

High-power ultrasound transducer for mitigating biofouling in subaquatic structures from the oil and gas industry

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Abstract: Biofouling, the accumulation of aquatic organisms on submerged structures, poses significant challenges to offshore operations by obstructing water flow and accelerating corrosion. Traditional mitigation methods are often environmentally harmful and demand frequent maintenance. This study explores the use of high-power ultrasound transducers as an eco-friendly solution for biofouling prevention in sea subaquatic structures. Numerical simulations and field experimental tests were performed. Results showed effective biofouling mitigation through ultrasonic pressure and microvibrations on the sea chest structures.

Keywords: Ultrasonic transducers, biofouling, acoustic cavitation, subaquatic structures

Introduction

Biological fouling, or biofouling, refers to the undesirable accumulation of organisms on artificial surfaces and structures immersed in water. This phenomenon poses a significant challenge to the marine industry, resulting in billions of dollars in annual maintenance costs and causing severe environmental impacts [1, 2]. This research and development project focuses on the study of biofouling on specific submerged marine structures, including sea chests and bell mouths.

In sea chests, the accumulation of fouling organisms can obstruct visibility and impede class inspection, requiring periodic cleaning by divers to allow proper access and evaluation. In bell mouths, biofouling, particularly the growth of barnacles on movable coupling components, can prevent the successful execution of riser pull-in operations, thereby compromising the interconnection between risers and the production unit. Consequently, pre-cleaning by divers becomes essential before such mechanical operations. Notably, no specific studies have been found addressing the growth dynamics of biofouling on these types of submerged structures.

Among the various fouling organisms, barnacles are of particular concern due to their size and tendency to colonize submerged surfaces in gregarious clusters. The barnacle life cycle includes six planktotrophic nauplius stages, a non-feeding cyprid larval stage, and a sessile adult stage. The cyprid stage is considered the most critical for biofouling control, as cyprids explore submerged surfaces to select settlement sites where metamorphosed barnacles will grow. Thus, deterring

or inhibiting cyprid settlement is a key strategy for barnacle biofouling prevention.

While biocidal antifouling coatings can be effective, their application is increasingly restricted or banned due to environmental concerns. One promising antifouling alternative is the use of ultrasound to prevent biofouling. The propagation of high-power ultrasonic waves in liquids and biological tissues can induce biological changes through thermal and non-thermal effects. In this study, thermal effects were not considered, as no temperature increase was detected during the experiments. Non-thermal effects are primarily attributed to ultrasonic pressure waves, acoustic cavitation, or a combination of both [3, 4].

Ultrasonic cavitation involves the formation, growth, and collapse of vapor or gas bubbles, which can be either stable or transient [2, 5]. In the context of biofouling, cavitation has been reported as the primary mechanism responsible for inhibiting bacterial growth, removing algae, and disrupting biofilms [3, 6, 7]. However, cavitation is influenced by several factors, including dissolved gas content, hydrostatic pressure, ambient temperature, liquid viscosity, ultrasound frequency, and acoustic intensity. Cavitation only occurs when the threshold energy level is reached, and studies have shown that degassed conditions require higher ultrasonic energy to initiate cavitation.

The use of ultrasonic waves has demonstrated promising results for the control of marine biofouling, particularly that induced by barnacles. For instance, [8] used ultrasound-induced cavitation to eliminate barnacle nauplii during ballast water treatment, while [9] re-

ported the inhibition of cyprid settlement, alterations in exploratory behavior, and reduced size of newly metamorphosed barnacles under ultrasonic exposure.

This work combined numerical simulations and experimental field tests to investigate a biocide-free strategy for the prevention of marine biofouling. To validate our work, a sea chest miniature structure was constructed to allow the coupling of Langevin-type ultrasonic transducers for the generation of acoustic cavitation. Field experiments were conducted in a seawater environment at Ubatuba Beach, Brazil, where the structures were deployed under real marine conditions. The preliminary results indicate that the ultrasonic system is capable of effectively preventing biofouling, particularly by barnacles, during 30 days of exposure. These findings suggest that ultrasonic cavitation may offer a promising approach for short-term biofouling mitigation on submerged structures.

Methodology

This study was divided into two main stages: numerical simulations, in which the entire ultrasonic system was designed, and field experiments, which involved the construction of sample structures, deployment at experimental sites, and evaluation of the effectiveness of ultrasound in preventing biofouling.

The design of the ultrasonic transducers was carried out through numerical simulations using the COMSOL Multiphysics software. Each transducer consists of four PZT-8 piezoelectric ceramic discs sandwiched between two metallic masses made of 7075 aluminum alloy, and mechanically clamped using a high-strength central bolt. These transducers operate as half-wavelength resonators, meaning that the overall length of the device is determined based on the acoustic wavelength in aluminum at the operating frequency. For the intended frequency, the wavelength in aluminum is approximately 300 mm, which was used as a reference for estimating the transducer's dimensions.

The numerical modeling was performed using a 2D axisymmetric geometry, employing the solid mechanics and electrostatics modules. The analyses were conducted in the frequency domain to identify the resonance frequency of the transducer assembly. To characterize the vibrational behavior of the device, simulations were used to generate electrical impedance and mechanical displacement plots. After the simulation and analysis of the transducer's resonance, a detailed technical drawing of each component was prepared to guide the fabrication of the parts. Fig. ?? shows a schematic representation of the transducer model and a photograph of the built transducers.

The field experiments were conducted at the Oceanographic Institute of the University of São Paulo,



Fig. 1: Illustration of the fabricated sea chest used in the experimental field tests.

located in Ubatuba. In Ubatuba, electrical and structural installations were carried out to support the experiments, which involved the submersion of sea chest models equipped with ultrasonic transducers beneath a floating pier.

Scaled-down model of the sea chest structure was fabricated and deployed under real marine conditions. A scaled-down model of the sea chest structure was fabricated, as illustrated in Fig. 1. Two units were fabricated: one to serve as the control (without ultrasound), and the other equipped with the ultrasonic system. The coating process for these marine structures was carried out on both sides of the steel plate using abrasive blasting to near-white metal, in accordance with the ISO 8501-1 standard, achieving an anchor profile between $80\ \mu\text{m}$ and $100\ \mu\text{m}$. Next, the protective coating was applied to both sides of the plate. The procedure consisted of two coats of PETROBRAS N-2680 paint, with a minimum dry film thickness (DFT) of $150\ \mu\text{m}$, followed by a single coat of PETROBRAS N-2677, with a minimum DFT of $70\ \mu\text{m}$.

After assembly, the sea chest structures were transported to the pier, where the installation of the ultrasonic transducers and functionality tests were initiated. Eight holes were drilled on the face of each sea chest to accommodate the transducers, resulting in the installation of eight transducer units per structure. The transducers were designed and constructed to operate at a frequency of 21 kHz, and each unit was supplied with an electrical power of approximately 250 W. The structures were submerged in the sea at a depth of approximately 1 meter, with the grated face oriented toward the sunrise. Fig. 2 shows an image of the transducer installation process on the sea chest structures.

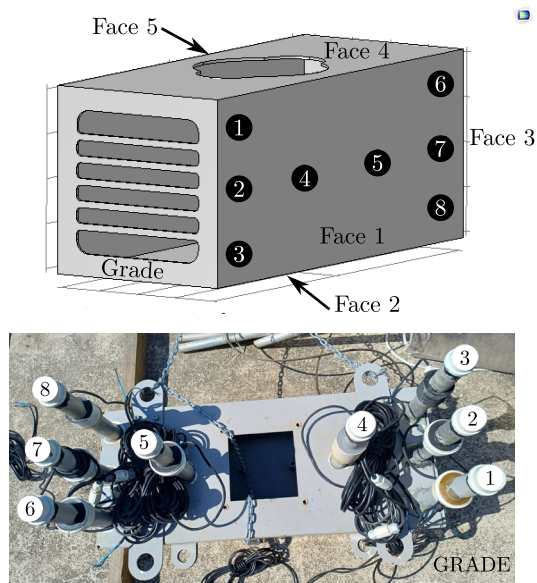


Fig. 2: Installation process of ultrasonic transducers in the sea chest structure, illustrating the transducer arrangement.

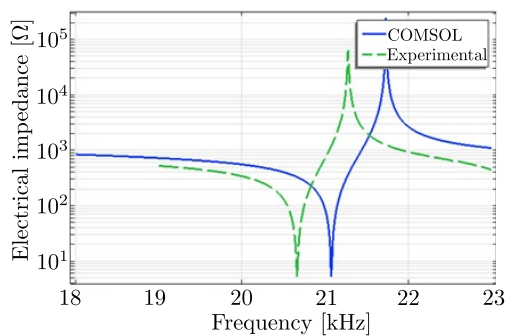


Fig. 3: Comparison between simulated and experimentally measured electrical impedance curves for the ultrasonic transducer.

Results

Before conducting the biofouling prevention tests on the sea chest structures, it was necessary to experimentally characterize the transducer designed through numerical simulations. The transducers were assembled, and their electrical impedance curves were measured under laboratory conditions. The experimental results were compared to the simulated impedance curves to validate the numerical model. Fig. 3 presents this comparison, showing good agreement between the numerical and experimental results. The minor discrepancies observed between the curves are attributed to variations in material properties used in the simulation model.

After the transducers were characterized, tests were initiated to evaluate the use of ultrasound for biofoul-

Position	Signal	Pressure
Grade	10 Vpp	380 kPa
Face 1	20 Vpp	760 kPa
Face 2	8 Vpp	304 kPa
Face 3	12 Vpp	456 kPa
Face 4	15 Vpp	570 kPa
Face 5	5 Vpp	190 kPa

Tab. 1: Acoustic measurement data at different positions inside the sea chest.

ing prevention in the sea chest structure. Although eight transducers were mounted, only four units were excited during the experiment, each powered at an average electrical power of 250 W. The remaining transducers were installed as backups, intended to replace any units that might become damaged or non-functional during testing. For this experimental campaign, transducers 1, 2, 3, and 7 were activated.

The acoustic pressure inside the sea chest was measured using a calibrated hydrophone (model: Brüel & Kjær). Table 1 presents the pressure values measured at a central point on each internal face of the structure, representing an average position within the volume.

The field experiments were conducted through daily monitoring, using photographic records of each internal face of the submerged sea chests with and without ultrasonic treatment. The ultrasonic system was programmed to operate in cycles, activating the transducers for 10 minutes followed by 15 minutes off, continuously over a 30-day period. All regions on the inner surfaces of both the ultrasound-treated and control sea chests were selected to monitor biofouling development.

Figure 4 presents the evolution of biofouling on Face 3, located at the end of the sea chest, for both the control (without ultrasound) and the ultrasound-treated structure. After 30 days of submersion, the sea chest equipped with the ultrasonic system exhibited only a small amount of algal fouling, with no significant colonization by macrofouling organisms. In contrast, the control structure showed visible colonization by various microorganisms, including bryozoans and barnacles. The appearance of barnacle fouling was first observed on day 17, indicating the settlement phase of these organisms on the untreated surface. A similar pattern was observed on Face 5, as shown in Fig. 5.

Conclusion

The study demonstrated the feasibility and effectiveness of using high-power ultrasonic transducers to mitigate biofouling in subaquatic structures commonly

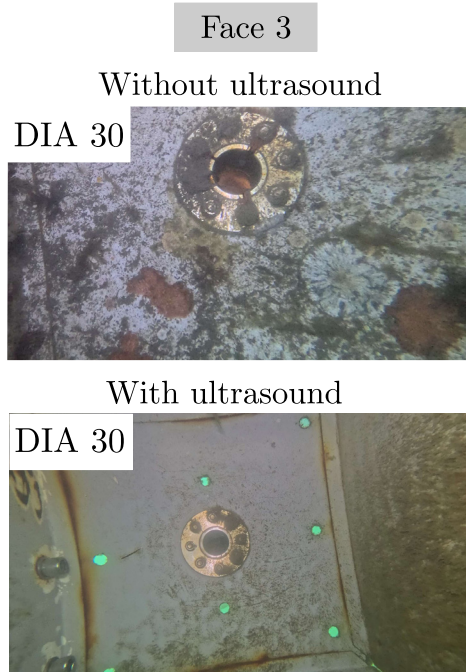


Fig. 4: Photographic comparison of biofouling evolution on Face 3 of the sea chest after 30 days of submersion, with (right) and without (left) ultrasound application

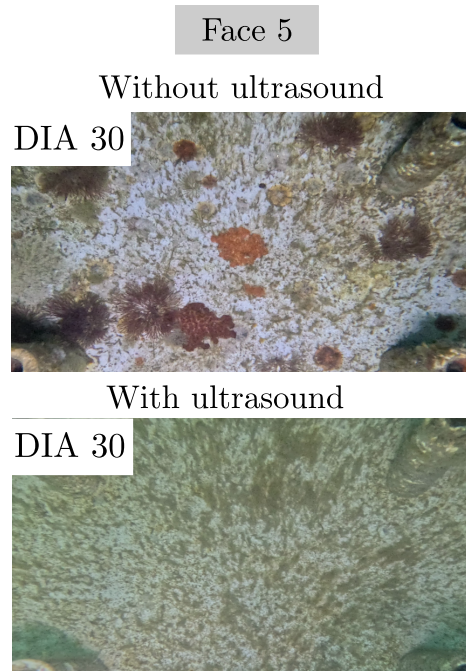


Fig. 5: Biofouling development on Face 5 of the sea chest under control conditions (without ultrasound) after 30 days, highlighting the presence of barnacles and bryozoans.

employed in the oil and gas industry, such as sea chests. Numerical simulations guided the design of half-wavelength Langevin transducers, which were validated experimentally through electrical impedance measurements. Field experiments conducted in a natural seawater environment revealed that the application of ultrasound significantly reduced biofouling, particularly the settlement of barnacles, when compared to control structures. After 30 days of exposure, the ultrasound-treated surfaces exhibited only minimal algal colonization, while control surfaces showed substantial fouling by macroorganisms

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