Design of a Downhole Acoustic Emitter for Impact on the Productive Formation and Enhanced Oil Recovery

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Abstract. In this paper deals with the issues of designing a downhole acoustic emitter designed to influence the productive formation in order to intensify oil production. The paper analyses acoustic technologies used in the oil industry, focusing on their impact on physical and chemical processes in the reservoir, such as reducing oil viscosity, improving rock permeability and increasing hydrocarbon production. A new method of impact using acoustic waves generated by a modernized emitter based on the jet-driven Helmholtz oscillator is developed. The experimental study of pressure oscillation generation on the emitter model is presented, and the economic efficiency and prospects of application of this technology in conditions of various geological formations are estimated. The work is of practical importance for optimization of methods of oil production intensification and development of new technologies to increase the degree of hydrocarbon recovery from the fields.

Keywords: Acoustic emitter · Jet-driven Helmholtz oscillator · Amplitude of pressure fluctuations · Enhanced oil recovery · Acoustic technologies · Oil viscosity · Rock permeability · Economic efficiency

1 Introduction

In recent decades, the oil industry has faced two major challenges: the depletion of conventional oil fields and the difficulty of extracting hydrocarbons from hard-to-reach reservoirs [1]. These challenges have made researching new technologies to improve oil production efficiency increasingly important. The main goals are to maximize hydrocarbon recovery from existing fields and minimize the environmental impact of production [2].

To improve extraction, the industry employs various stimulation techniques that enhance rock permeability, fluid dynamics, and hydrocarbon recovery. Hydraulic fracturing creates artificial fractures in formations by injecting high-pressure fluids, boosting permeability and oil flow but incurring high energy costs and potential environmental risks [3]. Gas lift involves injecting gas into wells to reduce oil density and is used in

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highly viscous reservoirs, though it can be costly [4]. Water injection is a conventional method of secondary recovery but is dependent on reservoir characteristics. However, the efficacy of this technique is contingent on reservoir characteristics and the manifestation of Saffman-Taylor instability [5, 6]. Thermal methods, such as steam or electric heating, are effective for viscous oils but can be expensive and limited by geological conditions. Chemical methods use substances like surfactants and polymers to modify oil properties but require careful management to avoid environmental harm [7, 8].

Acoustic stimulation is a promising technology that enhances rock permeability, boosts oil recovery, and improves filtration properties by creating microcracks, reducing oil viscosity, and modifying the pore structure [9–14]. Compared to traditional methods, it is less capital-intensive and has a more favorable environmental impact. However, it has not yet been widely adopted due to limited theoretical understanding, insufficient research on its effects in different geological conditions, and challenges in designing effective acoustic emitters.

Despite the advancements in acoustic impact technology, it has not been widely adopted in the oil industry. This is mainly due to limited theoretical foundations, insufficient research on the effects of acoustic waves in various geological conditions, and difficulties in designing effective acoustic emitters for wells. The goal of this study is to develop a downhole emitter that implements acoustic impact technology in the productive layers of oil fields to improve oil production. This research is crucial as it offers an innovative solution to a key challenge in the oil industry: boosting hydrocarbon recovery from existing fields.

2 Acoustic Exposure Parameter Requirements

The effectiveness of acoustic technologies relies on the careful selection of parameters such as frequency, amplitude, and impact duration, as well as the characteristics of the acoustic wave generator. These factors must be precisely calibrated to create optimal conditions for impacting the physical and chemical properties of both oil and rock. As shown in Fig. 1, one version of this technology uses a downhole emitter placed within the well at the productive formation level. The operating emitter generates pressure fluctuations that propagate through the formation, creating a wave field. The following discussion will outline the essential parameters for acoustic stimulation, which are critical for the efficient operation of the downhole emitter and achieving a significant increase in oil production.

2.1 Mechanisms of Acoustic Impact on Productive Formations

It is evident that acoustic waves, generated in productive formations, exert a certain impact on the physical and chemical properties of oil and rocks, thereby contributing to the intensification of hydrocarbon production processes. The effectiveness of acoustic impact is determined by numerous factors, including frequency, amplitude, and duration of impact, as well as the mechanisms of interaction of acoustic waves with rocks and fluids in the reservoir. The following literature review summarizes the main mechanisms through which acoustic stimulation affects reservoirs and oil production processes.

1) *Influence of acoustic waves on oil viscosity.* The efficiency of oil production is contingent on a number of factors, with oil viscosity being a primary consideration. The mobility of oil in the reservoir is influenced by its viscosity, with higher viscosities impeding the process of oil recovery, while lower viscosities facilitate oil displacement. Acoustic waves have been demonstrated to reduce oil viscosity by mechanical action on hydrocarbon molecules. This action results in the ordering of the oil molecules, leading to a reduction in the cohesive force between them and, consequently, a decrease in viscosity [15]. The viscosity of oil can also be subject to alteration in the presence of asphaltenes and resinous substances, with acoustic waves exerting a significant impact on such compounds [16]. The breakdown or redistribution of these compounds, consequent to acoustic wave action, results in a reduction in viscosity. The effectiveness of this process is contingent on the cavitation process, which typically occurs within the ultrasonic frequency range. Experimental studies demonstrate that the optimal frequency and amplitude of acoustic influence can significantly reduce the viscosity of oil, particularly in the presence of highly viscous hydrocarbons such as fuel oil. However, it has been observed that post-exposure, oil viscosity tends to increase and ultimately surpasses its initial level [17].

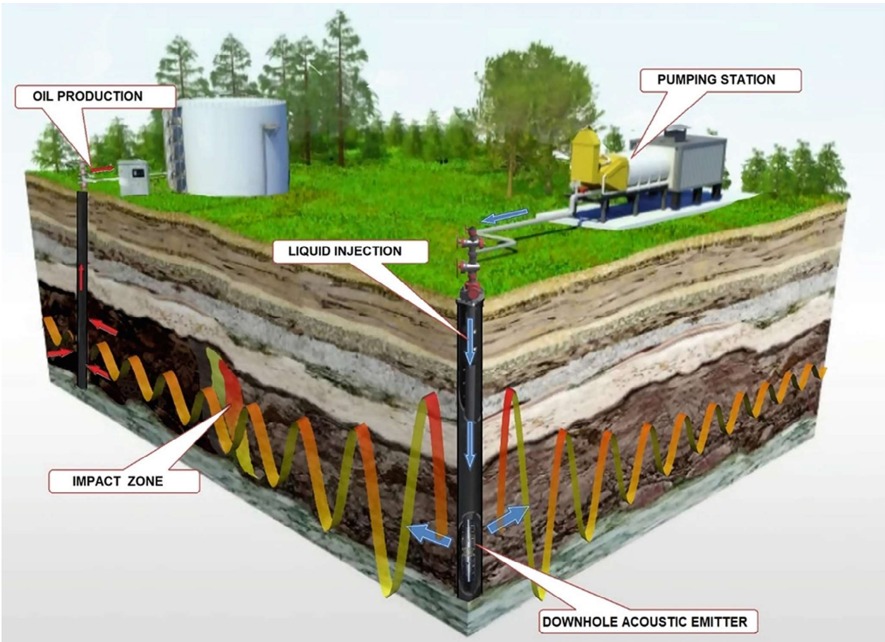

Fig. 1. Scheme of acoustic impact on the productive formation.

2) *Improvement of rock permeability.* Rock permeability is a critical factor determining a geological formation's ability to transmit oil and gas. Acoustic stimulation has been shown to enhance rock permeability through several mechanisms. First,

acoustic waves can induce microcracks in rock formations, reducing resistance to oil flow. Second, the mechanical effects of these waves can disrupt or weaken the bonds between rock particles, further increasing permeability. Third, solid particles such as colloidal particles, paraffin, and asphaltenes in formation fluids can clog pore passages during filtration [11, 18]. Mechanical vibrations help move these particles through the porous medium, similar to how flour passes through a sieve. These processes are especially important in tight, low-permeability formations, where acoustic stimulation can significantly improve well quality and production rates. Additionally, acoustic stimulation has been shown to promote the movement of water and gas within the reservoir, enhancing oil interaction with the pay zones.

3) *Activation of hydrocarbon filtration processes.* Acoustic waves can stimulate oil filtration processes, especially in formations with small pores or highly compressible layers. In these conditions, acoustic effects have been shown to weaken the cohesive forces between oil and rock particles, facilitating the acceleration of oil movement through the pores. Additionally, numerical modeling in [19] demonstrates that the superposition of pressure fluctuations creates directional flow, with a velocity comparable to that of the filtration process. Theoretical studies indicate that such flows can occur even without a pressure gradient [20]. The amplitude of pressure fluctuations is a critical factor in this phenomenon, particularly for enhancing the filtration properties of reservoir sections where conventional stimulation methods are ineffective. As a result, the impact of acoustic waves on filtration properties manifests in two ways: increasing the oil filtration rate and improving the uniformity of hydrocarbon distribution during production.
4) *Reducing oil density and increasing oil mobility.* It has been demonstrated that acoustic waves have the capacity to reduce the density of oil, thereby facilitating its movement through rocks. This effect is particularly pronounced for heavy and viscous hydrocarbons, which may experience impeded movement through pore spaces due to their high density [21]. The mechanism of density reduction involves the formation of microscopic bubbles in the fluid as a result of pressure fluctuations, which can weaken its viscous characteristics and facilitate its extraction from the reservoir.
5) *Thermodynamic effects of acoustic waves.* Localized temperature changes in the reservoir, induced by acoustic effects, have been shown to affect the physical and chemical properties of the oil. At high amplitudes of acoustic oscillations, heat is radiated, which has been demonstrated to liquefy the oil and facilitate its movement in the pores. Furthermore, thermodynamic effects have been shown to modify the structure of oil reservoirs, thereby increasing production. The modelling of the thermodynamics of acoustic stimulation is presented in [22].

The presented brief review demonstrates that the mechanisms of acoustic effects on reservoirs manifest in a variety of ways, each of which contributes to the enhancement of oil production efficiency. Acoustic waves have been shown to reduce oil viscosity, improve rock permeability, activate filtration processes and improve hydrocarbon mobility [23–25]. The combination of these effects makes it possible to achieve a significant increase in the volume of recoverable oil, especially in challenging geological conditions. It is also important to achieve the maximum possible amplitude of oscillations in the desired zone of the reservoir [26].

2.2 Energy Losses During Propagation of Pressure Fluctuations in the Productive Formation

The propagation of pressure fluctuations through borehole elements and the productive formation inevitably results in energy losses, which must be accounted for when designing and operating downhole acoustic emitters. Several mechanisms can contribute to energy loss as acoustic waves travel through solid, liquid, and porous media. A primary mechanism is the attenuation of sound wave intensity due to the shape of the wavefront. For a spherical wave, intensity decreases with the square of the distance, while amplitude decreases inversely with distance. In the case of a cylindrical sound source, pressure fluctuations propagate across the entire surface of the well, causing the amplitude to diminish in proportion to the square root of the distance from the well.

Beyond amplitude attenuation, viscous friction between fluid molecules and the porous rock structure results in acoustic energy absorption. These losses can be quantified by the absorption coefficient, which is influenced by factors such as porosity, density, viscosity, permeability, and frequency. For most oil fields, the absorption coefficient can be estimated using the formula provided in the referenced paper [27, 28]:

$$\alpha(f) = \frac{2\pi f}{c_{pf} Q}, \tag{1}$$

where f is the frequency of oscillations, c_{pf} is the sound speed in the productive formation, Q is the goodness of fit, the value of which for oil reservoirs is of the order of 30.

As shown in Fig. 2, the amplitude of pressure oscillations within the pay zone depends on both the distance to the well and the oscillation frequency. It is clear that as the oscillation frequency of acoustic waves increases, energy dissipation becomes more significant. This is due to higher energy absorption from viscous friction and wave scattering within the medium at elevated frequencies. Therefore, the effective design of downhole acoustic emitters must take these factors into account, optimizing emitter parameters to minimize energy losses and maximize the impact on the productive formation.

2.3 Downhole Acoustic Emitter Designs

Downhole acoustic emitters play a pivotal role in the process of stimulating the reservoir to enhance oil recovery. These emitters create acoustic vibrations, which in turn affect the physical and chemical properties of oil and rock. In the development of downhole emitters, the focus should be on devices that provide high efficiency of acoustic impact with minimal energy consumption.

Acoustic emitters are classified according to the principle of operation and application, with the following types being the most common:

– *Emitters with electromechanical energy conversion* utilize mechanical vibrations created by electromagnetic or piezoelectric systems, with the principle of operation being based on the fact that electromagnetic or piezoelectric elements generate acoustic waves by changing the shape or movement of the material when an electric current is applied. Despite their compactness and high accuracy, such emitters have limitations in power and efficiency in the high-pressure and high-temperature environments typical of oil wells.

- *Mechanical emitters* represent a class of emitters that generate acoustic waves through the utilization of jet or turbine mechanisms. The conversion of fluid energy into acoustic vibrations occurs through the action of mechanical elements. These devices find application in the generation of more powerful acoustic effects and are capable of operating at higher pressures. Sirens serve as illustrative examples of such emitters.
- *Flow-type emitters*, on the other hand, employ the flow of fluid injected into the reservoir to create acoustic vibrations. These emitters function by converting the kinetic energy of the fluid flow into acoustic energy, rendering them particularly effective in oil production environments where fluid flow is an essential element of the process.

In this study, the focus is on the design prototype of the emitter, with particular attention given to its flow type. The primary advantages of this design are twofold: firstly, the absence of moving components within the structure enhances reliability, and secondly, there is no requirement for additional mechanical or electrical energy. The jet-driven Helmholtz oscillator represents one of the most prevalent categories of flow emitters, operating on the principle of resonance within a confined space, formed by a liquid jet acting upon a resonator. Under specific conditions, it generates a liquid jet exhibiting cavitation, a property that has led to its occasional designation as a whistling nozzle. Such apparatus finds application in drilling and the surface treatment of hard materials.

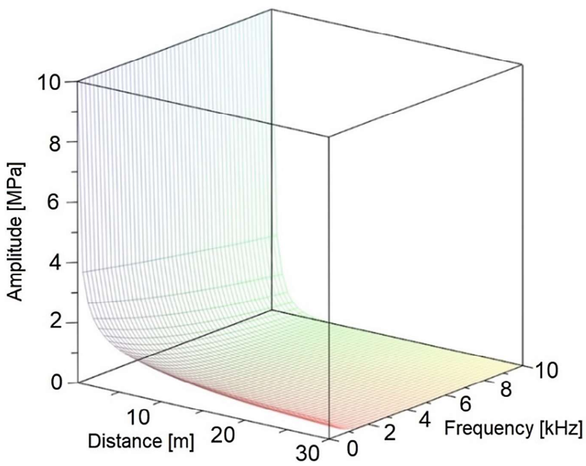

Fig. 2. Scheme of acoustic impact on the productive formation.

The oscillation generation mechanism in the jet-driven Helmholtz oscillator, as depicted in Fig. 3, can be outlined as follows [29–31]. Liquid flows through the device via an inlet nozzle of diameter d_1, forming a jet in a resonant chamber of diameter D

and length L. The presence of a jet leads to the formation of vortex structures in the mixing layer due to hydrodynamic instability. These vortices, in turn, generate primary pressure pulses as they flow onto the outlet opening, which has a diameter of d_2. These pressure pulses propagate upstream, thereby initiating the formation of new vortices. This process leads to the generation of auto-oscillations, characterized by a fundamental tone and multiples of its harmonics, whose frequencies depend on the jet velocity [32]. It is noteworthy that the frequency of these auto-oscillations increases with increasing jet velocity. At specific velocities, the frequency of these auto-oscillations aligns with the natural resonance frequency of the system, leading to an increase in oscillation amplitude.

The resonance frequency is determined by the speed of sound in the liquid and the geometric parameters of the device, as outlined in the following formula:

$$f_0 = \frac{c_l}{2\pi D\sqrt{L}}\sqrt{\frac{d_1^2}{l_{1e}} + \frac{d_2^2}{l_{2e}}}, \tag{2}$$

where c_l is the sound speed in the liquid, $l_{1\mathrm{e}} = l_1 + \pi d_1/4$, $l_{2\mathrm{e}} = l_2 + \pi d_2/4$ is the effective length of the inlet nozzle and outlet orifice, respectively.

Field tests of the previously developed emitter [32] led to an increase in oil production by more than 1.5 tonnes per day, with the amplitude of the generated oscillations reaching up to 1 MPa. Despite such impressive performance, it was identified that the back cover with the exit hole was the weak point in the system. The vortex structures within the resonance chamber create regions of low pressure, which ultimately result in cavitation and failure of this cover [33, 34]. The primary aim of this study is to develop a resonator configuration that generates oscillations effectively without compromising the integrity of the jet [35, 36]. To achieve this, two key research directions are proposed: reducing the length of the resonant chamber L and increasing the diameter of the outlet hole d_2. In order to assess the impact of these parameters, a physical model of the jet-driven Helmholtz oscillator was constructed. Table 1 outlines the ranges of variation for the main geometrical parameters of the device.

Table 1. Geometrical dimensions of the jet-driven Helmholtz oscillator.

Geometric parameter	Parameter value
Resonance chamber diameter D, mm	60
Resonance chamber length L, mm	2–14
Inlet nozzle diameter d_1, mm	12
Inlet nozzle length l_1, mm	10
Outlet diameter d_2, mm	13–24
Outlet length l_2, mm	0.9–12

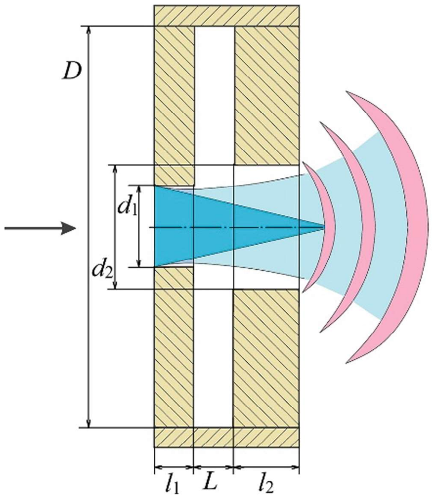

Fig. 3. Scheme of acoustic impact on the productive formation.

3 Results of Laboratory Tests

Before commencing the experimental investigation into the dynamic characteristics of the system, an analysis of the natural oscillation frequencies of the Helmholtz resonator was first conducted. To achieve this, the frequency characteristics of the incident "white noise" and the transmitted signal through the resonator were measured using two separate microphones. The ratio of the amplitude values of the transmitted wave to the incident wave was then used to construct resonance curves for each emitter configuration. The experiments in question employed Robotron high precision acoustic instrumentation. A representative resonance curve is shown in Fig. 4. Additionally, Fig. 5 presents a comparison between the experimental data and the theoretical values of the natural frequency, as calculated using Formula (2). The results demonstrate that the theoretical formula accurately predicts the natural frequencies of the investigated Helmholtz resonator.

As previously mentioned, the experiment was designed to investigate the influence of three variable parameters on the acoustic phenomena under study: the diameter and length of the exit orifice, as well as the length of the chamber. A series of experiments were conducted for each emitter configuration on the test bench described in [30, 37], with jet velocities ranging from 0 to 100 m/s. The pressure drop across the emitter was controlled using a vacuum pump, which induced the formation of a jet. The jet velocity was determined by the properties of the working medium (in this case, air) and the magnitude of the pressure drop, which was measured using a strain gauge pressure difference sensor. At a specific jet velocity, the generation of an orifice tone, amplified by resonance, was observed. The frequency of the generated pressure oscillations was found to closely match the natural frequency of the oscillator. As the jet velocity increased, the amplitude of the oscillations also increased, reaching a peak value determined by various factors. After this peak, the amplitude began to decrease, accompanied by slight increases in the frequency of the generated oscillations. This behavior, characterized by the relationship between jet velocity, oscillation amplitude, and frequency, is referred to as the oscillation mode in [29].

As shown in Fig. 6, the mean-square amplitude of the generated oscillations, normalized to the jet velocity head, exhibits a clear dependence on the jet velocity for various geometrical ratios of the outlet diameter, while maintaining a constant outlet opening length of $l_2 = 10$ mm and a chamber length of $L = 6$ mm. It is evident that as the jet velocity increases, the oscillation amplitude first rises and then declines. The maximum relative amplitude of oscillations occurs at the oscillator with an outlet hole diameter of $d_2 = 1.08d_1$, with the peak values of oscillation amplitude achieved at different jet velocities. This behavior can be attributed to the fact that changes in the outlet hole diameter lead to corresponding shifts in the natural oscillation frequency of the system. As a result, resonance conditions can be met at different jet velocities, as the frequency of the orifice tone and its harmonics are directly influenced by the jet velocity. The present study investigates the relationship between the root mean square amplitude of oscillations, jet velocity, and the length of the resonant chamber for a fixed outlet diameter ratio of $d_2/d_1 = 1.4$. It was found that for this particular ratio, the optimal chamber length occurs at $L/d_1 = 0.33$. Additionally, the study revealed that, compared to the "classical" Helmholtz oscillator, the emitter with a narrower chamber generates stronger oscillations over a broader range of jet velocities fig [29, 38]. Moreover, further investigation was conducted to assess the impact of the outlet length on oscillation amplitude, using a model with a chamber length of $L = 6$ mm and an outlet diameter of $d_2 = 16$ mm. The experimental results indicated a linear relationship between the maximum RMS amplitude of oscillations and the thickness of the outlet cover, which was defined as the length of the outlet hole. It was observed that increasing the length of the outlet opening led to a reduction in the maximum achievable amplitude of oscillations.

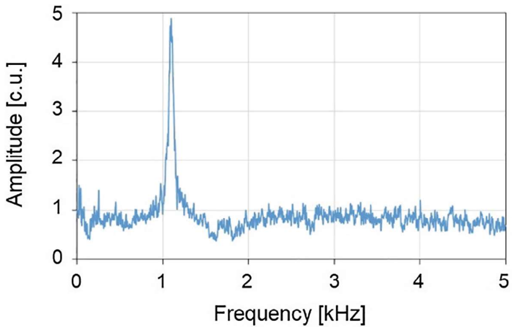

Fig. 4. Resonance curve of the emitter.

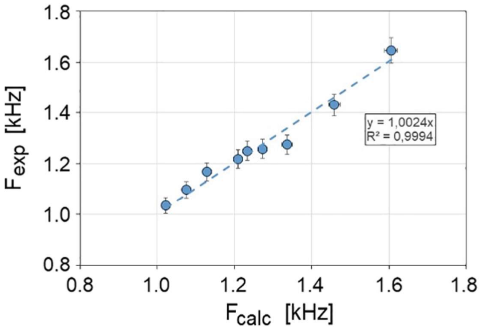

Fig. 5. Relationship between experimental and calculated values of natural frequency.

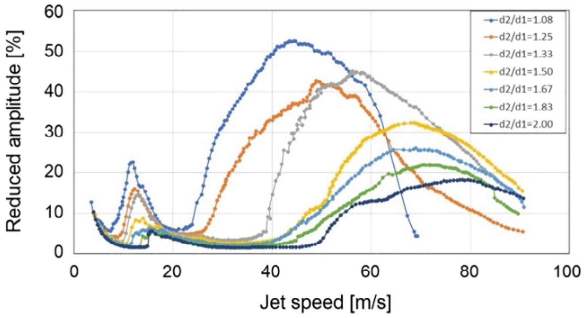

Fig. 6. Dependence of relative amplitude of oscillations on jet speed.

4 Conclusions

The paper under consideration places significant emphasis on the growing importance of enhanced oil recovery techniques in existing fields, particularly in light of the depletion of conventional oil sources and the increasing difficulty of extracting hydrocarbons from mature reservoirs. It is demonstrated that acoustic technologies hold considerable promise in improving oil extraction processes by reducing oil viscosity, enhancing rock permeability, and ultimately increasing hydrocarbon recovery. The article delves into the design of a downhole acoustic emitter specifically developed for the application of acoustic impact technology on productive formations to optimize oil production. The study presents a modernized emitter based on a jet-driven Helmholtz oscillator, a type of flowing sound emitter capable of generating powerful pressure fluctuations at natural frequencies. Experimental results confirm that the oscillator with a slit chamber generates higher amplitude oscillations compared to one with a longer chamber, highlighting the efficiency of the slit chamber design. Furthermore, the research explores the relationship between pressure oscillation amplitude and jet velocity. The findings indicate that the range of jet velocities at which acoustic modes are generated is significantly broader for the slotted chamber oscillator compared to the longer chamber configuration. These results provide valuable insights for the development of flow emitters that could be applied not only for enhancing oil production but also for various industrial applications requiring acoustic oscillations to intensify processes involving a working agent. The study opens the door for more efficient and environmentally friendly technologies in the oil industry, paving the way for future advancements in acoustic stimulation techniques.

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