generator at an appropriate frequency and controls the voltage at the output of the regulated power supply. The voltage level of the power supply will determine the power of the generated signal. The signal from the generator is fed to the piezo elements of the ultrasonic instrument, which are electrically the combination of connected capacitors, coils and resistors. The values of the current and voltage at the instrument input are measured using analog-digital converters of the microcontroller via feedback lines. Based on the feedback signals, the microcontroller can estimate the amplitude of oscillations, and their spectral composition, and respond to changes in the resonant frequency by changing the output pulses and the supply voltage.

This design of the functional circuit was chosen for the reason of providing digital feedback in the presence of full digital control of the frequency and phase of the generated signals, which will allow the implementation of the most complex control algorithms.

A scheme was developed for a digitally controlled generator of high-power ultrasonic signals (Figure 2). The circuit provides inputs for microcontroller (control 1, control 2), and outputs for providing digital feedback. Control signals are applied to field-effect transistors, which generate a meander signal. In such a switching circuit, transistor overheating is minimized. Through the step-up transformer, the signal is fed to the high-voltage circuit to which the ultrasonic instrument is connected. For matching with the capacitive load inductance is included in the circuit.

As a block of the microcontroller in this layout it is proposed to use the STM32F407 microcontroller, which provides the ability to transmit and receive real-time signals. The microcontroller control algorithm with digital feedback would optimize operating frequency.

The field-effect transistor IRFZ44N was chosen as the main elements controlling powerful electrical signals, since its parameters meet the requirements for power, heat dissipation, performance, and are widely available for mass production of products from it.
Figure 1. Functional diagram of the layout of the control unit and generating a powerful ultrasonic signal.

For electrical isolation of the surgical instrument and the generator, a transformer with a transmission coefficient of 10 is used, which makes it possible to increase the voltage on the instrument relative to the power supply 10 times - this is enough to excite piezoelectric elements PZT8 and their operation with the minimum mass of the transformer.

Figure 2. Electrical circuit of a controlled generator of high-power ultrasonic signals.

This layout reproduces the electrical diagram of the original generator without taking into account the housing, controls and the system of radiator cooling. Applying NI Multisim we have estimated resonance amplitude increasing (Figure 3).
Figure 3. Simulated signal of generator on resonance frequency 40 kHz.

During the work on the model, the need was established to change the way the signal power was adjusted depending on the mode of operation. Figure 4 shows the modified and modified functional layout of the layout.

Figure 4. Modified functional layout scheme.

The microcontroller generates a rectangular signal of a given frequency. Since the outputs of the microcontroller do not provide sufficient current strength for the field-effect transistors to work optimally, it was decided to use a transistor control driver that provides the necessary gain of the control signal of the microcontroller.

For power control, it was originally proposed to use a pulse-controlled power supply. The advantage of this solution was the possibility of smooth adjustment of voltage within the specified limits. In the process, it was found that the exact setting of the output parameters is not necessary. At the same time, impulse control means the need to install additional integrating circuits, which leads to a significant deterioration in the weight and size characteristics, as well as a decrease in the overall efficiency of the installation.

In this regard, it was decided to abandon the pulse adjustment of the power source. In place of this, the power control is carried out by changing the transmission coefficient of the transformer in the matching circuit, by switching its secondary windings. This adjustment method does not produce nonlinear signal transformations, which eliminates the need to add additional integrating circuits to the system, and does not lead to a significant deterioration in the weight and size characteristics.

The feedback of the microcontroller and the power amplifier allows real-time analysis of the signal applied to the instrument, which allows for the dynamic adjustment of the control signal, if necessary, to ensure a given operating mode.
The power circuit of the installation is galvanically isolated from the controller both via the control channel and the feedback channel, which ensures the protection of the microcontroller from failure.

4. Conclusions
We proposed generator circuit of a powerful ultrasonic signal with digital feedback. It is proposed to adjust the power through switching the secondary winding of a transformer with a different number of turns. The control algorithm analyzes the current and voltage feedback signals to determine the optimal operating frequency. The generation of a powerful ultrasonic signal is carried out by switching large currents in the primary winding of a step-up transformer with powerful field-effect transistors. Thanks to the binary control of transistors, through the driver, which provides a large charge current of the gate, minimal overheating of the field-effect transistors is ensured. A sufficiently high voltage is formed on the secondary winding of the step-up transformer to excite ultrasonic vibrations in the piezoelectric elements based on PZT8. Measuring the current passing through the piezoelectric elements and the voltage on them allows you to receive a feedback signal indicating the presence of resonance. At resonance, the voltage and current increase many times.

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