

Application of Ultrasonic Cavitation in Ship and Marine Engineering

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Abstract

Biofouling on ships and offshore structures has always been a difficult problem to solve, which not only jeopardizes the structural strength but also brings great economic losses. Ultrasonic cavitation is expected to solve this problem due to its characteristics of no damage to structures and no pollution. Starting from the phenomenon and mechanism of ultrasonic cleaning, this paper introduces the application of ultrasonic cavitation in ship, pipeline and oil cleaning as well as ballast water treatment. By reviewing the existing studies, limitations such as insufficient ultrasonic parameter studies, lack of uniform cleanliness standards, and insufficient cavitation studies are summarized to provide traceable research ideas for improving ultrasonic cavitation technology and to guide the expansion and improvement of its applications.

Keywords Ultrasonic cavitation; Cavitation mechanism; Ultrasonic cleaning; Ship and marine engineering; Application status

1 Introduction

The formation of organisms can cause damage to the surface of immersed ships, submarines, and offshore platforms (Salters and Piola, 2017) (Figure 1). With moderate biofouling, a 100 000 DWT ocean liner will experience a 30% increase in navigational resistance and will consume more than 10 tons of fuel per day (Song and Cui, 2020). The shipping industry loses approximately more than 30 billion dollars each year due to biofouling (Schultz et al., 2011). In addition to the high economic costs and

emissions caused by biofouling, the risk of biological invasion is also inevitable (Goldsmith et al., 2018). Biofouling will also increase the structural weight of the offshore platform, which will result in a high center of gravity, as well as decrease its stability and resistance to wind and waves, conceal the structural defect, and raise the risk of accidents (Wang et al., 2018a). Therefore, the industry regularly cleans ships and offshore structures.



Figure 1 Biofouling of ships, submarines, and marine platforms

Article Highlights

- In order to study the application potential of ultrasonic cleaning, it is necessary to analyze and summarize the cleaning mechanism of ultrasonic cavitation.
- The study focuses on the application of ultrasonic cavitation in ship and marine pipeline, ballast water treatment, oil cleaning and separation.
- The study analyzes and summarizes the strengths and limitations in previous studies by reviewing the existing studies.
- The study provides traceable research ideas for improving ultrasonic cavitation technology and its applications.

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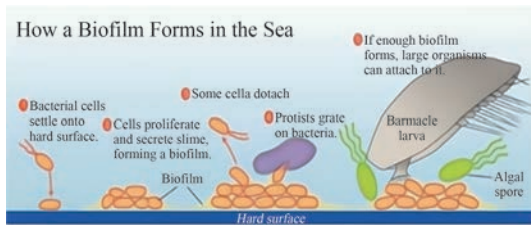
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The accumulation of organisms on submerged surfaces (Figure 2(a)), also called biofouling, has been a known problem for centuries. The traditional means of biofouling control relies on antifouling coating, sandblasting, mechanical brush turning, and high-pressure water jet and underwater cavitation jet cleaning technology. Antifouling coatings were previously extensively employed, but their use is currently prohibited because they pose a significant environmental hazard. Sandblasting and mechanical brush turning produce good cleaning results; however, they are not widely used due to expensive labor costs and lengthy docking times, which are inefficient for ship operations.

The use of high-pressure water jets and underwater cavitation jets to clean submarines may cause hull and anechoic tile damage and other issues (Figure 2(b)), indicating that cavitation intensity cannot be precisely regulated.



(a) Biofouling formation mechanism (Salters and Piola, 2017)



(b) US nuclear submarine anechoic tile damage

Figure 2 Biofouling formation mechanism and submarine anechoic tile damage

Without the use of cleaning agents, ultrasonic cavitation technology provides excellent cleaning effects for complex and delicate structures due to its tunability. In recent years, this technology has been widely utilized in fields such as food processing, chemical, medical, and other fields, including disinfection of fruits and vegetables, instrument cleaning, and ultrasonic lithotripsy (Zhang et al., 2014; Zwaschka et al., 2018; Agi et al., 2018; Alenyorege et al., 2020; Liao and Wang, 2020; Yu et al., 2022; Xue, 2022). This paper provides some research ideas and suggestions for improving and expanding the application of ultrasonic cavitation cleaning technology by introducing its current situation and research progress in ship and marine engineering and summarizing the limitations and shortcomings of the current research and application.

2 Mechanism of ultrasonic cavitation cleaning

When ultrasonic waves (frequency greater than 20 kHz) are applied, tiny bubbles (cavitation nuclei) in liquids undergo a sequence of dynamic processes, including oscillation, expansion, contraction, and collapse. At the instant of bubble collapse, the energy contained within the bubble is rapidly released, which results in high temperatures, excessive pressure, and even luminescence within the cavitation area. The bubble rapidly contracts and collapses simultaneously, releasing shockwaves and even high-speed jets

(Feng, 2003). This phenomenon is an extremely complex and fast-moving natural occurrence. Rayleigh first systematically described the bubble equation of motion for an ideal incompressible fluid in 1917 (Rayleigh, 1917). Plesset later obtained the classical Rayleigh–Plesset equation by considering viscosity and surface tension on the basis of Rayleigh’s research (Plesset, 1949), which built a foundation for subsequent research on the dynamics of air bubbles. Keller and Miksis (1980) further developed the model, in which the wave and incompressible Bernoulli equations have been used extensively. Lezzi and Prosperetti (1987) created a bubble dynamics model for the compressibility of the far-field fluid by adopting the perturbation. These models have been extremely influential in the theoretical investigation of bubble dynamics in a free field. However, isolated bubbles rarely occur and are constantly coupled with different boundary conditions, resulting in highly complex dynamics. Zhang et al. (2023) proposed the unified bubble theory, which can simultaneously consider the effects of boundaries, bubble interaction, ambient flow field, gravity, bubble migration, fluid compressibility, viscosity, and surface tension while maintaining a unified and elegant mathematical form. They conducted numerical experiments comparing the present theory with the classical theories proposed by previous scholars, and the results showed that the unified theory has higher accuracy and applicability. Since then, numerous scholars have conducted in-depth studies on cavitation phenomena, allowing for the cross-fertilization of vacuole dynamics with other disciplines, which expands the possibilities for ultrasonic cavitation technology.

The inner temperature and pressure may theoretically approach 5 000 K and 50 MPa, respectively, at the collapse stage of the cavitation bubble (Suslick, 1990). Microjets with speeds of up to 300 m/s (Figure 3) and strong shock waves are also generated (Figure 4(a)). Simultaneously, chemical substances such as hydroxyl groups are produced in the liquid, creating “hot spots” (Didenko and Suslick, 2002; Gogate and Pandit, 2001; Suslick et al., 1986). Flynn and Church classified cavitation bubbles into stable and transient cavitations based on different bubble kinetic characteristics (Flynn and Church, 1984). Stable cavitation refers

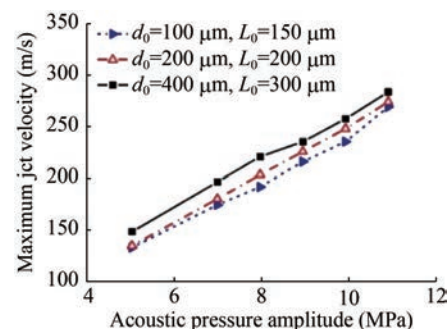
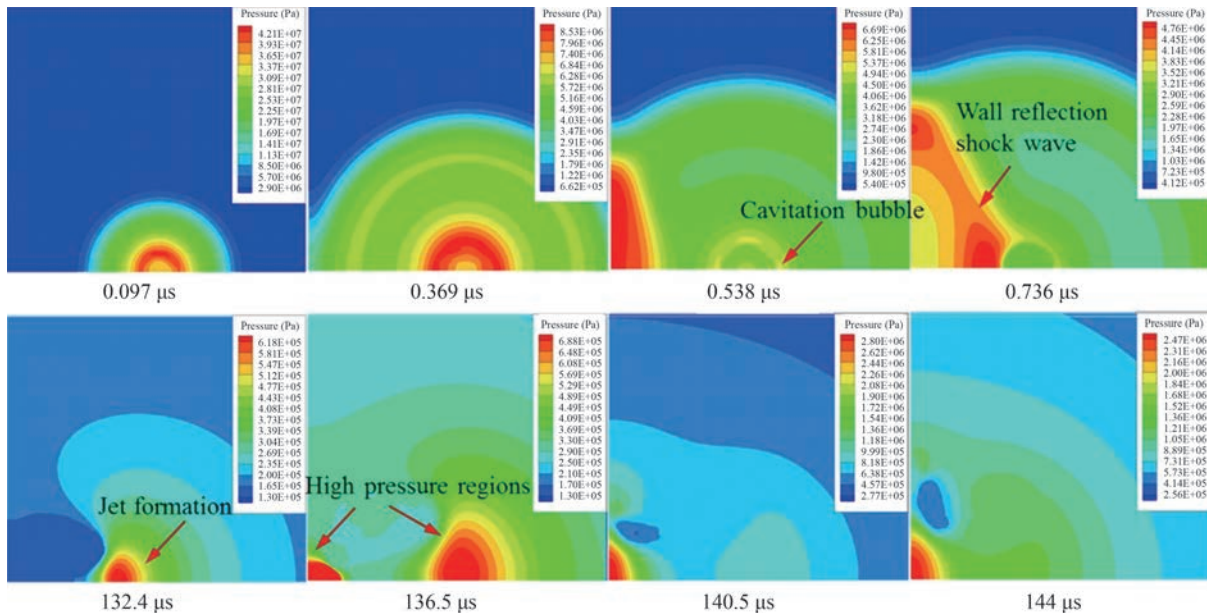


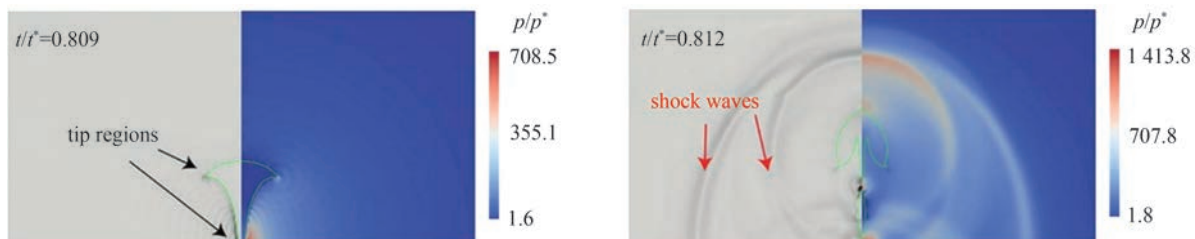
Figure 3 Variation of the maximum jet velocity with the acoustic pressure amplitude (Zhao et al., 2021)

to the oscillatory growth cycle of bubbles, maintaining their stable oscillatory state near their equilibrium size. Transient cavitation is the collapse of bubbles, in which the radius of the cavitation bubble varies by several orders of magnitude within a single oscillation cycle, causing the

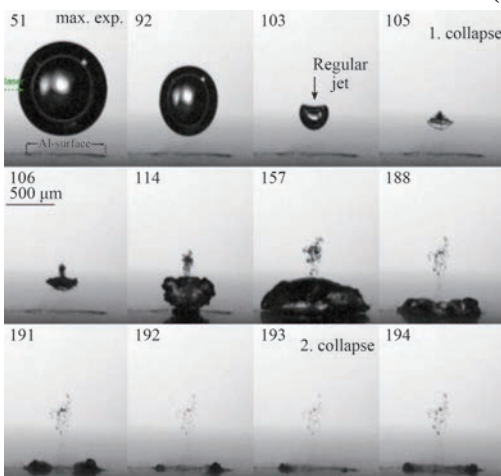
bubble to cycle from explosive growth to violent collapse. The shock wave generated by the collapse can break the fouling. Therefore, ultrasonic cavitation for dirt removal has become a focus of research and development for numerous scholars and businesses.



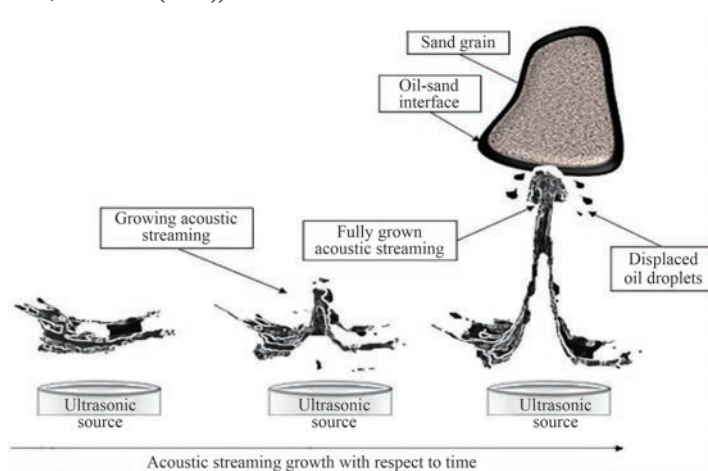
(a) Diagram of pressure field distribution at different times (The shock wave maintains a high pressure of 4.28×10^7 Pa at $0.097 \mu\text{s}$) (Zhang et al., 2021)



(b) Numerical schlieren (left of each panel) and pressure field (right of each panel) of a wall-attached bubble ($D=0.2$; Tian et al. (2023))



(c) High-speed imaging (1×10^{12} frame/s) of bubble jet formation and slamming (Abedini et al., 2023)



(d) Diagram of acoustic streaming (Mat-Shayuti et al., 2019)

Figure 4 Images and parameters related to shockwave and microjetting

Ultrasonic cavitation, a complex series of physicochemical phenomena, is currently widely accepted for cleaning in the following ways (Feng and Huang, 1994) (Figure 5).

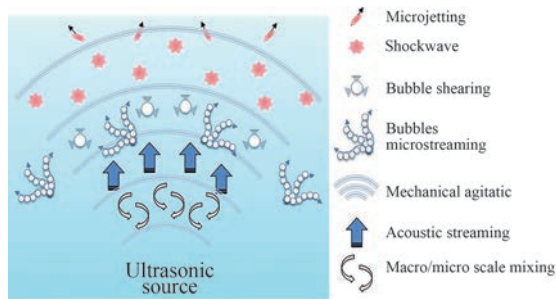


Figure 5 Mechanism of ultrasonic cavitation (Mat-Shayuti et al., 2019)

1) The cavitation bubbles in the liquid will oscillate under the action of ultrasonic waves. When the ultrasonic pressure reaches a certain level, the bubbles will rapidly collapse, and the shock wave generated at the moment of bubble collapse can form a surrounding pressure of thousands of atmospheres (Figure 4(b)). This pressure can destroy the polymerized contaminants and disperse them in the liquid.

2) The collapse of transient cavitation bubbles near the surfaces of structures can produce thousands of megapascals of microjet impact load (Figure 4(c)), destroying dirt adsorption and causing dirt to fall off.

3) Stable cavitation bubbles oscillate close to the solid surface in a continuous cycle of expansion and contraction, generating shear force at a flow rate of approximately 100 $\mu\text{m/s}$ (Figure 6) (Leong et al., 2011) to promote fluid flow, increase mass transfer, and also enter cracks in the soil during oscillation.

4) When the bubbles coalesce and oscillate, they can drive the liquid to produce micro-acoustic flow, thereby accelerating the agitation and scrubbing effects and promoting dirt detachment (Ma et al., 2018).

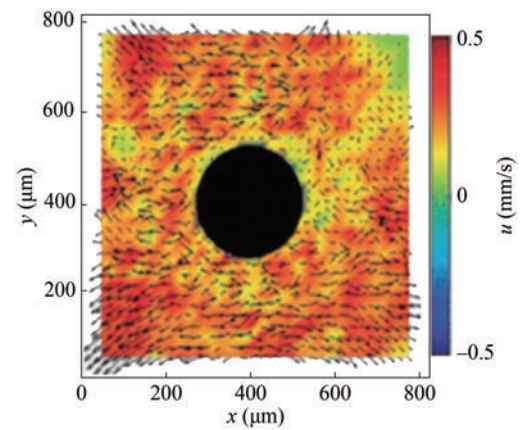
5) The acoustic flow can separate the oil from the structure during ultrasonic treatment of oil-containing structures by removing the oil boundary layer on the surface (Mason, 2016) (Figure 4(d)).

6) Propagation of the ultrasonic wave through the liquid can induce vibration of mass, causing the dirt to be slammed by the cleaning liquid and separated from the structure.

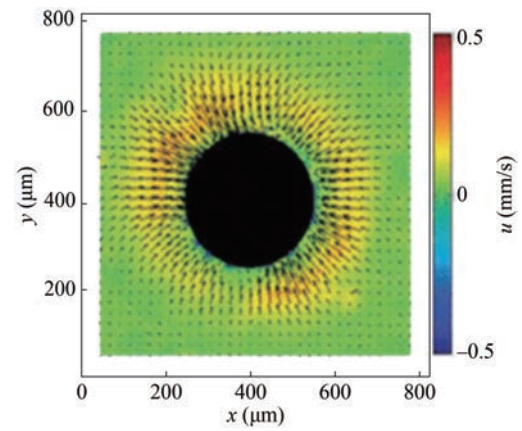
3 Ultrasonic cleaning application

3.1 Application of ultrasonic cavitation in ship and marine pipeline cleaning

Ultrasonic cavitation, as an early proven cleaning technology, is widely used in the field of decontamination and antifouling. This section will mainly focus on the research



(a) The case with surface oscillations resulting in chaotic low



(b) The case without surface oscillations and ordered flow

Figure 6 PIV velocity vector fields for ultrasonic cavitation. The left vertical and horizontal coordinates indicate the image acquisition range (μm), and the right vertical coordinate indicates the particle velocity (mm/s) (Leong et al., 2011)

and application of ultrasonic cavitation in the cleaning of ships and marine pipelines.

The application of ultrasonic cavitation to ship cleaning and antifouling dates back to 1974, when approximately 20 Soviet ships were equipped with ultrasonic antifouling systems. The antifouling effect was observed when an inner hull-mounted transducer emitting ultrasonic waves between 17 and 30 kHz was used. However, this transducer was unsuitable for the bulkhead and frame joints because of the fast sound intensity and frequency decay at these joints.

The discovery of the potential of ultrasonic cavitation for antifouling prompted extensive research into determining the optimal frequency for ultrasonic cleaning. Researchers from various disciplines devoted their efforts to uncovering the ideal frequency range through meticulous experimentation. They aimed to maximize the effectiveness of ultrasonic cleaning by finetuning the frequency, leading to improved decontamination and enhanced fouling prevention capabilities. Kitamura et al. (1995) investigated the effect of ultrasound on barnacles at three different fre-

quencies (19.5, 28, and 50 kHz), and the experimental results revealed that the most significant removal of barnacles occurred at a frequency of 19.5 kHz.

Seth et al. (2010) utilized ultrasonic cavitation to clean and crush barnacle microalgae and calculated the energy of ultrasonic waves produced during the crushing process using the heat absorption method. Guo et al. (2011) investigated the effect of ultrasonic frequencies of 23, 63, and 102 kHz at 20 kPa on the inhibition of barnacle sedimentation. Similar to Kitamura et al. (1995), Guo et al. (2011) found that 23 kHz was the most effective frequency through experimentation. The optimal cleaning frequencies determined by these studies can only be considered relative due to the random nature of the frequency selections in these studies.

Guo et al. (2014) demonstrated that the ultrasonic cavitation phenomenon inhibits the settling of barnacles by modifying the cavitation threshold while maintaining the same acoustic pressure. They also found that intermittent ultrasonic treatment of barnacles with low-frequency and low-intensity ultrasound produced the same effect as continuous ultrasound treatment. In terms of equipment cleaning efficacy and serviceability, an on-and-off cycle of 5 min on and 20 min off is the most appropriate treatment mode. Furthermore, the ultrasonic effect on the adhesion strength of barnacles of different ages was studied using a microscope (Figure 7), and the entire process of barnacle removal by ultrasonic cavitation was filmed using a high-speed camera, visually demonstrating the mechanism and the effect of ultrasonic barnacle removal. However, finding this effect in the acoustic performance parameters, such as frequency, sound intensity, and amplitude, in these experiments, which are highly arbitrary and likely to be displaced from the optimum, is easy.

Simultaneously, scholars are also exploring the application of ultrasonic cleaning in marine pipelines and buoys to decontaminate and prevent fouling. Bott (2000) conducted a cleaning experiment using ultrasound on biofilms comprising bacteria and algae deposits in the pipeline. The experimental results revealed that the biofilm thickness was reduced by 92.6% when the bioadhesion in the pipeline was treated with 240 W and 24 kHz ultrasonics. However, the pipe contained only pure water at a constant flow rate, and

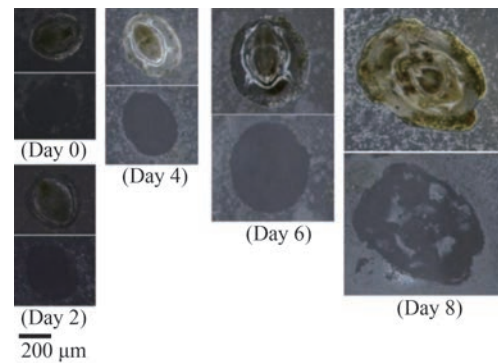


Figure 7 Microscopy images of surfaces after removal of different age barnacles (Guo et al., 2014)

the pipe's geometry was disregarded as a study parameter.

Traditional cleaning methods must be conducted when ships, offshore platforms, and marine pipelines are not in operation. Lais et al. (2018) performed local ultrasonic cleaning of the inner walls of calcite-contaminated pipelines using a three-dimensional laser Doppler vibrometer (3D-LDV) for acoustic pressure and displacement acquisition to solve this issue (Figure 8). The validity of external ultrasonic removal for pipeline fouling is demonstrated, confirming its consistency with the COMSOL model (Figure 9).

Zhang et al. (2017) installed ultrasonic cleaning equipment on the ACLW-CAR buoy to prevent fouling and biofouling from causing the failure of the offshore buoy monitoring system. The effect of ultrasonic cleaning on the ACLW-CAR buoy after one year of operation demonstrates that the ultrasonic cleaner can effectively prevent biofouling (Figure 10).

The practicality of utilizing ultrasonic cavitation for decontamination and antifouling in localized or small structures has been successfully demonstrated. Furthermore, this technology is steadily advancing from laboratory-scale experiments to real-world implementation on large ships, marking a significant step toward its widespread adoption in the marine industry. Mazue et al. (2011) attempted to design an ultrasonic cleaning device comprising three low-frequency ultrasonic transducers operating automatically to reduce ship maintenance docking time (Figure 11). Mazue et al. (2011) conducted feasibility tests on small samples and real ship hulls to obtain design laws and determine the effect

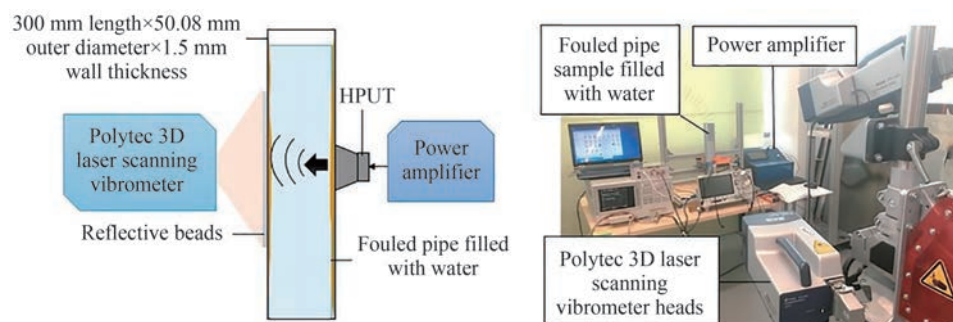


Figure 8 Schematic of fouling removal experimental setup and photograph of the experimental setup (Lais et al., 2018)

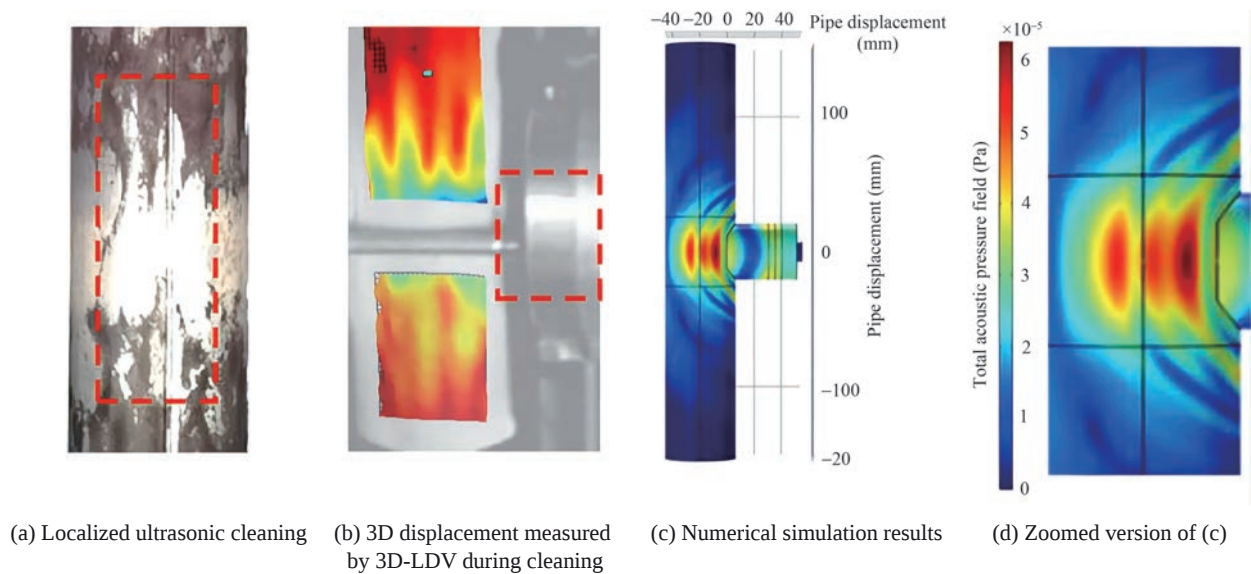


Figure 9 Comparison of numerical and experimental results (Lais et al., 2018)



Figure 10 Effect of ultrasonic cleaning equipment (Zhang et al., 2017)



Figure 11 Ultrasonic cleaning device physical picture and cleaning before and after comparison (Mazue et al., 2011)

of parameters, such as transducer-surface distance, displacement speed, and emission power, on hull cleaning. The distance between the transducer rod and the hull should always be as small as possible due to ultrasonic decay in water, and the cleaning device should operate at a speed of less than 5 cm/s. However, this condition depends on the degree of hull soiling, the transducer arrangement, and the number of transducers. A large-diameter transducer was also found to be highly conducive to rapid cleaning and decontamination. Figure 8 shows a comparison between a dirty hull before and after ultrasonic cleaning.

Considering the impact of transducer arrays and synthetic signals on offshore structural antifouling, Salimi et al. produced a novel ultrasonic system using high-power ultrasound transducers (HPUTs) and the best synthesis signal

type for offshore structural cleaning under sea standard noise levels (Salimi et al., 2023). They examined the effect of 28 kHz ultrasound vibration of HPUT on removing biofouling after immersion by conducting an experiment of up to three months on a rectangular plate immersed in sea water (Figure 12). This experiment was performed using a single HPUT to prevent biological contamination from attaching to a plate locally in the exchanger's position.

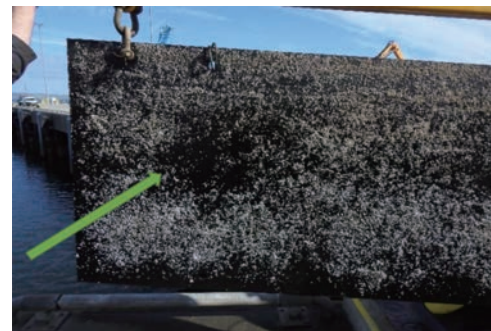


Figure 12 Biofouling removal using an HPUT. The green arrow shows the location of the HPUT at the back of the plate (Salimi et al., 2023)

Park and Lee (2018) installed six ultrasonic projectors on the starboard side of a 96 000 m³ large drillship, while the port side was left untreated (Figure 13). Ultrasonics at 23 kHz frequency induced cavitation in the surrounding water to prevent the fouling organism settlement. After four months, the starboard hull plate was relatively clean, while the port side was heavily fouled (Figure 14). The experimental results not only demonstrated that ultrasonic cavitation effectively inhibits the formation of fouling on the hull but also confirmed the efficacy of ultrasonic cavitation applied to large ships. However, the sea trials did not fully investigate fouling deposition by ultrasonic equip-

ment, the effect of ultrasonic on the ship structure, or coating disbondment. Therefore, conducting long-term trials may be necessary to investigate the unresolved issues.

Yan et al. (2018) designed a multifunctional tug to monitor and clean ship bottom fouling (Figure 15). In addition to the multicolor-assisted light source fouling monitoring system, the tug also integrated a fouling removal robot (ROV) utilizing cavitation jet and ultrasonic cavitation technologies. The ROV was equipped with a cavitation jet cleaning disc and an ultrasonic cavitation cleaning device to remove rigid attachments, such as shells and corals, through

the use of cavitation jet. Both cleaning methods can be employed to clean the ship's hull and improve cleaning quality.

The absence of a universally accepted standard for assessing the effectiveness of ultrasonic cleaning poses a significant obstacle. Therefore, most studies rely on subjective comparisons of dirt levels before and after experiments or approximate quantifications of dirt removal. This lack of standardized evaluation methods hampers the commercial viability of ultrasonic cleaning devices. In addition, none of the aforementioned studies considered the potential impact of corrosion on the surface of the ship's hull.

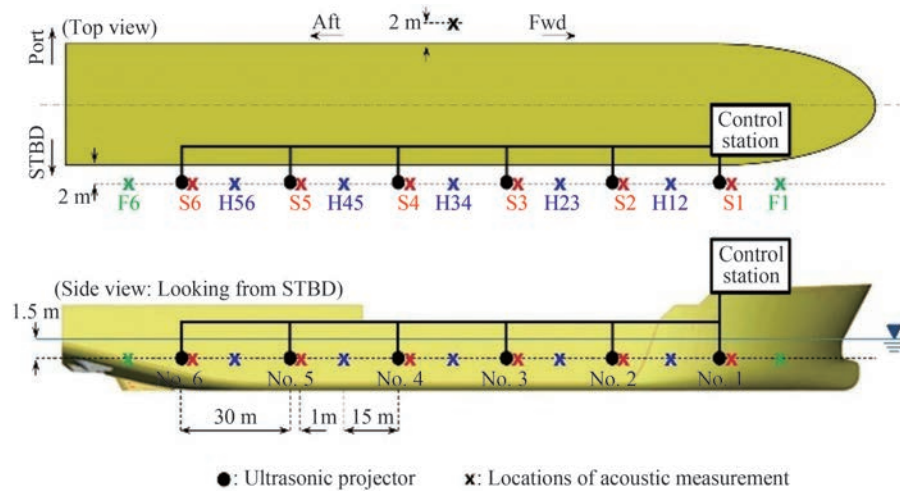


Figure 13 Arrangement of the six projectors and the locations for acoustic measurements (Park and Lee, 2018)

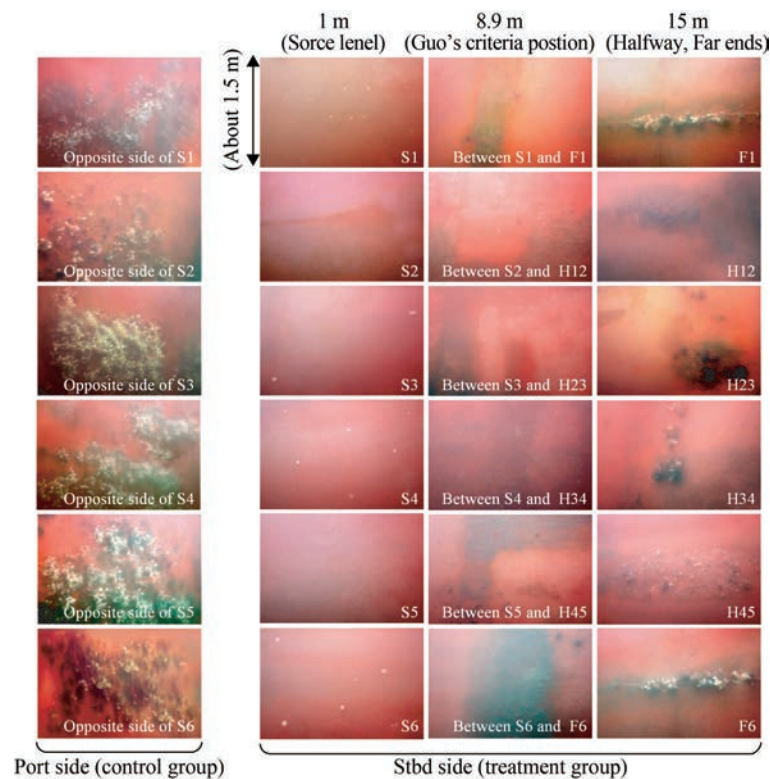


Figure 14 Underwater inspection of the hull plate after the sea trial (Park and Lee, 2018)

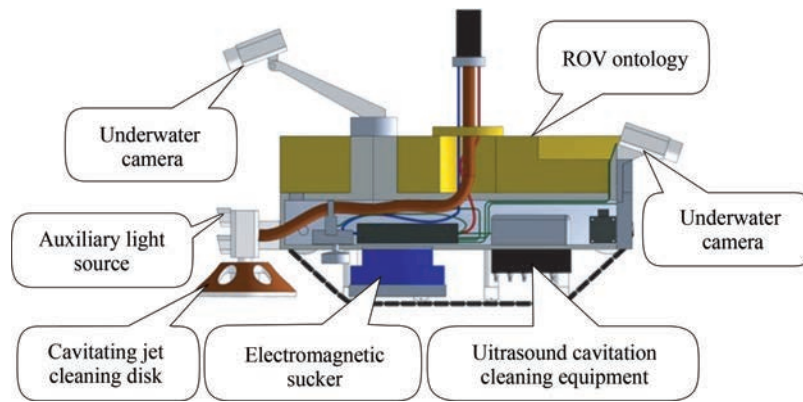


Figure 15 Side view of ROV (Yan et al., 2018)

Fatyukhin et al. (2022) later used 21.5 kHz ultrasonics to treat the surfaces of 45 and 40 Kh steels in liquid (Figure 16). They found that the erosion process comprises at least three stages. In the first stage, the geometric properties of the surface change slightly with the accumulation of internal stress and the increase of micro-hardness. In the second stage, which involves structural finetuning, roughness and sub-microscopical rudeness increase, and surface erosion develops. In the third stage, the surface properties do not noticeably change when a certain limit state is reached. These results can be used to improve the cleaning process for ship hulls.

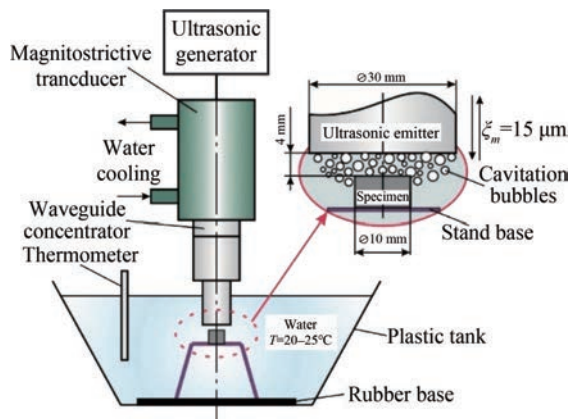


Figure 16 Ultrasonic treatment scheme (Fatyukhin et al., 2022)

Zhong et al. (2022) combined ultrasonic and submerged cavitation jet cleaning. They evaluated the effect of cavitation erosion on the hull at pump pressures of 10 and 20 MPa (Figure 17). Experimental results indicated that the mass loss of 1 060 aluminum plates resulted from the combined action of a submerged cavitation jet and ultrasound at pump pressures of 10 and 20 MPa. The cavitation pit area and depth are the largest at target distances of 40 and 55 mm, respectively. When the pump pressures are 10 and 20 MPa, the maximum increase reached 12.9% and 9.5%, respectively, which initially verified that the combination technology can improve the cleaning effect. However, additional consideration of the impact of working conditions and operational modes is required.

Such erosion research currently remains at the laboratory stage and has not been conducted on actual ships, possibly due to the lack of large-scale equipment and the influence of various factors on experimental results. Further advancements are necessary to bridge this gap and facilitate real-world experimentation aboard ships.

3.2 Application of ultrasonic cavitation in ballast water treatment

Several researchers used ultrasonic cavitation to treat ship ballast water after establishing its capability to inactivate bacteria. This section mainly introduces the research and application of ultrasonic cavitation in ballast water treatment.

Numerous microorganisms, pathogens, and sediments are living in ballast water tanks. These organisms can be dispersed globally by the improper discharge of ballast water from ships, resulting in biological invasions or widespread diseases that threaten the natural environment and human health (Marbuah et al., 2014). In recent years, ultrasonic waves have been shown to deactivate bacteria and algae (Lee et al., 2001; Gavand et al., 2007; Ma et al., 2005).

Scherba et al. (1991) treated ballast water with 26 kHz for 30 min and discovered the elimination of up to 80% of *P. aeruginosa* and 75% of *Bacillus subtilis* and the mortality of *Staphylococcus aureus* as high as 45%.

Holm et al. (2008) investigated the power levels and number of applications necessary for 19–20 kHz ultrasound to eliminate bacteria, phytoplankton, and zooplankton in ballast water treatment applications. They discovered that ultrasonic inactivation rates differed depending on the size of the organisms examined. Deactivation of 90% of zooplankton took only 39 s. Comparatively, smaller bacteria and phytoplankton required between 1 and 22 min to achieve comparable results. The authors hypothesize that this phenomenon may occur because particles smaller than the size of the collapsed cavitation bubble are incapable of generating microjets and, therefore, require additional deactivation time. They concluded that ballast water-independent ultrasonic treatment systems operating at 19–20 kHz

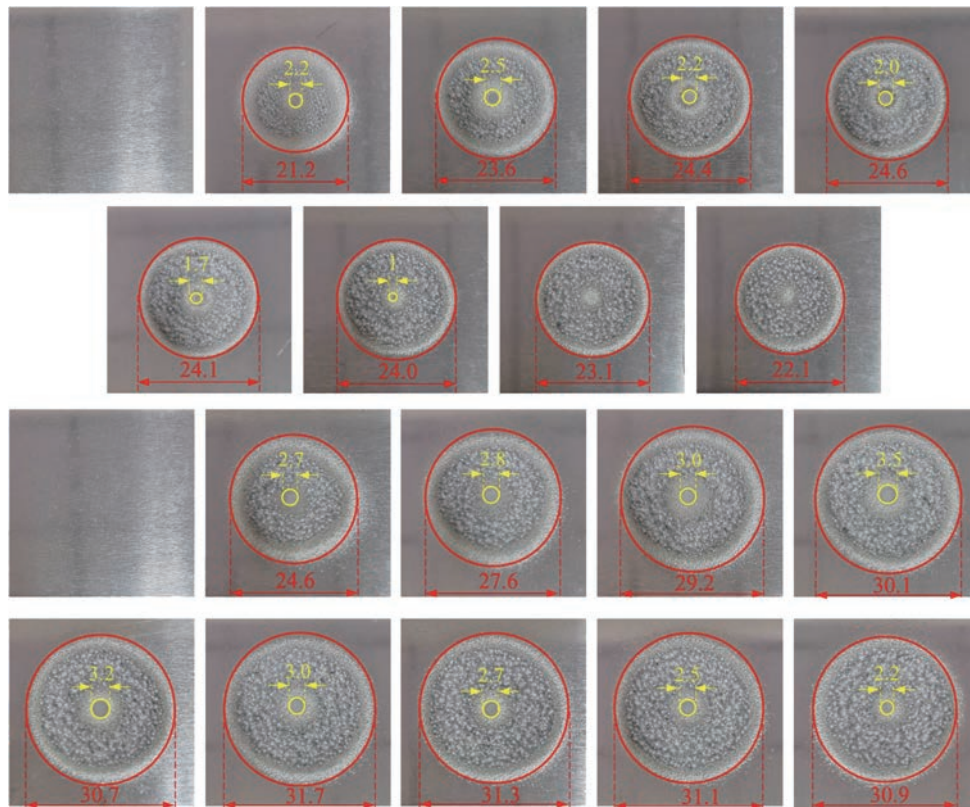


Figure 17 Surface morphologies of the 1 060 aluminum sheets before and after erosion by the combined work of the submerged cavitation jet under the pump pressure of 10 MPa and the ultrasonic with 40 kHz/50 W (Zhong et al., 2022)

may be effective for plankton larger than 100 μm . However, the inactivation characteristics of small plankton and bacteria require further investigation.

Joyce et al. (2010) treated microalgae liquids with ultrasonic at 20, 40, 580, 864, and 1 146 kHz and discovered that the algal cell concentration decreased for a time and then increased during 20 and 40 kHz ultrasonic treatments (Figure 18). They concluded that ultrasound treatment has two effects: inactivation, which reduces cell concentration; and fragmentation, which breaks the algal mass into individual cells, increasing the concentration. The experimental results showed that the fragmentation effect was prevalent at low frequencies (Figure 19).

Continuous research is being conducted to enhance the effectiveness and efficiency of ultrasonic treatments for

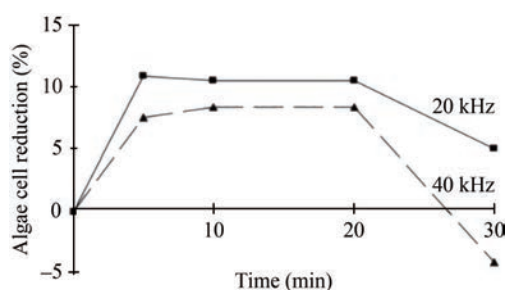


Figure 18 Inactivation of 200 mL *Microcystis aeruginosa* using the 20 kHz probe and 40 kHz bath (Joyce et al., 2010)

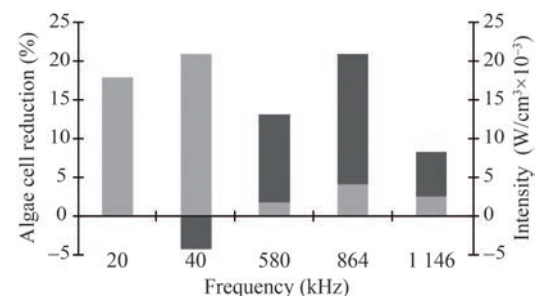


Figure 19 Ultrasonic treatment of 200 mL *microcystis aeruginosa* at different frequencies (Joyce et al., 2010)

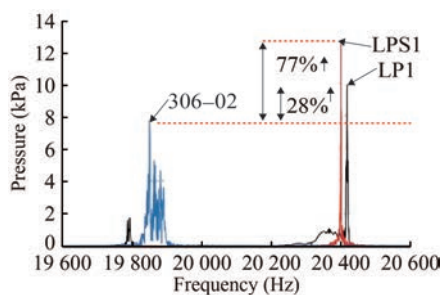
ballast water. Scientists and engineers are exploring various avenues, such as advanced ultrasonic technologies, optimized system designs, and multitechnological integration methods. These efforts aim to deliver highly effective and environmentally friendly solutions for the treatment of ballast water, ultimately protecting marine ecosystems and human health. Osman et al. (2017, 2016) designed a MOR ultrasonic resonator for ballast water disinfection (Table 1). With the same vibration amplitude, the MOR provides higher sound pressure and a one-order-of-magnitude larger radiating surface area than a probe-type ultrasonic device (Figure 20). Acoustically, the MOR resonator is highly effective and efficient, but the specific effects of plankton and bacterial inactivation require further investigation.

Table 1 Comparison of MOR resonator design outcomes (Osman et al., 2016)

Parameters	Designs			
	LP1	LPS1	LPS2	LPS3
Mode shape				
Res. freq. (Hz)	20 070	20 091	20 112	20 097
Δ Res. freq. (Hz)	+70	+73	+113	+92
Norm. mass	1.000	0.971	0.997	0.992
Norm. radiating area	1.000	1.959	1.745	1.841
Norm. area/mass	1.000	2.018	1.750	1.856



(a) Fabricated devices for acoustic pressure measurement



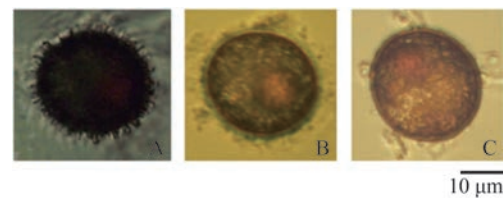
(b) Measured acoustic pressure spectrum at the same position

Figure 20 Fabricated devices for acoustic pressure measurement and measured acoustic pressure spectrum at the same position (Osman et al., 2016)

In addition to improving the disinfection efficiency of the ultrasonic element, Laksono et al. (2022) also proposed the design of combining slow-release pertechnetate with ultrasonic treatment equipment for the disinfection of ballast water and calculated the amount of compound used in the treatment process as well as the operation mode of the ultrasonic equipment.

In a study comparing the treatment of microalgal spores using ultrasound alone and combined UV/ultrasound/heating (Figure 21), Wang et al. (2018b) discovered that the spore extinguishing efficiency was higher with the combination of ultrasonic and other means. Moreover, the fouling deposition exhibited a protective effect on the microalgal spores (Figures 22–24). This result indicates that future re-

search should combine ultrasonic and multiple treatment methods to improve the efficacy of ballast water treatment.

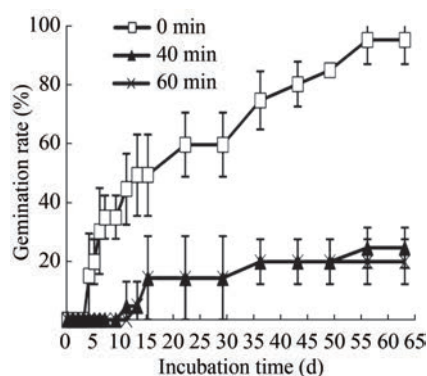
**Figure 21** Microscopic photos of cysts of *Scrippsiella trochoidea* by freshwater treatment showing corrosion/dissolution of the calcareous cyst wall (Wang et al., 2018b)

The aforementioned experiments have demonstrated that the integration of ultrasonic technology with other decontamination methods leads to enhanced cleaning effectiveness and efficiency. Examining the combined cleaning effect of ultrasound with various treatment techniques is crucial in future research, paving the way for further advancements in the field.

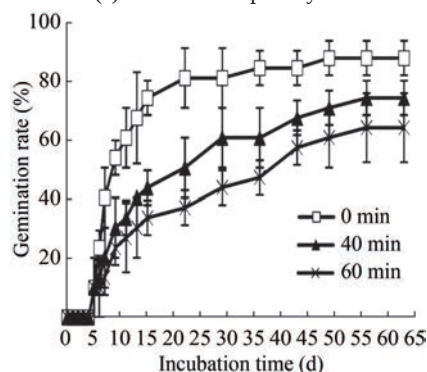
3.3 Application of ultrasonic cavitation in oil cleaning and separation

One of the most effective methods for cleaning oil-contaminated sand is considered to be ultrasonic energy. Ultrasonic cleaners typically use acoustic waves to generate cavitation and shockwaves, which can break the bond between oil contaminants and sand. In addition, ultrasonic technology is safer and cleaner than other methods, such as heat, microwaves, and chemicals. This section will focus on the research and applications of ultrasonic cavitation in oil-contaminated sand cleaning and separation.

Ship operations frequently require the regular replacement or cleaning of oil filters to prevent engine breakdowns and guarantee efficient operation. Traditional manual cleaning processes often use strong polar solvents such as methyl halides, which are not only corrosive to the fil-



(a) Treatment on pure cypsts

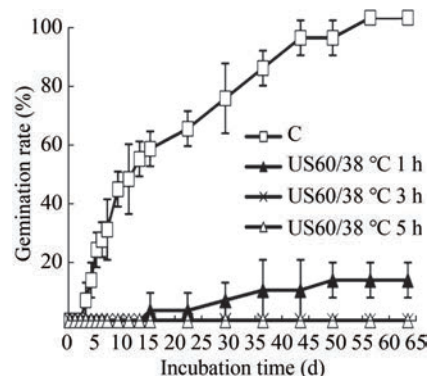


(b) Treatment on cypsts in sediment

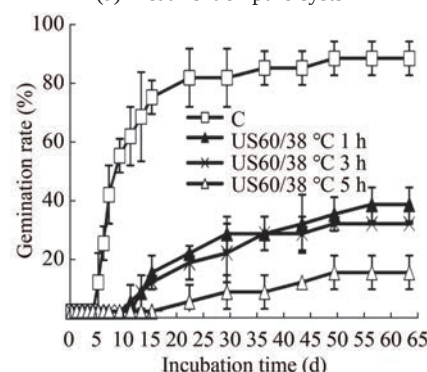
Figure 22 Accumulative germination rate of cypsts of *Scrippsiella trochoidea* after treatment by ultrasound (US, 40 kHz) (Wang et al., 2018b)

ters but also harmful to the surrounding environment and machinery. Therefore, from this viewpoint, ultrasonic cleaning using smaller quantities of less corrosive solvents is superior to traditional cleaning methods. Nguyen et al. compared the cleaning effect of two solvents under ultrasonic treatment using the pressure drop method (Nguyen et al., 2016). They discovered that the ultrasonic cleaning effect was superior when the filter oil was industrial kerosene KO as opposed to diesel DO. In addition, they found a significant relationship between solvent temperature, filter pressure loss, and ultrasonic treatment time (Figure 25). Moreover, the pressure drop decreased significantly (by more than 300 Pa) when the filter was cleaned manually and then ultrasonically, and the optimal ultrasonic cleaning time for the filter was approximately 60 min. Thus, this research demonstrates the commercial viability of ultrasonic filter cleaning.

Waste mineral oil and oil sludge produced by shipyards during ship disassembly and maintenance, oil pipeline failure or oil spill caused by tanker dumping at will, and crude oil-contaminated sand produced during offshore oil and gas production are all highly susceptible to oil spill accidents due to their high mobility, causing severe damage to the environment, nature, and all forms of life, including humans. Numerous methods of oil sand cleaning are available, but most of these methods are limited by costly



(a) Treatment on pure cypsts



(b) Treatment on cypsts in sediment

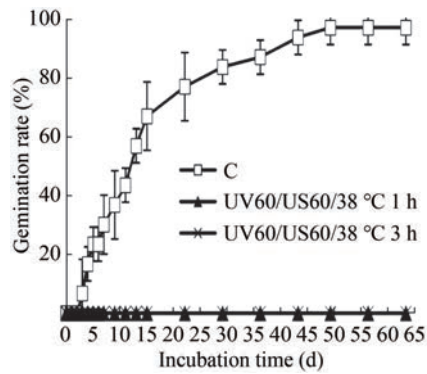
Figure 23 Accumulative germination rate of cypsts of *Scrippsiella trochoidea* after the combined treatments by ultrasound (US) and heating (38°C) (Wang et al., 2018b)

chemical solvents, high energy consumption, and harmful effects on animals and plants. Ultrasonic energy is an established method for cleaning oil sand. Mud and sand are cleansed of oil using ultrasonic cavitation. No chemical agents are added throughout the entire treatment process. In a time of increasing environmental degradation and stringent regulations, ultrasonic cleaning is becoming popular as a treatment option.

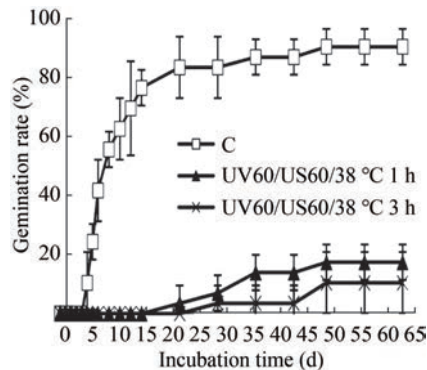
Kim and Wang (2003) and Manson et al. (2004) published the earliest studies on oil separation from soil or sand using ultrasonic energy. Abramov et al. (2009a, 2009b) studied the impact of temperature and ultrasonic power on the degree of oil–sand separation and discovered that the separation rate of oil from sand was low for less viscous oil, and the rate of oil removal was slow for small sand particles.

A study conducted by Hu et al. (2014) revealed that treating sand-containing sludge at room temperature with 75 W of ultrasonic energy recovered 60% of the oil within 6 min and reduced the salt content. Zhang et al. (2019) used ultrasonic equipment with a power of 45 W and a frequency of 40 kHz at a temperature of 55°C to treat sludge at the bottom of an oil tank for 15 min. Their results demonstrated that the ultrasonic method could successfully extract oil and grease components from the oil-bearing sludge.

Mat-Shayuti et al. (2021) treated samples of crude oil-



(a) Treatment on pure cysts



(b) Treatment on cysts in sediment

Figure 24 Accumulative gemination rate of cysts of *Scrippsiella trochoidea* after the combined treatments by ultraviolet (UV), ultrasound (US), and heating (Wang et al., 2018b)

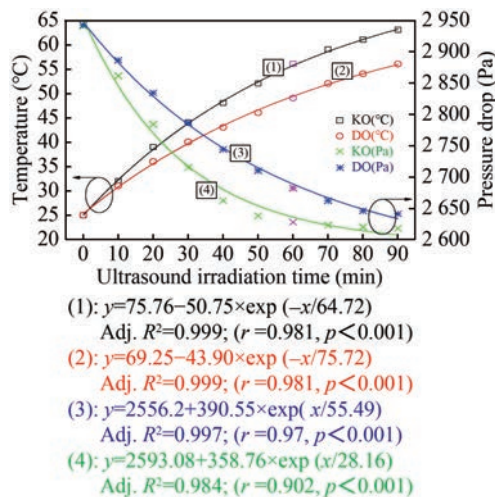


Figure 25 Variation of temperature and pressure drop over ultrasound irradiation time (Nguyen et al., 2016)

contaminated beach sand and offshore well output sand for 10 min at a power of 30–120 W, a frequency of 25–60 kHz, and a sand loading of 10–100 g to improve process efficiency. The effect of ultrasonic power, frequency, and load on the cleaning effect of crude oil-contaminated sand was investigated by ANOVA (Figure 26).

However, the effects and interactions of ultrasonic parameters and oil-contaminated sand are not well under-

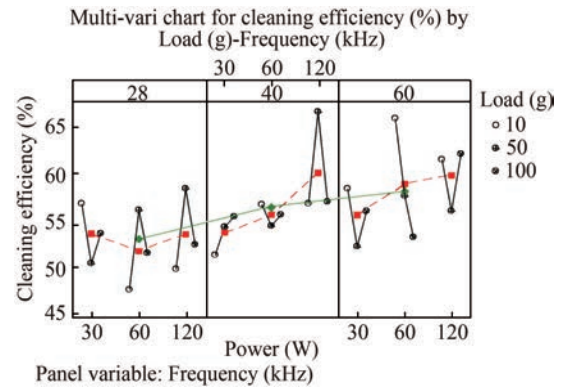


Figure 26 Multi-vari chart of cleaning efficiency for the reference sand (Mat-Shayuti et al., 2021)

stood. Zhao et al. (2021) studied the effect of cavitation microjets on oil droplet desorption. The adsorption state of oil droplets in oil stains was investigated using microscopy. The generation of microjets during the collapse of bubbles near a rigid wall was investigated at varying acoustic pressure amplitudes. The results demonstrated that the acoustic pressure had a large effect on the microjet velocity, and the initial diameter of the cavitation bubble had a significant effect on the microjet cross-sectional area. Moreover, the microjet was the most influential factor in the removal of desorbed stripped oil droplets. Thus, the microjet produced by cavitation bubbles with a small initial diameter (0.1 mm) is better suited for stripping oil droplets from narrow or acute angle gaps.

Ultrasonic cavitation has promising application potential in the treatment of oily sludge, but not all treatments can achieve the desired effect. For treatment standards requiring less than or equal to 3% oily sludge, ultrasonic cavitation must be further investigated in conjunction with other processes to improve crude oil extraction.

Jin et al. (2012) utilized an ultrasonic cavitation-assisted extraction method to treat oil sludge generated by oil tankers. The oil sludge content was reduced from 51.74% prior to treatment to 1.25% at a constant temperature of 55°C, a power of 150 W, and a frequency of 28 kHz. The 15 min use of ultrasonic equipment on oil sludge resulted in a crude oil recovery rate of 97.58%, achieving the optimal pretreatment. The oil content of the sludge was reduced from 51.74% prior to treatment to 1.25% after treatment, and the crude oil recovery rate was 97.5%, achieving the optimal pretreatment effect.

Using samples from an Austrian oil field, Xu et al. (2017) discovered that ultrasonic treatment alone could separate 88% of the oil from the contaminated sand. Their results agree with Son et al. (2012) revealing that cleaning efficiency increased to 99.5% when ultrasonic energy was combined with mechanical agitation.

Mullakaev et al. (2018) developed a sonochemical technology using ultrasonic equipment for separating oil sludge or oil-contaminated soil and performed at an industrial fa-

cility (Figure 27). The experiments indicated that the separation efficiency is increased by adding several alkaline reagents into a working solution. For example, when Na_2SO_3 is used, achieving an almost complete recovery of bitumen (up to 95%) from oil sand after 20–40 min at 70–

75°C is possible. They also found that introducing an ultrasonic probe into the reactor significantly improved the recovery intensity of petroleum products compared to an ultrasonic bath.

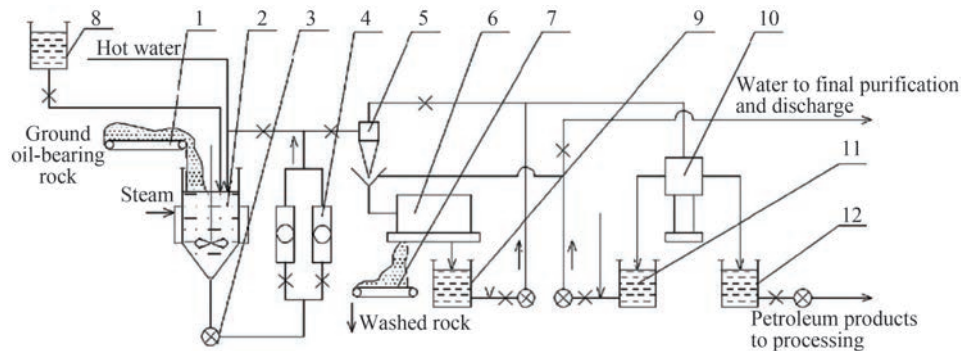


Figure 27 Flow diagram for processing oil-containing soil using ultrasonic equipment: 1–conveyor for oil-bearing rock, 2–mixer, 3–pumping unit, 4–ultrasonic reactor, 5–hydrocyclone, 6–centrifuge, 7–conveyor for washed rock, 8–tank for a chemical agent, 9–collector for washing centrifuge concentrate, 10–separator, 11–collector for treated water, and 12–collector for petroleum products (Mullakaev et al., 2018)

4 Summary

Ultrasonic cleaning is an advanced and effective cleaning method that uses ultrasonic cavitation to remove dirt. This method has promising application prospects in ship and marine engineering. In comparison to traditional chemical, physical, and electrochemical cleaning methods, ultrasonic cleaning has a superior cleaning effect and does not cause secondary pollution. Ultrasonic cleaning can clean and decontaminate all aspects of a structure, regardless of surface size, shape, or complexity. Thus, decontamination via ultrasonic cleaning includes everything from small precision components to large ships and submarines. However, ultrasonic cleaning in ship and marine engineering is still in its infancy. The following limitations are encountered in the research of the aforementioned academics:

1) Experimentation on acoustic parameters is conducted arbitrarily. Finding the acoustic performance parameters, such as frequency, sound intensity, and amplitude, in these experiments is easy, which are highly arbitrary and likely to be displaced from the optimum.

2) No unified standard for measuring the efficacy of ultrasonic cleaning is available. Some scholars believe that the acoustic cavitation signal can be used to evaluate ultrasonic cleaning efficiency (Uchida, 2021). The ultrasonic cleaning effect is affected by a variety of factors, and no clear relationship with the washing effect of a unified standard evaluation method exists. Thus, assessing the efficiency of various ultrasonic cleaning experiments is difficult. Consequently, the majority of studies are determined by comparing the level of dirt before and after an experiment or by converting the amount of dirt stripped into quantitative

estimates. This strategy is detrimental to the commercialization of ultrasonic cleaning devices.

3) Minimal research has been conducted on the effect of ultrasonic transducer placement. The studies discussed above did not mention the multifrequency or multi-array transducer cleaning effect. Therefore, the arrangement of transducer placement or the development of multifrequency ultrasonic instruments to improve cleaning efficiency is also one of the urgent issues to be resolved.

4) Research on the influence of specific working conditions and other factors on the ultrasonic cleaning effect is also limited. Take the ultrasonic cleaning pipeline as an example. Some scholars found (Liu et al., 2021) that the influential factors of the cleaning effect mainly include fluid properties, pipe shape and size, and ultrasonic parameters. Therefore, the influence of external factors on the cleaning effect must be further studied.

5) Avoidance of surface erosion of structures due to ultrasonic cavitation is less explored. Additional research into the erosion effect of ultrasonic cavitation on structural surfaces is required to commercialize ultrasonic cleaning. The current research focused on cleaning, while the impact of erosion on the cleaning surface has not been adequately explored.

6) The above experiments demonstrated that the cleaning effect and efficiency are improved when ultrasonic treatment is combined with other decontamination and antifouling methods. Future research should investigate the cleaning effect of ultrasound in conjunction with a variety of treatment techniques.

7) The lack of selectivity of ultrasonic cleaning agents, the corrosiveness of the cleaning fluid to the structure, and

the quality monitoring of the cleaning fluid during the cleaning process deserve further investigation. However, most of the current ultrasonic cleaning research using water as a cleaning agent lacks selectivity. Thus, researchers should attempt to develop multi-enzyme cleaning agents from an environmental protection perspective to achieve an enhanced cleaning effect.

8) The noise produced by ultrasonic equipment may negatively impact marine animals. A study indicated that marine mammals show behavioral disorders when exposed to noise above 230 dB for 24 h (Trickey et al., 2022). In addition, the high intensity noise may harm the hearing of marine organisms or even cause the risk of death. Thus, follow-up research examining the cleaning effect should consider the potential harm caused by ultrasonic to protect the environment.

Overall, ultrasonic cavitation has significant growth potential in ship and marine engineering. However, limited large-scale equipment, external factors that affect cleaning, and other problems still exist. Thus, the application of ultrasonic cavitation in ship and marine engineering will be improved and expanded through continuous investigations and experiments to compensate for the shortcomings of previous achievements, and its contribution to human development will be achieved.

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References

- Abedini M, Hanke S, Reuter F (2023) In situ measurement of cavitation damage from single bubble collapse using high-speed chronoamperometry. *Ultrasonics Sonochemistry* 92: 106272. DOI: 10.1016/j.ultsonch.2022.106272
- Abramov OV, Abramov VO, Myasnikov SK, Mullakaev MS (2009a) Extraction of bitumen, crude oil and its products from tar sand and contaminated sandy soil under effect of ultrasound. *Ultrasonics Sonochemistry* 16(3): 408-416. DOI: 10.1016/j.ultsonch.2008.10.002
- Abramov OV, Abramov VO, Myasnikov SK, Mullakaev MS (2009b) Ultrasonic technologies for extracting oil products from oil-bearing sands and contaminated soils. *Theoretical Foundations of Chemical Engineering* 43(4): 504-510. DOI: 10.1134/s0040579509040265
- Agi A, Junin R, Yahya A, Gbadamosi A, Abbas A (2018) Comparative study of continuous and intermittent ultrasonic ultrafiltration membrane for treatment of synthetic produced water containing emulsion. *Chemical Engineering and Processing-Process Intensification* 132: 137-147. DOI: 10.1016/j.cep.2018.08.016
- Alenyorege EA, Ma H, Aheto JH, Agyekum AA, Zhou C (2020) Effect of sequential multi-frequency ultrasound washing processes on quality attributes and volatile compounds profiling of fresh-cut Chinese cabbage. *LWT-Food Science and Technology* 117: 108666. DOI: 10.1016/j.lwt.2019.108666
- Bott TR (2000) Biofouling control with ultrasound. *Heat Transfer Engineering* 21(3): 43-49. DOI: 10.1080/014576300270898
- Didenko YT, Suslick KS (2002) The energy efficiency of formation of photons, radicals and ions during single-bubble cavitation. *Nature* 418(6896): 394-397. DOI: 10.1038/nature00895
- Fatyukhin DS, Nigmatzyanov RI, Prikhodko VM, Sukhov AV, Sundukov SK (2022) A comparison of the effects of ultrasonic cavitation on the surfaces of 45 and 40Kh steels. *Metals* 12(1): 138. DOI: 10.3390/met12010138
- Feng R (2003) Ultrasonic cavitation and ultrasound therapy. *Nature Magazine* 25(6): 311-314. (in Chinese)
- Feng R, Huang JL (1994) Ultrasonic cleaning and its physical mechanism. *Application Acoustics* 13(1): 42-47. (in Chinese)
- Flynn H, Church CC (1984) A mechanism for the generation of cavitation maxima by pulsed ultrasound. *The Journal of the Acoustical Society of America* 76(2): 505-512. DOI: 10.1121/1.391592
- Gavand MR, McClintock JB, Amsler CD, Peters RW, Angus, RA (2007) Effects of sonication and advanced chemical oxidants on the unicellular green alga *Dunaliella tertiolecta* and cysts, larvae and adults of the brine shrimp *Artemia salina*: A prospective treatment to eradicate invasive organisms from ballast water. *Marine Pollution Bulletin* 54(11): 1777-1788. DOI: 10.1016/j.marpolbul.2007.07.012
- Gogate PR, Pandit AB (2001) Hydrodynamic cavitation reactors: a state of the art review. *Reviews in Chemical Engineering* 17(1): 1-85
- Goldsmith J, Archambault P, Chust G, Villarino E, Liu G, Lukovich JV, Barber DG, Howland KL (2018) Projecting present and future habitat suitability of ship-mediated aquatic invasive species in the Canadian Arctic. *Biological Invasions* 20(2): 501-517. DOI: 10.1007/s10530-017-1553-7
- Guo S, Khoo BC, Teo SLM, Zhong S, Lim CT, Lee HP (2014) Effect of ultrasound on cyprid footprint and juvenile barnacle adhesion on a fouling release material. *Colloids and Surfaces B-Biointerfaces* 115: 118-124. DOI: 10.1016/j.colsurfb.2013.11.020
- Guo S, Lee HP, Khoo BC (2011) Inhibitory effect of ultrasound on barnacle (*Amphibalanus amphitrite*) cyprid settlement. *Journal of Experimental Marine Biology and Ecology* 409(1-2): 253-258. DOI: 10.1016/j.jembe.2011.09.006
- Holm ER, Stamper DM, Brizzolara RA, Barnes L, Deamer N, Burkholder JM (2008) Sonication of bacteria, phytoplankton and zooplankton: Application to treatment of ballast water.

- Marine Pollution Bulletin 56(6): 1201-1208. DOI: 10.1016/j.marpolbul.2008.02.007
- Hu GJ, Li JB, Thring RW, Arocena J (2014) Ultrasonic oil recovery and salt removal from refinery tank bottom sludge. *Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering* 49(12): 1425-1435. DOI: 10.1080/10934529.2014.928556
- Jin Y, Chu X, Zheng X, Chi Y, Yan J (2012) Experimental study on ultrasound assisted extraction of crude oil from oil sludge. *Journal of Zhejiang University. Engineering Science* 46(12): 2178-2183
- Joyce EM, Wu XG, Mason TJ (2010) Effect of ultrasonic frequency and power on algae suspensions. *Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering* 45(7): 863-866. DOI: 10.1080/10934521003709065
- Keller JB, Miksis M (1980) Bubble oscillations of large-amplitude. *Journal of the Acoustical Society of America* 68(2): 628-633. DOI: 10.1121/1.384720
- Kim YU, Wang MC (2003) Effect of ultrasound on oil removal from soils. *Ultrasonics* 41(7): 539-542. DOI: 10.1016/s0041-624x(03)00168-9
- Kitamura H, Takahashi K, Kanamaru D (1995) Inhibitory effect of ultrasonic waves on the larval settlement of the barnacle, *Balanus amphitrite* in the laboratory. *Marine Fouling* 12(1): 9-13
- Lais H, Lowe PS, Gan TH, Wrobel LC (2018) Numerical modelling of acoustic pressure fields to optimize the ultrasonic cleaning technique for cylinders. *Ultrasonics Sonochemistry* 45: 7-16. DOI: 10.1016/j.ultrasonch.2018.02.045
- Laksono FB, Majid D, Prabowo AR (2022) System and eco-material design based on slow-release ferrate (VI) combined with ultrasound for ballast water treatment. *Open Engineering* 12(1): 401-408. DOI: 10.1515/eng-2022-0042
- Lee TJ, Nakano K, Matsumura M (2001) Ultrasonic irradiation for blue-green algae bloom control. *Environmental Technology* 22(4), 383-390. DOI: 10.1080/0959332208618270
- Leong T, Collis J, Manasseh R, Ooi A, Novell A, Bouakaz A, Ashokkumar M, Kentish S (2011) The role of surfactant headgroup, chain length, and cavitation microstreaming on the growth of bubbles by rectified diffusion. *The Journal of Physical Chemistry C* 115(49): 24310-24316
- Lezzi A, Prosperetti A (1987) Bubble dynamics in a compressible liquid. Part 2. 2nd-order theory. *Journal of Fluid Mechanics* 185: 289-321. DOI: 10.1017/s0022112087003185
- Liao H, Wang Y (2020) Effect of cleaning loaner instrument with medical vacuum ultrasonic cleaner. *Chinese Journal of Medical Physics* 37(2): 254-256
- Liu H, Chen Y, Hu J (2021) Study on the application of automatic cleaning technology of the inner wall of pipeline. *Journal of Physics: Conference Series* 1820(1): 012194. DOI: 10.1088/1742-6596/1820/1/012194
- Ma BZ, Chen YF, Hao HW, Wu MS, Wang B, Lv HG, Zhang GM (2005) Influence of ultrasonic field on microcystins produced by bloom-forming algae. *Colloids and Surfaces B-Biointerfaces* 41(2-3): 197-201. DOI: 10.1016/j.colsurfb.2004.12.010
- Ma XJ, Xing TY, Huang B, Li QH, Yang YF (2018) Combined experimental and theoretical investigation of the gas bubble motion in an acoustic field. *Ultrasonics Sonochemistry* 40: 480-487. DOI: 10.1016/j.ultrasonch.2017.07.035
- Marbuah G, Gren I-M, McKie B (2014) Economics of harmful invasive species: a review. *Diversity* 6(3): 500-523
- Mason TJ (2016) Ultrasonic cleaning: An historical perspective. *Ultrasonics Sonochemistry* 29: 519-523. DOI: 10.1016/j.ultrasonch.2015.05.004
- Mason TJ, Collings A, Sumel A (2004) Sonic and ultrasonic removal of chemical contaminants from soil in the laboratory and on a large scale. *Ultrasonics Sonochemistry* 11(3-4): 205-210. DOI: 10.1016/j.ultrasonch.2004.01.025
- Mat-Shayuti MS, Tuan Ya TMYS, Abdullah MZ, Othman NH, Alias NH (2021) Exploring the effect of ultrasonic power, frequency, and load toward remediation of oil-contaminated beach and oilfield sands using ANOVA. *Environmental Science and Pollution Research* 28(41): 58081-58091. DOI: 10.1007/s11356-021-14776-8
- Mat-Shayuti MS, Tuan Ya TTMYS, Abdullah MZ, Megat Khamaruddin PNF, Othman NH (2019) Progress in ultrasonic oil-contaminated sand cleaning: a fundamental review. *Environmental Science and Pollution Research* 26: 26419-26438
- Mazue G, Viennet R, Hihn JY, Carpentier L, Devidal P, Albaina I (2011) Large-scale ultrasonic cleaning system: Design of a multi-transducer device for boat cleaning (20 kHz). *Ultrasonics Sonochemistry* 18(4): 895-900. DOI: 10.1016/j.ultrasonch.2010.11.021
- Mullakaev MS, Vexler GB, Mullakaev RM (2018) Sonochemical technology for separating oil sludge and oil-contaminated soil. *Petroleum Science and Technology* 36(8): 604-608. DOI: 10.1080/10916466.2018.1440297
- Nguyen DD, Ngo HH, Yoon YS, Chang SW, Hong HB (2016) A new approach involving a multi transducer ultrasonic system for cleaning turbine engines' oil filters under practical conditions. *Ultrasonics* 71: 256-263. DOI: 10.1016/j.ultrasonch.2016.07.001
- Osman H, Lim F, Lucas M (2017) Vibration response of a high-power compact large-area ultrasonic resonator. *The IEEE International Ultrasonics Symposium (IUS)*, Washington, DC
- Osman H, Lim F, Lucas M, Balasubramaniam P (2016) Development of an ultrasonic resonator for ballast water disinfection. *The 45th Annual Symposium of the Ultrasonic-Industry-Association*, Seattle
- Park JS, Lee JH (2018) Sea-trial verification of ultrasonic antifouling control. *Biofouling* 34(1): 98-110. DOI: 10.1080/08927014.2017.1409347
- Plesset MS (1949) The dynamics of cavitation bubbles. *Journal of Applied Mechanics-Transactions of the ASME* 16(3): 277-282
- Rayleigh L (1917) On the pressure developed in a liquid during the collapse of a spherical cavity. *Philosophical Magazine* 34(199-04): 94-98. DOI: 10.1080/14786440808635681
- Salimi M, Livadas M, Teyeb A, El Masri E, Gan T-H (2023) Biofouling removal using a novel electronic system for driving an array of high power marinised transducers. *Applied Sciences-Basel* 13(6): 3749. DOI: 10.3390/app13063749
- Salters B, Piola R (2017) UVC light for antifouling. *Marine Technology Society Journal* 51(2): 59-70. DOI: 10.4031/mts.j.51.2.10
- Scherba G, Weigel RM, O'Brien WD (1991) Quantitative assessment of the germicidal efficacy of ultrasonic energy. *Applied and Environmental Microbiology* 57(7): 2079-2084. DOI: 10.1128/aem.57.7.2079-2084.1991
- Schultz MP, Bendick JA, Holm ER, Hertel WM (2011) Economic impact of biofouling on a naval surface ship. *Biofouling* 27(1): 87-98. DOI: 10.1080/08927014.2010.542809
- Seth N, Chakravarty P, Khandeparker L, Anil AC, Pandit AB (2010) Quantification of the energy required for the destruction of *Balanus amphitrite* larva by ultrasonic treatment. *Journal of the Marine Biological Association of the United Kingdom* 90(7): 1475-1482. DOI: 10.1017/s0025315409991548
- Son Y, Nam S, Ashokkumar M, Khim J (2012) Comparison of energy consumptions between ultrasonic, mechanical, and combined soil washing processes. *Ultrasonics Sonochemistry* 19(3): 395-398.

- DOI: 10.1016/j.ultsonch.2011.11.002
- Song CH, Cui WC (2020) Review of underwater ship hull cleaning technologies. *Journal of Marine Science and Application* 19(3): 415-429. DOI: 10.1007/s11804-020-00157-z
- Suslick KS (1990) Sonochemistry. *Science* 247(4949): 1439-1445
- Suslick KS, Hammerton DA, Cline RE (1986) Sonochemical hot spot. *Journal of the American Chemical Society* 108(18): 5641-5642
- Tian L, Zhang YX, Yin JY, Lv L, Zhang JY, Zhu JJ (2023) Study on the liquid jet and shock wave produced by a near-wall cavitation bubble containing a small amount of non-condensable gas. *International Communications in Heat and Mass Transfer* 145: 106815. DOI: 10.1016/j.icheatmasstransfer.2023.106815
- Trickey JS, Cardenas-Hinojosa G, Rojas-Bracho L, Schorr GS, Rone BK, Hidalgo-Pla E, Rice A, Baumann-Pickering S (2022) Ultrasonic antifouling devices negatively impact Cuvier's beaked whales near Guadalupe Island, Mexico. *Communications Biology* 5(1): 1005. DOI: 10.1038/s42003-022-03959-9
- Uchida T (2021) Quantitative evaluation of ultrasonic cleaning ability using acoustic cavitation signal. *Japanese Journal of Applied Physics* 60(SD): SDDD04. DOI: 10.35848/1347-4065/abec5d
- Wang W, Li WH, Song LY, Fan WJ, Liu XJ, Zheng HB (2018a) Numerical simulation and re-design optimization of impressed current cathodic protection for an offshore platform with biofouling in seawater. *Materials and Corrosion-Werkstoffe Und Korrosion* 69(2): 239-250. DOI: 10.1002/maco.201709685
- Wang ZH, Liang WB, Guo X, Liu L (2018b) Inactivation of *Scrippsiella trochoidea* cysts by different physical and chemical methods: Application to the treatment of ballast water. *Marine Pollution Bulletin* 126: 150-158. DOI: 10.1016/j.marpolbul.2017.11.002
- Xu Y, Langbauer C, Hofstaetter H (2017) The application of ultrasonic technology for cleaning oil contaminated sand. The SPE Asia Pacific Health, Safety, Security, Environment and Social Responsibility Conference, SPE-185261-MS
- Xue X (2022) Study on polyvinylidene fluoride ultrafiltration membrane for wastewater treatment by ultrasonic cleaning. The International Conference on Optoelectronic Materials and Devices (ICOMD 2021)
- Yan H, Yin Q, Peng J, Bai B (2018). Multi-functional tugboat for monitoring and cleaning bottom fouling. The 4th International Conference on Advances in Energy Resources and Environment Engineering (ICAEESEE), Chengdu
- Yu Y, Mahmud M, Vyas N, Smith WR, Wang Q, Walmsley AD (2022) Cavitation in a periodontal pocket by an ultrasonic dental scaler: A numerical investigation. *Ultrasonics Sonochemistry* 90(8): 106178. DOI: 10.1016/j.ultsonch.2022.106178
- Zhang AM, Li SM, Cui P, Li S, Liu YL (2023) A unified theory for bubble dynamics. *Physics of Fluids* 35(3): 033323. DOI: 10.1063/5.0145415
- Zhang GH, Liu SX, Qin QL (2017) The antifouling of ACLW-CAR based on ultrasonic cleaner. The 3rd Annual International Workshop on Materials Science and Engineering (IWMSE), Guangzhou
- Zhang HF, Lu ZB, Zhang PH, Gu JY, Luo CH, Tong YQ, Ren XD (2021) Experimental and numerical investigation of bubble oscillation and jet impact near a solid boundary. *Optics and Laser Technology* 138(7): 106606. DOI: 10.1016/j.optlastec.2020.106606
- Zhang XD, Gao LJ, Xu S, Yang JH (2019) Ultrasonic treatment of oil-bearing sludge indoor experimental analysis. *Journal of Petroleum and Petrochemical Energy Conservation* 9(1): 5-8. (in Chinese)
- Zhang Y, Wang LL, Liu DX, Ma YW, Ma HJ (2014) Analysis of the effect of ultrasonic cleaning machine on the cleaning of the speculum. *Chinese Journal of Disinfection* 31(9): 1021-1022. (in Chinese)
- Zhao F, Yan Q, Cheng D (2021) Numerical study on the desorption processes of oil droplets inside oil-contaminated sand under cavitation micro-jets. *Ultrasonics Sonochemistry* 78(2): 105745. DOI: 10.1016/j.ultsonch.2021.105745
- Zhong X, Dong JM, Liu MS, Meng RX, Li S, Pan XX (2022) Experimental study on ship fouling cleaning by ultrasonic-enhanced submerged cavitation jet: A preliminary study. *Ocean Engineering* 258(1): 111844. DOI: 10.1016/j.oceaneng.2022.111844
- Zwaschka TA, Ahn JS, Cunitz BW, Bailey MR, Dunmire B, Sorensen MD, Harper JD, Maxwell AD (2018) Combined burst wave lithotripsy and ultrasonic propulsion for improved urinary stone fragmentation. *Journal of Endourology* 32(4): 344-349. DOI: 10.1089/end.2017.0675