A methodology for removing biofouling of the hull based on ultrasonic guided waves

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Abstract. Marine biofouling is considered as the undesired growth and accumulation of biological organisms on the surface of materials submerged in seawater. Marine biofouling could increase the resistance and fuel consumption of ships. In this paper, a novel method for removing biofouling on ship hull based on cavitation effect and ultrasonic guided waves (UGWs) is proposed, which is eco-friendly and could remove biofouling online. The simulation model is established by finite element method to study the sound pressure distribution on the steel plate. The biofouling removal experiment is designed, which reveals that it is feasible to remove biofouling efficiently with UGWs.

1. Introduction
Biofouling on ship hulls needs to be removed in time, and it is inevitable for marine vessels in the sea to produce fouling on the surface of hull[1, 2]. Once the surface is immersed in water, a biofilm consisting principally of dissolved organic material will be formed[3]. Subsequently, microorganisms and marine invertebrates attached and propagated on the surface of ship hull. The extra energy consumption and great economic losses could be produced due to biological fouling[4]. Figure 1 shows the biofouling on the hull of Chinese aircraft carrier Liaoning.

The traditional fouling removal methods for ship hull mainly include abrasive blasting, the rotating brush, high-pressure water jet method. However these traditional methods have limitations. The sand blowing resulting from abrasive blasting could increase the risk of silicosis among cleaners[5]. The rotating brush might damage the antifouling paint while removing biofouling[6]. It is much likely to consume a large amount of clean water with high-pressure water Jet cleaning method, which results in the waste of resources.

Herein, a novel method for biofouling removal on ship hulls based on UGWs has been studied, which might get rid of the above limitations of traditional methods. The study reveals three main advantages of the proposed methodology: eco-friendly, non-destructive and the ability to large-scale remove biofouling online. This technique with broad development prospects could provide a reference for effective biofouling removal on ship hulls.

UGWs could realize long-distance propagation in solid medium. UGW is widely employed including but not limited to non-destructive testing for materials, however, it is less explored in biofouling removal. This paper presents the study of removing biofouling on the surface of steel plate
based on UGW and cavitation. Biofouling removal model is introduced in section 2. The experiment and result are described in section 3, and the conclusion is presented in section 4.

2. Biofouling removal model
The principle of descaling and the sound pressure model by finite element simulation are analyzed in this section.

2.1. Biofouling removal principle
The guided wave is a stress wave propagating in a finite medium and guided by the waveguide boundary\cite{7}. The main difference between bulk wave propagation and guided wave propagation is that guided wave propagation requires boundary. Due to the effect of medium boundary, the wave reflecting and mode conversion occur at medium boundary when UGWs propagate in the solid medium\cite{8}. Since ultrasonic guided waves belong to the mechanical wave, the attenuation and loss of wave energy are inevitable when ultrasonic guided waves are propagating in the medium. When the ultrasonic guided wave propagates in plate, the liquid provides a path for the energy of wave to leak from the layer of solid to liquid. The principle of biofouling removal method based on ultrasonic guided wave and cavitation are described in Figure 2.

Once the oscillating pressure field is deployed over the free surface of a liquid in a reservoir, if the oscillating amplitude is large enough, cavitation bubbles may appear in the liquid\cite{9}. The phenomenon that UGWs leak into liquid might cause cavitation effect. As shown in figure 3, the radius of bubbles increases under negative pressure and decreases under positive pressure during the oscillation of bubbles\cite{10}. If the sound pressure amplitude is higher than the cavitation threshold, bubbles will collapse and release much energy to remove biofouling on the surface of materials effectively.

![Figure 2. The principle of descaling based on ultrasonic guided wave and cavitation.](image-url)
The cavitation threshold can be expressed as:

\[ P_s = P_0 - P_v + \frac{2}{3} \left[ \frac{2 \sigma}{R_0^3} \right]^{\frac{1}{2}} \left( \frac{P_0 - P_v + \frac{2 \sigma}{R_0}}{P_0 - P_v + \frac{2 \sigma}{R_0}} \right)^{\frac{1}{2}} \]  

(1)

where \( P_v \) is the saturated vapor pressure, \( \sigma \) is the surface tension coefficient of liquid, \( R_0 \) is the initial radius of a bubble.

Rayleigh-Plesset equation can explain the nonlinear properties of a single spherical oscillating cavitation bubble:

\[ \frac{p(t) - p_\infty(t)}{\rho_\infty} = \frac{d^2 R}{dt^2} + \frac{3}{2} \frac{dR}{dt} \left( \frac{dR}{dt} \right)^2 + \frac{4 \nu_\infty}{R} \frac{dR}{dt} + \frac{2S}{\rho_\infty R} \]  

(2)

where, \( p(t) \) is the pressure within the bubble, \( p_\infty(t) \) is the external pressure infinitely far from the bubble, \( \rho_\infty \) is the radius of the bubble, \( \nu_\infty \) is the kinematic viscosity of the surrounding liquid. \( S \) is the surface tension of bubbles.

2.2. Finite Element Analysis model

The propagation of UGWs in the plate is analyzed by finite element simulation software. In the simulation model, the plate is Q235 steel, whose length, width and thickness are 1 m, 0.5 m and 10 mm, respectively.
The two transducers are fixed on the steel plate to excite UGWs. The other side of the plate is in contact with liquid. The sound pressure distribution of steel plate in liquid at the excitation frequency of 38kHz is solved. Figure 4 describes the result of sound pressure simulation with UGWs propagating in steel plate. If the amplitude of alternating sound pressure is higher than the cavitation threshold, it will be more likely for cavitation to occur in liquid. According to Eq. (1), the cavitation threshold is approximately 50kPa at room temperature [13]. In Figure 4, the positive and negative pressure of sound field on the steel plate surface are alternately distributed, and the sound pressure in most regions is higher than 50kPa, which means that cavitation will occur in most areas of the steel plate surface.

3. Experiment and result
This section is composed of the experiment and analysis of biofouling removal.

3.1. Biofouling removal experiment
Figure 5 shows the wedge-shaped piezoelectric transducer used in this paper. The piezoelectric material of transducer is lead zirconate titanate piezoelectric ceramic, and its electrodes are copper plate with holes.

In our work, the transducer and biofouling are located on different sides of the steel plate, which correspond to the inner and outer surface of the ship hull respectively. To simulate the biofouling on the ship hull, the shellfish hard-shell organisms commonly found on the hull are attached to the steel plate surface, and the shellfish hard-shell organisms are tightly attached to the steel plate surface due to the effect of biological mucus. Figure 6 indicates the side of transducer and marine biofouling.

Figure 5. The hull of Chinese aircraft carrier Liaoning.

Figure 6. The removal experiment of biological attachments.
Figure 7 describes the whole system structure in this work. The signal generator generates a continuous sinusoidal signal with a frequency of 38kHz, and the power amplifier amplifies the voltage to 400Vp-p. Finally, two transducers are applied to the steel plate, and the whole experiment lasts for one hour.

3.2. Experimental result and analysis
The result of biofouling removal is shown in Figure 8. Most of the shellfish attachments on the steel plate have been removed, and a small number of attachments remain on the plate only (in the red circle). The experimental result indicates that there exists satisfactory fouling removal performance with UGWs. The sound pressure distribution on a flat plate excited by UGWs could be obtained via numerical simulation. The simulation results show that the sound pressure higher than the cavitation threshold, with the help of exciting two transducers, could be formed in most regions of steel plate surface, which means that there would exist cavitation in these regions. These shellfish crustaceans on the surface of steel plate can be removed effectively due to the cavitation erosion resulting from cavitation bubble collapse. Therefore, our experimental results are consistent with the theoretical model of biofouling removal. The proposed method based on UGWs could remove marine attachments on the ship hull.

4. Conclusion
A novel biofouling removal method based on ultrasonic guided waves on steel plate has been presented in this paper. The fouling removal model is analyzed by finite element method, and the performance of our removal system is evaluated via experiment. The results indicate that 400 Vp-p and 38 kHz sinusoidal signals are applied to excite two transducers for 1 hour, which could remove biofouling on the steel plate effectively. The proposed methodology is characterized by low energy consumption and environmental protection, and possesses the ability to large-scale remove biofouling.
online. This method with a broad application prospect in the field of ship cleaning could provide a reference for removing marine biofouling.

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