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RATIONAL SHAPE OF THE TANK OF A SMALL-SIZED ULTRASONIC SYSTEM FOR THE INTENSIFICATION OF EXTRACTION PROCESS

Functional food products allow a person to maintain his/her health, as well as fully meet the physiological needs for energy and nutrients that the body uses to build cells, organs and tissues. Extraction is one of the most common methods used in the process of obtaining biologically active substances from plant or animal raw materials. Extraction efficiency can be increased by using intensifying methods used in the extraction process, such as ultrasound.

The paper considers the design and features of mathematical description of ultrasonic systems for the intensification of the extraction process, the principle of operation of which is based on the use of piezoelectric ultrasonic radiators. A computer model of an ultrasonic system to intensify the extraction process with a tank of different shapes has been built using the COMSOL Multiphysics software package, taking into account the full set of geometric, physical, mechanical and electrical parameters. As a result, the frequency is determined at which the maximum amplitudes of oscillations of ultrasonic systems with a tank in the form of a horn are provided for intensifying the extraction process, which leads to the implementation of the most efficient resonant mode of operation of the system. The locations of the maximum acoustic pressure on the object of extraction in an ultrasonic system to intensify the extraction process in the manufacture of concentrated drinks for functional purposes are determined.

Further research by the authors can be directed to the experimental studies of the horn-shaped ultrasonic system, as well as determining the most efficient tank geometry of the ultrasonic horn-shaped tank system using the COMSOL Multiphysics application package.

Keywords: *piezoelectric element, ultrasonic system, extraction process, acoustic pressure, modelling.*

Introduction. Today, functional food products, especially health-improving and preventive ones, with a high content of vitamins, trace elements, macronutrients, essential amino acids, and biologically active substances (BAS), are becoming more popular. Such products allow a person to maintain his/her health, as well as fully meet the physiological needs for energy and nutrients that the body uses to build cells, organs and tissues. Therefore, it is the food industry that is currently an important component of healthcare and occupies a special place in the field of intellectual and industrial human activity [1, 2]. According to the Law of Ukraine "On the quality and safety of food products and food raw materials", a functional food product is a food product that contains medicinal components and/or can be used to prevent or mitigate the course of human disease [3].

Extraction is one of the most common methods used in the process of obtaining biologically active substances from plant or animal raw materials. Extraction efficiency can be increased by using intensifying methods used in the extraction process, such as ultrasound.

One of the promising physical methods of influencing substances in order to intensify biotechnological processes is a method based on the use of acoustic vibrations of ultrasonic range [4].

All ultrasonic technologies are based on the effects of the interaction of ultrasound with the medium. Powerful ultrasound causes several specific effects in liquid media – cavitation, intense micro- and macro-flows, leading to rapid and high-quality mixing of medium components, the formation of stable emulsions, extraction of soluble components from particles that are in the liquid, the swelling and destruction of these particles [5]. Piezoelectric transducers are applied in the design and development of highly efficient ultrasonic systems for the intensification of biotechnological processes, which are widely used

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in various fields of science and technology, in particular medicine. Piezoelectric transducers are widely used as sources of ultrasonic vibrations. The change of the characteristics of piezoelectric components can have technological and dimensional limitations, especially for mobile small-sized ultrasonic equipment. Modelling of their characteristics can drastically reduce the number of experiments that are necessarily performed during the development of new devices. Moreover, with the help of a mathematical model, it is possible to make a rational choice of production technology that is to choose from a number of technologies the least expensive one.

Problem statement. Extraction is one of the most common methods used in the process of obtaining biologically active substances from plant or animal raw materials. All extraction processes are limited by diffusion at the interface of the phases through the diffusion layer with the gradient of the concentrations of the extracted substance. The use of mixing devices does not significantly improve an interphase mass transfer.

Despite the rapid development of the production of synthetic food flavours, flavour additives, and nutraceuticals, a lot of biologically active substances are still obtained from natural plant or animal raw materials.

Extraction of biologically active substances is the most time-consuming stage of raw material processing. Traditional extraction methods often take hours, days, or even weeks. The use of ultrasound can significantly expedite the extraction process, increase the yield and reduce the cost of the extracted substance, improve working conditions and increase its productivity.

The possibilities of significantly increasing the efficiency of extraction technologies and devices through ultrasound are far from being depleted. This reduces the need for chemical additives, and new principles of radiator design decrease the credibility of the inactivation of biologically active substances.

Traditional extraction methods are very long and time-consuming. One of the promising methods is the use of ultrasonic extraction. It is necessary to find an individual approach to the choice of optimal modes of ultrasonic processing to achieve the maximum yield of valuable components in the liquid phase while maintaining their structure [5].

The use of ultrasound has significant advantages over traditional raw material processing technologies. In particular, it provides deeper penetration of the solvent into the material with a cellular structure, reduces the processing time, provides a higher product yield and reproducibility, reduces solvent consumption, increases the speed of the process, and allows the extraction of thermolabile substances. The equipment does not require large maintenance costs, less energy is consumed for processing; as a result, the process becomes more environmentally friendly and economically justified.

Currently, ultrasonic equipment is underused due to the high cost, narrow specialization and low efficiency of previously developed large-sized industrial plants, the lack of small-sized high-efficiency ultrasonic devices for modern small and medium-sized industries, military units, and individual applications.

The development of ultrasonic technology is also hindered by the low awareness of consumers about the effectiveness of ultrasonic impacts and the lack of methodological recommendations that take into account the peculiarities of the use of ultrasonic technologies in small production.

Intensification of extraction by ultrasonic exposure can be achieved due to the following factors: acceleration of diffusion of interacting substances on the verge of separation of phases and liquid transfer inside the extracted material; violation of colloidal structures in the adjacent layer and reduction of viscosity in the volume of the medium. In this case, during the extraction process in a cavitating liquid, it is possible to increase the efficiency of the process.

Under the influence of ultrasonic vibrations, faster and more active destruction of intracellular tissues of plant raw materials occurs, which leads to an intensification of the extraction process and allows to increase the content of biologically active compounds in the solution. An increase in the coefficient of internal molecular diffusion under other equal conditions can be achieved by reducing the size of the extracted material.

Modern ultrasonic technologies are based on the use of two properties that certain materials have: piezoelectricity and magnetostriction. The works [6-8] consider the design of ultrasonic systems for the intensification of biotechnological processes, containing a piezoelectric ultrasonic generator, based on the generation of electrical oscillations of a certain frequency, which a mate-

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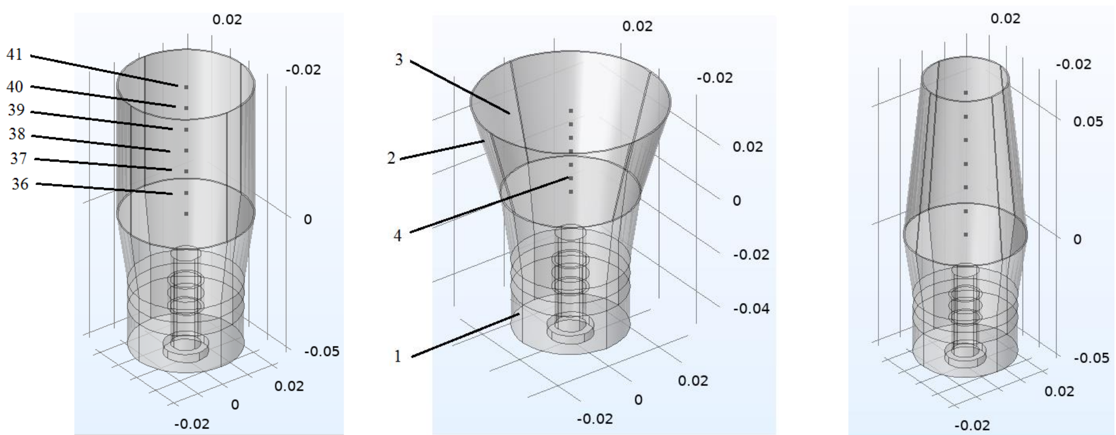
rial with piezoelectric properties (transducer) transforms into mechanical oscillations. The papers [9-11] present the features of modelling ultrasonic systems for the intensification of cavitation processes, the principle of operation of which is based on the use of piezoelectric ultrasonic radiators. However, the considered works are not united by any systematic approach, they have the character of disparate episodes, on the basis of which it can be argued that at present there is a need to create a holistic technique for modelling of piezoelectric transducers, which could be used as a theoretical basis for calculating the characteristics and parameters of systems based on their basis. Thus, the relevance of the development of physically meaningful models of systems with piezoelectric transformations remains at the present time.

The ***aim*** of the work is to determine the rational shape of the tank of an ultrasonic system for the intensification of the extraction process.

To determine the rational shape of the tank of the ultrasonic system, it is necessary to perform the following tasks: create virtual models with different shapes of tanks similar to physical models and determine the acoustic pressure in the liquid.

Materials and methods. The COMSOL Multiphysics software has been used to create a virtual model and study the acoustic pressure during the operation of an ultrasonic system to intensify the extraction process [12].

Figure 1 shows the variants of the investigated axonometric models of an ultrasonic system for intensifying the extraction process in the manufacture of functional concentrated drinks with various tank options.



a) *b*) *c*)

Figure 1. General view of axonometric models of ultrasonic systems for intensifying the extraction process with different shapes of tanks: *a*) of a cylindrical shape: 1 – ultrasonic radiator; 2 – tank, 3 – liquid, 4 – points where acoustic pressure is recorded (36-41 numbering of points corresponds to the numbering of the COMSOL Multiphysics model and is the same for all structures); *b*) in the form of a horn; *c*) in the form of a tapering horn

Details of a mathematical model that takes into account multiphysics processes described by a combination of various partial differential equations and some of the highlights of calculations using the Piezoelectric Effects module and the COMSOL Solid Mechanics and Electrostatics tools are detailed in [13, 14]. The analysis of the operation of the ultrasonic system for the intensification of the extraction process has been carried out in the Frequency response mode. The Pressure Acoustics, Frequency Domain module is used to determine the acoustic pressure. Acoustic-Structure Boundary is used to combine the above modules.

Direct is used as a resolver, in which the SPOOLES numerical method is chosen for solving systems of linear equations with sparse matrices [15].

The dimensions of the tank shapes are chosen in such a way that the volume remains constant. For our case, it is $7{,}116 \cdot 10^{-5}\ \text{m}^3$.

Tank dimensions: for the model with a tank in the form of a cylinder, the diameter is 45 mm, the height is 49 mm, the wall thickness is 1 mm; the horn-shaped tank model has a bottom diameter of 45 mm, a top diameter of 64 mm, a height of 33.2 mm, and a wall thickness of 1 mm; the tapering horn tank model has a diameter

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of 45 mm, a top diameter of 32 mm, a height of 65.9 mm, and a wall thickness of 1 mm.

The dimensions of the ultrasonic transducer are the same for all models: waveguide diameter maximum is 55 mm, waveguide diameter minimum is 45 mm, waveguide length is 24 mm, reflector thickness is 12 mm, piezoelectric elements diameter is 45 mm, total length is 46 mm. The tank and the ultrasonic radiator are connected using epoxy glue. As a material for modelling a piezoelectric transducer, a brand of piezoceramics PZT-4 is used. The grade of the material of the waveguide and reflector of the ultrasonic radiator, as well as the tank corresponds to AISI 4340 steel. Water is used as a liquid.

When modelling an ultrasonic system to intensify the extraction process, the type of boundary conditions Fixed to the upper end of the tank is adopted. Electric potential 300 V is applied to the outer sides of piezoelectric elements, and the common "minus" (Ground) – to the sides of piezoelectric elements connected to each other. The polarization of piezoelectric parts is opposite.

The principle of operation of the ultrasonic system is as follows. When an alternating electrical voltage is applied to piezoelectric elements, mechanical vibrations occur, which are transmitted to the liquid tank, resulting in acoustic pressure in the liquid.

Numerical experiments and research results. An important step in obtaining reliable results of numerical simulation is the construction of a finite element model of the ultrasonic system design by introducing a mesh (Mesh), on which the results of calculations significantly depend. The computational mesh of finite elements is chosen with such conditions. We have used Lagrangian finite elements with elementary basis functions of the second order – Lagrange-Quadratic. The number of Lagrangian elements is 6 per local wavelength, which propagates in the structure and in water. The mesh is built by a tetragonal partition, a variant of one of which is shown in Figure 2.

The main resonance of the ultrasonic radiator used is designed for a frequency of 40 kHz. Since the strength of the acoustic impact directly depends on the choice of the operating (resonant) frequency of the ultrasonic emitter, the determination of the maximum acoustic pressure is carried out at frequencies in the range from 37 kHz to 47 kHz, which is carried out using the Acoustic-Structure Boundary multiphysical connection, we determine the acoustic pressure in the control points according to Figure 1.

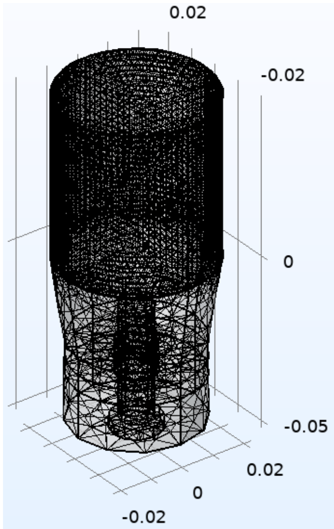

Figure 2. Finite element model of an ultrasonic system for intensifying the extraction process with a tank in the form of a cylinder

The results of simulation of the ultrasonic system for the model with a tank in the form of a cylinder are shown in Figure 3.

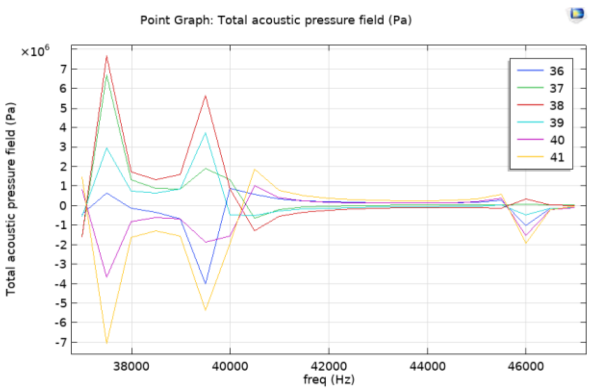

Figure 3. Frequency response of acoustic pressure in a tank in the form of a cylinder with liquid in an ultrasonic system

The results of simulation of the ultrasonic system for the model with a tank in the form of a horn and tapering horn are shown in Figures 4, 5.

Figures 3-5 show that the maximum sound pressure corresponds to frequencies of 37.5 kHz, 38 kHz, 39.5 kHz, 41 kHz and 45 kHz. It should be noted that values of acoustic pressure above zero correspond to the upward direction of the vector, and below zero – to the downward vector direction of the ultrasonic radiator.

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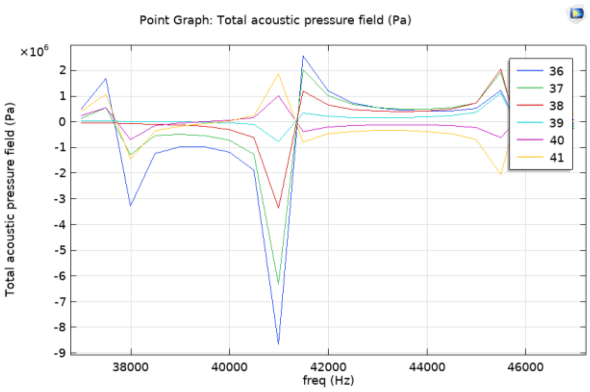


Figure 4. Frequency response of acoustic pressure in a tank in the form of a horn with liquid in an ultrasonic system

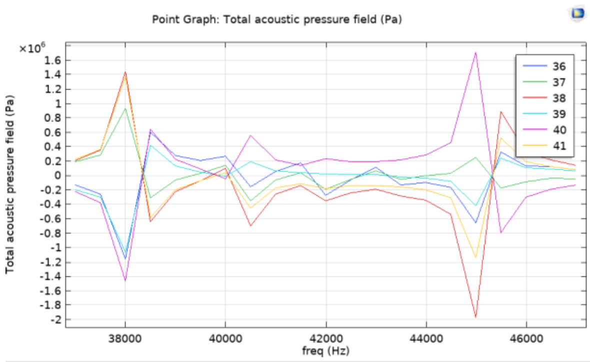
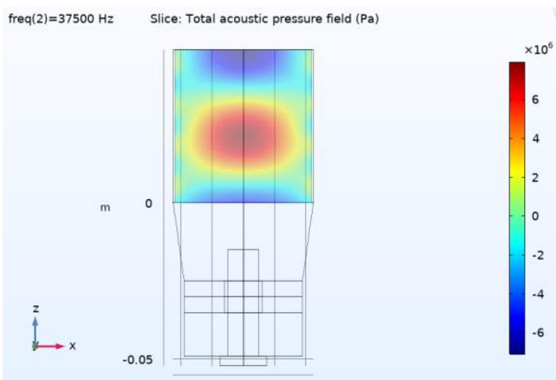
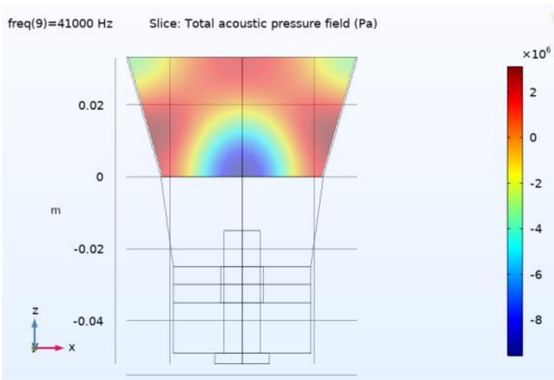


Figure 5. Frequency response of acoustic pressure in a tank in the form of a tapering horn with liquid in an ultrasonic system

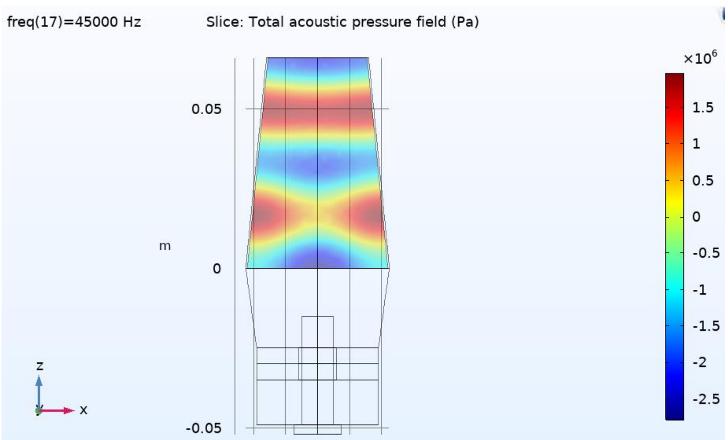
In addition to graphical results in the calculation process, a visualization of the propagation of acoustic pressure is also obtained, which is shown in Figure 6. These results are presented as a longitudinal section about the centre and correspond to the highest acoustic pressure.



a)



b)



c)

Figure 6. Results of numerical simulation to determine the acoustic pressure in ultrasonic systems with different shapes of the tank with liquid at frequencies:
a) 37.5 kHz; *b*) 41 kHz; *c*) 45 kHz

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From Figure 6 (on the scale on the right side) it can be seen that the highest acoustic pressure reaches $8.6 \cdot 10^6$ Pa at a resonance frequency of 41 kHz for the construction of an ultrasonic system with a tank in the form of a horn.

Discussion of results. It can be seen from the graphs that the maximum acoustic pressure: for an ultrasonic system with a tank in the form of a cylinder is observed at a frequency of 37.5 kHz and 39.5 kHz at points 38 and 41 and is $7.6 \cdot 10^6$ Pa and $5.6 \cdot 10^6$ Pa, respectively; for an ultrasonic system with a tank in the form of a horn is observed at a frequency of 41 kHz at point 36 and is $8.63 \cdot 10^6$ Pa; for an ultrasonic system with a tank in the form of a tapering horn is observed at frequency of 38 kHz and 45 kHz at point 38 and is $1.44 \cdot 10^6$ Pa and $1.96 \cdot 10^6$ Pa, respectively. This means that the intensification of the extraction process will be faster in an ultrasonic system with a tank in the form of a horn.

To test ultrasonic system for extraction, an experimental sample is developed (Figure 7). Cylindrical tank dimensions: diameter is 45 mm, height is 49 mm, wall thickness is 1 mm.

Figure 7. Experimental sample of ultrasonic system for extraction

The essence of the experiment is as follows. The tank is filled with liquid (water), and the object of extraction (propolis with a volume of 1 cm^3) is also placed there at a distance of 1 cm from the bottom. Then, a signal from a high-voltage generator with a frequency of 38.5 kHz and an amplitude of 300 V is applied to piezoceramic elements of the ultrasonic system. As a result, mechanical vibrations have arisen, which are transmitted to the tank with liquid, as a result of which the propolis extraction process takes place. The test results of the experimental sample have confirmed the operability of the developed design.

Conclusions. The design of tanks of ultrasonic systems, the principle of operation of which are based on the use of piezoelectric ultrasonic radiators, for increasing acoustic pressure to intensify the extraction process is considered.

The scientific novelty of the work lies in the improvement of the computer model of the ultrasonic system for intensifying the extraction process using the COMSOL Multiphysics software package, taking into account the full set of geometric, physical, mechanical and electrical parameters.

The practical value of the work is as follows:

– the rational shape of the tank of the ultrasonic system and the frequency at which the maximum acoustic pressure of ultrasonic systems is provided for the intensification of the extraction process have been determined, which leads to the implementation of the most efficient resonant mode of operation of the system;

– places of concentration of maximum acoustic pressure on the extraction object in the ultrasonic system to intensify the extraction process have been defined;

– the obtained data can be used in the design of devices based on ultrasonic radiating systems to intensify the extraction process in the production of functional concentrated beverages.

Further research by the authors may be aimed at experimental studies of the horn-shaped ultrasonic system, as well as determining the most efficient tank geometry of the ultrasonic horn-shaped tank system using the COMSOL Multiphysics application package.

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РАЦІОНАЛЬНА ФОРМА РЕЗЕРВУАРУ МАЛОГАБАРИТНОЇ УЛЬТРАЗВУКОВОЇ СИСТЕМИ ДЛЯ ІНТЕНСИФІКАЦІЇ ПРОЦЕСУ ЕКСТРАКЦІЇ

Сьогодні популярнішими стають харчові продукти функціонального призначення, зокрема оздоровчого та профілактичного, з підвищеним вмістом вітамінів, мікроелементів, макроелементів, незамінних амінокислот та біологічно активних речовин. Такі продукти дають людині змогу зберігати своє здоров'я, а також повністю задовольнити фізіологічні потреби в енергії та харчових сполуках, якими користується організм для побудови клітин, органів і тканин.

Екстракція – один з найбільш поширених методів, використовуваних у процесі отримання біологічно активних речовин з рослинної або тваринної сировини. Ефективність екстракції може бути збільшена, використовуючи інтенсифікуючі методи впливу, що застосовуються в процесі екстракції, наприклад ультразвук.

В роботі розглянуто конструкцію резервуарів ультразвукових систем для збільшення акустичного тиску при інтенсифікації процесу екстракції, принцип дії яких базується на використанні п'єзоелектричних ультразвукових випромінювачів.

Наукова новизна роботи полягає в удосконаленні комп'ютерної моделі ультразвукової системи для інтенсифікації процесу екстракції за допомогою пакета програм COMSOL Multiphysics, враховуючи повний набір геометричних, фізико-механічних та електричних параметрів. Практична цінність роботи полягає у визначенні раціональної форми резервуару ультразвукової системи та частоти, при якій забезпечуються максимальний акустичний тиск ультразвукової системи для інтенсифікації процесу екстракції, що приводить до реалізації найбільш ефективного резонансного режиму роботи системи. Отримані дані можуть бути використані при проектуванні пристроїв на основі ультразвукових випромінюючих систем для інтенсифікації процесу екстракції при виготовленні концентрованих напоїв функціонального призначення. Подальші дослідження авторів можуть бути спрямовані на експериментальні дослідження ультразвукової системи у формі рупора.

Ключові слова: *п'єзоелемент, ультразвукова система, процес екстракції, акустичний тиск, моделювання.*

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