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Increasing the efficiency of water well regeneration with ultrasound by using acoustic transducers consisting of elements in flexural vibration

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Abstract

In this article of principle construction of water wells and their regeneration methods are discussed. Commonly occurring reasons of water well obstruction are described and presented. The regeneration process of water wells using ultrasound is examined in detail along with the benefits of using this method. The regenerating process of ultrasound is possible because of cavitation effect. The process of cavitation is described and illustrated. Methods of generating ultrasound are presented. Implemented examples of actual regeneration systems are also described and presented along with their technical parameters. Possible improvements to increase the efficiency of these regeneration systems are given. This is achieved by using ultrasonic transducers in flexural vibration. The property of flexural vibrations to radiate energy at an angle, depending on the velocity of flexural wave in the operating element of the transducer can be used to significantly increase the effectiveness of the ultrasonic method for well regeneration. Diagrams for composite ultrasonic transducers with transformation of vibrations are given to illustrate the process of transforming longitudinal vibrations into flexural vibrations. The benefits of such transformation of vibrations are explained. Sources of information for various designs of composite acoustic transducers are also presented.

Keywords: water well regeneration; ultrasound; high energy ultrasound; ultrasonic transducers; ultrasonic transducer in flexural vibration; circular plate in flexural vibration; intense ultrasonic fields; flexural vibrations; elements in flexural vibrations; ultrasound radiation; ultrasound velocity, magnetostrictive transducer; piezoelectric transducer; ultrasonic cleaning; cavitation; design of transducers

Introduction

Water wells are made to provide drinking water, one of the most essential food products. Because the quality requirements for drinking water are very high, great care must be taken when drilling the well to ensure that the drinking water is not contaminated with surface water and other foreign materials. The throughput and longevity of the well depend directly on the quality of its installation. Most of the time water wells are made by inserting a filter tube (Fig. 1) consisting of a protective pipe and a filter [1].

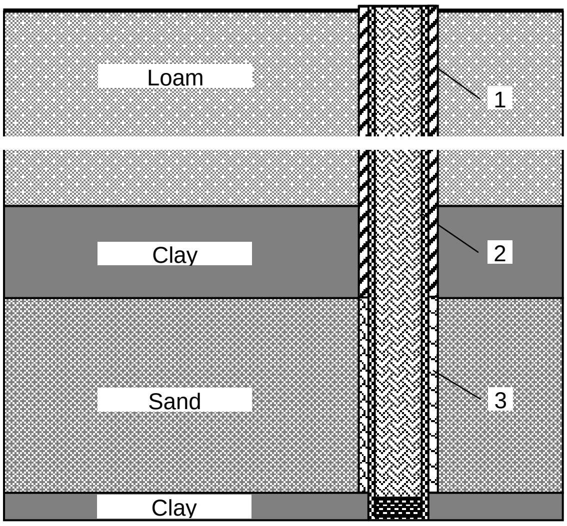


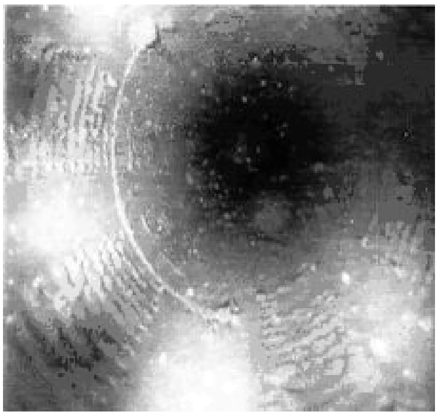
Fig.1. **Schematic diagram of a water well, where: 1 – protective pipe; 2 – filter; 3 – permeable filter gravel**

To reduce the filter resistance, the permeability of the filter must be similar to the permeability of the environment (sand), providing the drinking water. Filter tube must also suppress grainy particles, but have the largest possible permeable structure. As the well ages, the throughput of the filter is slowly decreasing. The main reasons for decreased filter throughput are sand obstruction, corrosion, calcification and the accumulation of deposits. Various examples of water well aging are presented in Fig 2 [1, 2].

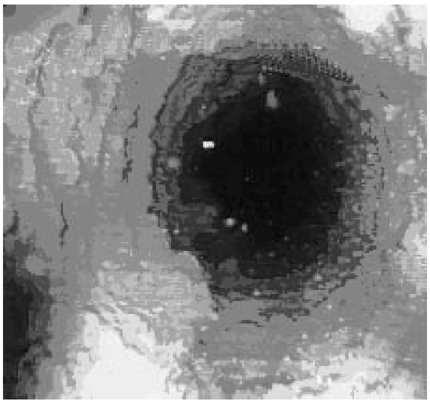
To increase the throughput of the aged filter, various methods of regeneration (cleaning) are used. At present, mostly mechanical and chemical regeneration methods are used. The shortcomings of these methods are the use of large quantity of water, using chemicals harmful to the environment and long periods when the water well is not operational.

One of the alternatives is the ultrasonic regeneration method [3-5]. When using the ultrasonic method, the walls of the filter and the protective pipe are initially cleaned using brushes. Then an ultrasonic transducer (or an array of transducers) is immersed into the well. The entire filter tube is gradually affected by ultrasound (each segment takes about 5 minutes).

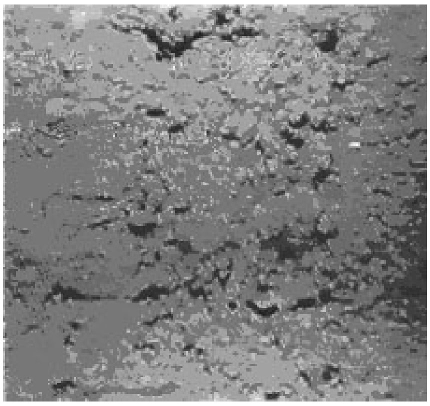
The cleaning effects of ultrasound [6-15] are achieved by the formation of cavities in the water through which the ultrasound propagates. The formation of cavities is a result of the rarefaction of the medium and consequently bubbles are formed (Fig. 3). Cavitation bubbles are created at sites of rarefaction as the water fractures or tears because of the negative pressure of the sound wave in the water. As the wave fronts pass, the cavitation bubbles oscillate under the



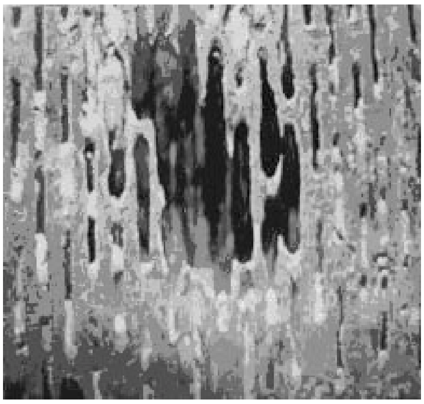
a. **Filter gaps are blocked with iron-manganese hydroxides (radial view)**



b. **Filter walls are covered with iron-manganese hydroxides. Filter gaps are completely blocked (radial view)**



c. **Filter walls are heavily overgrown with deposits. Filter gaps are completely blocked (axial view)**



d. **Filter has been damaged by corrosion (axial view)**

Fig.2. **The examples of water well aging**

influence of positive pressure, eventually growing to an unstable size. Finally, the violent collapse of the cavitation bubbles results in implosions, which cause shock waves to be radiated from the sites of the collapse. The collapse and implosion of cavitation bubbles throughout an ultrasonically activated liquid result in the effect commonly associated with ultrasonics. It has been calculated that temperatures in excess of 6000 °K and pressures in excess of 600 bar are generated at the implosion sites of cavitation bubbles.

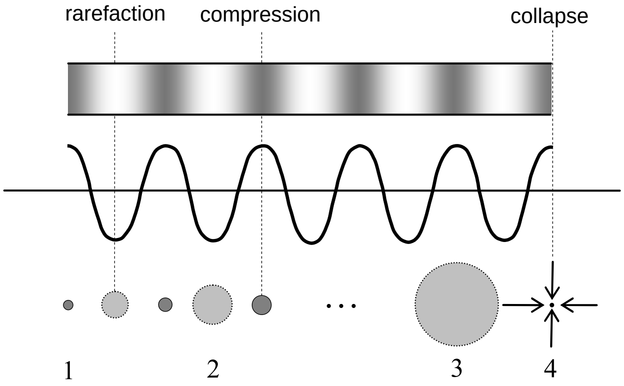


Fig.3. **Schematic diagram of the cavitation process, where: 1 – cavitation bubble forms; 2 – bubble expands; 3 – bubble reaches unstable size; 4 – bubble collapses**

When high-energy ultrasonic waves propagate through water, many collapse regions form and emit shockwaves. The dynamic of the cavitation bubble in the ultrasonic field has similarities with processes, which happen when cleaning dirt with a high-pressure water jet. The cleaning process in the ultrasonic field happens when small streams of water form due to cavitation cavern collapse. In such regions, those small water streams can oscillate from 50 m/s to 150 m/s. When these streams hit a solid object, they tear off all deposits attached to it.

Ultrasound can be generated by using a piezoelectric or magnetostrictive transducer. Both of these transducers are successfully used to regenerate water wells. Various sources [3-5] propose that by using the ultrasonic method, the throughput of water wells can be increased from 0 % to 200 %. There is also data that show the increase of cavitation effectiveness when the water pressure and the acoustic wave pressure increase. Because of this, increasing the effectiveness of acoustic transducers is relevant.

Practical implementation

The use of ultrasound for water well regeneration is a relatively new method [3-5, 16]. The high-energy ultrasonic regeneration method, compared to conventional methods (mechanical and chemical), is environmentally friendly, because the well is not being contaminated with any chemical or physical materials. In addition, the ultrasonic method does not negatively influence the structure of the well.

There is conflicting data on the efficiency of ultrasound. A goal of the research project in Germany, carried out by SONIC Umwelttechnik is to find the conditions under which the high-energy ultrasound is most effective for water well regeneration. For this purpose an experimental station was constructed to carry out laboratory examinations on the influence of different parameters (hydrostatic pressure, temperature, different types of filter gravel and filter tube materials, sonic frequency and intensity) on ultrasonic cleaning efficiency. The whole installation was made to be suitable for pressures up to 20 bar, similar to the conditions in real water wells. Results showed a clear difference of ultrasound penetration through different filter pipe materials, through different particle sizes of filter gravel, and through different hydrostatic pressures within the well.

A new system was developed for acoustic regeneration of wells (Fig. 4).

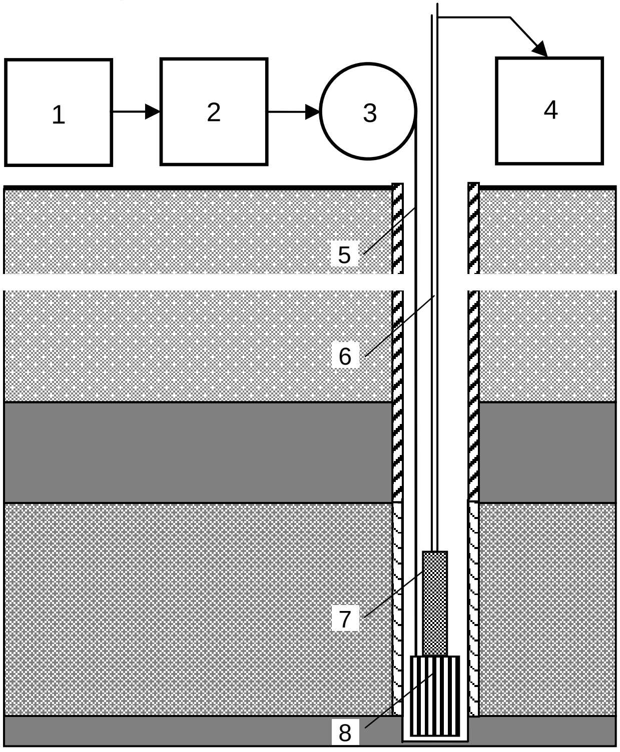


Fig.4. **Schematic diagram of the ultrasonic well regeneration system, where: 1 – power generator; 2 – switching cabinet; 3 – cable drum; 4 – dirty water container; 5 – cable; 6 – tubes; 7 – dirty water pump; 8 – submersible ultrasonic device**

Two designs were proposed for the submersible ultrasonic devices (Fig. 5). One with a surface-based power source and one with a power source, attached to the submersible device. The new power generators feature two channels for the ultrasonic signal formation. Therefore, it is possible to connect two magnetostrictive transducers, each with a power of 4 kW, to both sides of the emitter. The submersible device is designed with diameters of 42 mm and 108mm. Such construction makes it possible to use it in two different well regeneration system designs. One design uses one submersible device, attached to a pump-compressor pipe. The second design can use two submersible devices attached to a pump-compressor pipe. Each system can operate at high pressures and temperatures and has very good technical parameters (power, reliability, etc.).

Well regeneration with ultrasound requires several devices. An ultrasonic device, lowered down into the well, is the essential part of the ultrasonic regeneration system.

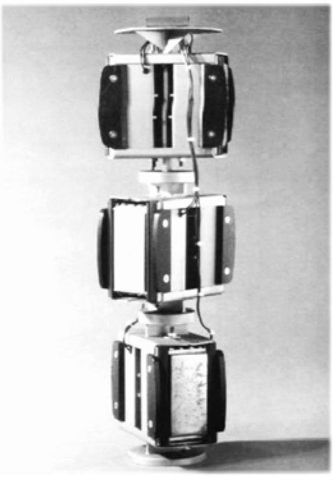


Fig.5. **Diagram of the ultrasonic submersible regeneration device B20/3 with three ultrasonic transducers (SONIC Umwelttechnik)**

Ultrasound generators, transforming the current from a power supply into a high frequency alternating current, are installed in a switching cabinet. The ultrasonic transducers are excited using this high frequency current. All other required control and monitoring devices are also installed in the same switching cabinet. A special power cable on a motor driven cable drum is required to transfer this high energy to the submersible ultrasonic probe. This probe consists of several ultrasonic transducers. These transducers emit ultrasonic waves radially outwards. The diameter of the submersible probe is 140 mm. The filter tube in the well therefore has to have a minimum diameter of 150 mm.

The submersible device is available in two versions: The standard unit B20/6 is equipped with six transducers. It can be used in wells with diameters ranging from 150 mm to 1000 mm. The smaller unit B20/3 is equipped with three transducers and can be used in wells with diameters ranging from 150 mm to 300 mm.

The technical parameters for the individual ultrasonic transducer, submersible device and the whole regeneration system are presented in Table 1, Table 2 and Table 3 respectively.

Table 1. **Technical parameters of the ultrasonic transducer**

Parameter name	Value
Operating frequency	20 kHz
Rated power	2000 W
Peak power	4000 W
Weight	18 kg
Sound radiating surface	85 x 185 mm
Sound energy (rated/peak energy)	12/25 W/cm²
Modulation	Double half wave
Transducer technology	magnetostrictive

Table 2. **Technical parameters of the submersible regeneration device**

Parameter name	B20/6	B20/3
Number of ultrasonic units	6	3
Total power	12 kW	6 kW
Weight	120 kg	60 kg
Length	160 cm	80 cm
Outer diameter	140 mm	140 mm
Usable for well diameters	150-1000 mm	150-300 mm
Maximal depth	250 m	100 m

Table 3. **Technical parameters of the complete regeneration system**

Parameter name	B20/60	B20/30
Total power	15 kW	8 kW
Mains voltage	230/400V/50 Hz	230/400V/50 kHz
Weight of switching cabinet	200 kg	100 kg
Cable weight	2 kg	1 kg
Weight of cable drum without cable	150 kg	150 kg
Outer dimensions of switching cabinet, WxHxD	800x1800x600	800x1800x600
Maximal depth	250 m	100 m

It needs to be mentioned that a transducer produced by Hielscher presented in Fig. 6 can replace the array of the transducers presented in Fig. 5.

Fig.6. **Diagram of the UIP4000 ultrasonic transducer in longitudinal vibration with a special operating element, produced by Hielscher Ultrasonics GmbH.**

The use of ultrasonic transducers in flexural vibration for well regeneration

Acoustic transducers presented in Fig. 5 generate longitudinal vibrations [3-5]. The amplitude of vibrations, generated by these transducers, is restricted by the highest possible tensions in the oscillating elements [17-21]. Mechanical stress in the oscillating elements depend on the type of vibrations [22-26]. When the transducer produces longitudinal vibrations of a given amplitude, higher stress by around a factor of 10 are present, compared to a transducer which produces flexural vibrations [24]. Because of this, about ten times larger amplitudes can be generated using transducers in flexural vibration than with transducers in longitudinal vibration.

The velocity of harmonic flexural waves in the elastic plate is calculated using expression:

$$v_{pl} = \sqrt[4]{\frac{Eh^2}{12\rho\left(1-\sigma^2\right)}}\sqrt{\omega}\,, \tag{1}$$

where v_{pl} is the velocity of harmonic flexural waves in the elastic plate; E is the Young's modulus of the elastic plate; h is the thickness of the elastic plate; ρ is the density of the elastic plate; σ is the Poisson's ratio of the elastic plate; ω is the cyclic frequency.

The velocity v_{pl} of harmonic flexural waves in elastic plates is significantly lower than the velocity v_l of harmonic longitudinal waves in elastic plates [23,24,28-31]. The velocity ratio of flexural waves and longitudinal waves in the elastic plate changes, depending on the ratio of the thickness h of the elastic plate and the wavelength λ_l of the longitudinal acoustic wave in the elastic plate [32]. This dependence is presented in Table 4.

Table 4. **The dependence of ratio v_{pl} / v_l on the ratio h / λ_l**

h / λ_l	0.0001	0.001	0.01	0.1
v_{pl} / v_l	0.0135	0.0426	0.135	0.426

The figures from Table 4 indicate that as the thickness of the elastic plate decreases, the ratio v_{pl} / v_l is also decreasing.

The radiation of the acoustic transducer depends not only on the type of vibrations, but also on the shape of vibrations on its surface [22,24,32-42]. The most effective radiation of energy happens, when nodal lines of vibrations on the surface of the rectangular transducer in flexural vibration are parallel to one another [39,42-50,]. In case when the radiating surface of the transducer is circular, most effective radiation of energy happens, when nodal lines of vibrations on the transducer's surface are distributed in concentric circles [51-53]. If the nodal lines of flexural vibrations are distributed parallel to one another on the transducer's surface, the angle θ, between the direction of radiation of the transducer and its surface is [24]:

$$\Theta = \pm\arcsin\frac{\lambda_W}{\lambda_T}\,, \tag{2}$$

where θ is the an angle between a flat transducer's surface and direction of radiation; λ_W is the length of acoustic wave in water; λ_T is the length of acoustic wave on the surface of the transducer.

The sign ± in Eq.2 indicates that in the transducer with a finite surface, standing waves are generated and the radiation of energy happens in two directions.

The array of transducers presented in Fig. 5 can be enhanced by attaching a concentrator of ultrasonic vibrations to the surface of the transducer [46] (Fig. 7). Circular elastic plate must be attached to the end of the concentrator.

In such design of the transducer, transformation of vibrations from longitudinal to flexural is implemented. The transducer '1', shown in Fig. 7, is operating as an oscillating piston. In the elastic plate '3', shown in Fig. 7, flexural vibrations are generated. This way the transformation of vibrations is implemented in such transducer and the amplitude of vibrations, radiated from its surface is increased.

Because the elastic plate '3', shown in Fig. 7, radiates energy at an angle θ, the efficiency of removing deposits in the water well is greatly increased. To increase the effectiveness of well regeneration, the diameter of this elastic plate must be as close as possible to the diameter of the filter tube in a water well.

In this case, a single transducer, presented in Fig. 7, can replace the transducer array, presented in Fig. 5. The

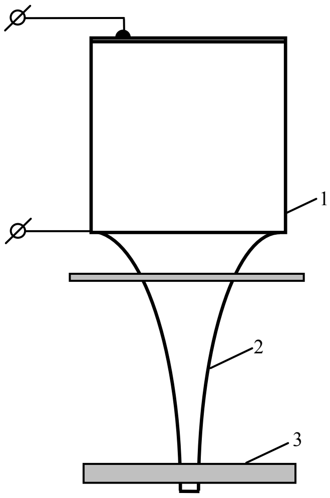


Fig.7. **Cross section of composite transducer with transformation of vibrations: 1 – rectangular or circular piezoelectric or magnetostrictive transducer; 2 – concentrator of acoustic waves; 3 – rectangular or circular elastic plate**

axis of the concentrator of acoustic waves should be aligned with the axis of the water well.

In place of the elastic plate '3' shown in Fig. 7 elastic elements of other shapes can be used. Such elements are presented in Fig. 8, 9 and 10.

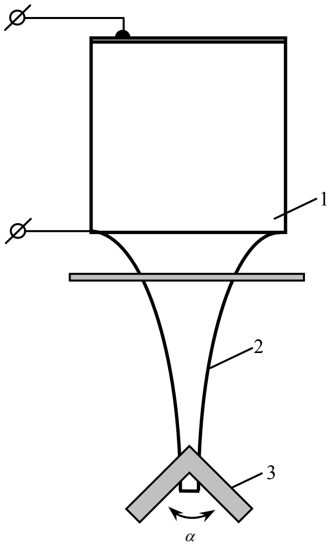


Fig.8. **Cross section of composite transducer with transformation of vibrations: 1 – circular piezoelectric or magnetostrictive transducer; 2 – concentrator of acoustic waves; 3 – elastic plate**

There are many available sources [54-63] for the design of composite acoustic transducers. The main principle when designing ultrasonic sensors is the matching of resonance frequencies of the different compositional parts of the transducer.

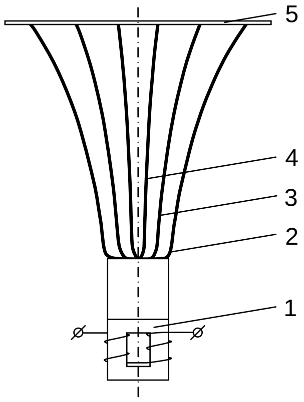


Fig.9. **Composite transducer with transformation of vibrations: 1 – magnetostrictive transducer; 2, 3, 4 – concentrator of acoustic waves; 5 – circular elastic plate**

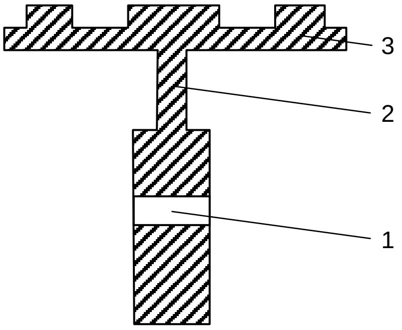


Fig.10. **Schematic diagram of composite transducer with transformation of vibrations: 1 – magnetostrictive transducer; 2 – concentrator of acoustic waves; 3 – circular radiating element**

Conclusions

Using ultrasound for water well regeneration does not cause any environmental damage, because it does not require any use of chemicals. During the regeneration process, neither harmful substances nor harmful radiation is produced. The proper disposal of chemically affected water is no longer necessary.

Well regeneration by using ultrasonic methods is highly efficient and works in many different conditions. Segments of the filter tube need to be affected by ultrasound very briefly, therefore it is highly economical. Ultrasound exposure does not negatively affect the structure of the well. No special permits are required to use ultrasonic methods for well regeneration.

Frequent well regeneration helps maintain the high throughput of the well for longer. The more frequently the well is regenerated the more useful lifespan it will have. Regular regeneration of the well slows down its aging process.

Any method of well regeneration should be applied not when the throughput of the well is completely marginal, but when it just begins to decrease. The chosen regeneration method should be effective, not damaging to the structure of the well, inexpensive and environmentally friendly. Ultrasonic well regeneration method meets these requirements.

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Vandens gręžinių valymo ultragarsu efektyvumo didinimas naudojant akustinius keitiklius su lanksčiai virpančiu darbiniu paviršiumi

Reziumė

Apžvelgiamas akustinių keitiklių panaudojimas vandens gręžinių filtrams atnaujinti ir aptariamos šiuolaikinės akustinių keitiklių konstrukcijos. Pažymima, kad efektyviam tokių keitiklių darbui pasiekti reikia suderinti akustiškai aktyvių paketų virpesius su tamprių darbinių elementų, prie kurių šie paketai pritvirtinti, virpesiais. Apskaičiuojant keitiklių kryptines charakteristikas, svarbu įvertinti jų virpesių formų išraiškas. Siūloma keitiklių darbinius paviršius žadinti lankstymosi virpesiais. Apskaičiuojant lankstymosi virpesių darbinių elementų spinduliavimo charakteristikas, galima laikyti jų virpesių pasiskirstymą ant darbinio paviršiaus harmoniniu. Pabrėžiama, jog keitiklių darbinių elementų, sužadintų lankstymosi virpesiais, spinduliavimo kampas priklauso nuo akustinių bangų ilgio santykio darbinio elemento paviršiuje ir darbo aplinkoje. Pateikiama konkrečių siūlymų dėl akustinių keitiklių konstrukcijų. Juos įgyvendinus padidėtų tokių keitiklių darbo efektyvumas.

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