Ultrasonic Cleaner using Two Transducers for Ship Hull Cleaning Robot

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Abstract

Fuel consumption of the ship gets worse by barnacles and stains put on its bottom, so that the ship hull should be cleaned regularly. Usual methods such as cleaning by special divers and cleaning after pulling up to the dock are not used frequently due to those high cost and the heavy burden on cleaners. We proposed a cleaning method using underwater vehicle with brushes, however there is a possibility to remove paints on the hull. To improve cleaning performance of the underwater vehicle, the ultrasonic cleaner is developed by using cavitation occurred by sound waves of the acoustic transduces. The cleaner generates sound waves with sound pressure of 0.2MPa or more required to occur cavitation at the point where sound waves from two transducers overlap. In experimental results, the cleaner occurred cavitation enough to make two holes in the aluminum foil located 50mm away from transducers.

Keywords: Ultrasonic Cleaner, Ship Hull Cleaning, Cavitation

1. Introduction

Various marine organisms such as sea lettuce and barnacles adhere to ships and make problems to ships that the weight and water flow resistance of the ship increase, which reduces thrust and increases fuel consumption. It is reported that if the bottom of the ship is not cleaned, the fuel efficiency will deteriorate by about 20% in one year after leaving the dock, and if it is not cleaned after that, the fuel efficiency will deteriorate by up to about 50% [1]. To prevent the adhesion of barnacles and stains put on its bottom, the ship hull should be cleaned regularly. Usual methods such as cleaning by special divers and cleaning after pulling up to the dock are not used frequently due to those high cost and the heavy burden on cleaners. We proposed a cleaning method using underwater vehicle with brushes [2], however there is a possibility to remove paints on the hull. To improve cleaning performance of the underwater vehicle, the ultrasonic cleaner is developed by using cavitation occurred by sound waves of the acoustic transduces.

In this study, we propose ship bottom cleaning using ultrasonic cleaning in order to improve the cleaning ability. Ultrasonic cleaning can control the cleaning position and cleaning strength, and since it is non-contact cleaning, it is considered that the coating is less likely to peel off than the method using a brush. However, ultrasonic cleaning for cleaning the bottom of the ship has not been performed, therefore, the purpose of this study is to investigate ultrasonic cleaning and evaluate its performance for adapting to ship bottom cleaning. We investigate the occurrence of cavitation using an ultrasonic array and discuss the possibility of the ultrasonic cleaning of ship hulls.

2. Ultrasonic cleaner for ship hull

2.1. *Cavitation*

When the pressure of water is lowered with keeping constant temperature, the pressure drops below the saturated vapor pressure and the state changes to a gas. The phenomenon bubbles generated at this time is called cavitation, occurs especially in rotating marine propeller and pump impeller [3][4]. In order to generate cavitation by ultrasonic waves, it is necessary to give water a sound pressure that is lower than the saturated vapor pressure and negative sound pressure is generated in the half cycle of ultrasonic decompression and cavitation occurs (see Fig. 1).

In order to generate cavitation in water, the saturated vapor pressure at an arbitrary temperature is needed. The saturated vapor pressure can be approximated by Wagner's vapor pressure equation in eq. (1) and (2).

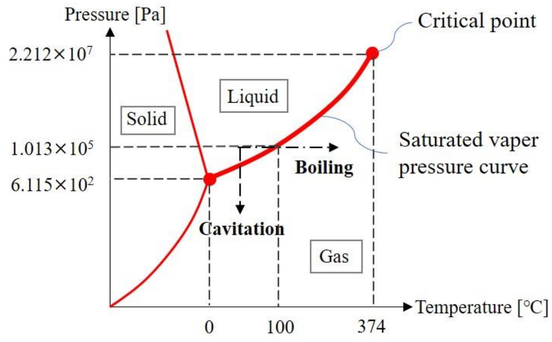
$$p_{ws} = p_c \cdot \exp\left(\frac{A\cdot x + B\cdot x^{1.5} + C\cdot x^3 + D\cdot x^6}{1-x}\right) \quad (1)$$

$$x = 1 - \left(\frac{T}{Tc}\right) \quad (2)$$

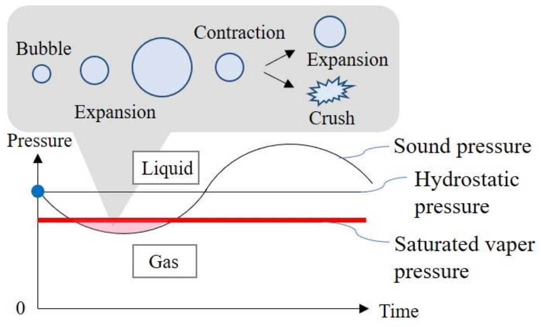
Here, p_{ws} : Wagner's strict vapor pressure [Pa], p_c: critical pressure [Pa], T: temperature [K], T_c: critical temperature [K], A: -7.6451, B:1.4583,C: -2.7758,D: -1.2330 are coefficients for approximation curve. This equation shows an approximate equation of the saturated vapor curve by changing the temperature starting from the pressure at the critical point and the critical temperature. Based on eq. (1), sound pressure with an amplitude of about 0.2 [MPa] is required for cavitation to occur under water at a standard temperature of 25 [C]. In addition, the sound pressure required for cavitation increases as the water depth increases.

2.2. *System architecture of ultrasonic cleaner*

In order to generate cavitation on the surface of the bottom of the ship, we propose a cleaning system that generates cavitation at surface positions with synthetic



(a) Water phase diagram



(b) Cavitation generation process

Fig.1 Water phase diagram and cavitation generation process using ultrasonic wave.

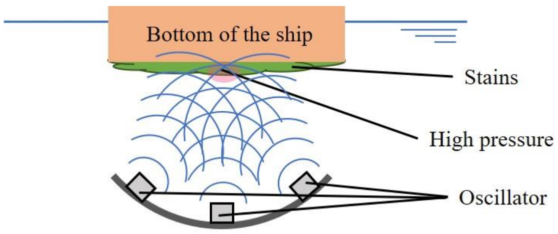


Fig.2 Concept of ultrasonic cleaner for shup hull. Ultrasonic transducer array is used to enhance the power

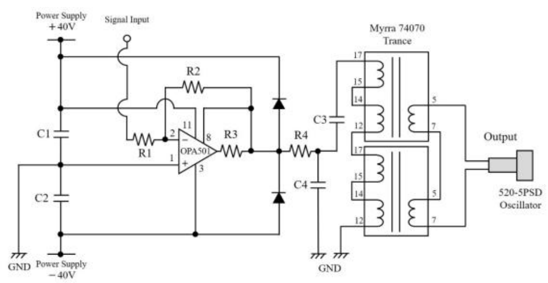


Fig.3 Amplifier circuit for ultrasonic transducers. The voltage of transducers are 300 [Vp-p].

waves using multiple oscillators as shown in Fig. 2. This ultrasonic array does not require a standing wave, and it is possible to obtain as high a sound pressure as the number of oscillators.

FURUNO's 520-5 PSD is used to configure the ultrasonic cleaning system. The specifications of the oscillator are 50-200 [kHz], 600 [W]. We used mainly 50 [kHz], which frequency is within the band 28 to 100 [kHz] often used in general ultrasonic cleaning. The amplifier circuit shown in Fig. 3 was designed to emit high-voltage and high-frequency sound waves using the oscillator. Two regulated power supplies of ± 40 [V] were used as the power supply, and the Tektronix AFG3022 function generator was used as the control voltage signal. To amplify the voltage, TI OPA541 amplifiers and Myrra 74070 trans with 50 [kHz] were used in series. Capacitors C1, C2 and C3 were set to 470 [μF], C4 was set to 0.1 [μF], resistance R1 was set to 1 [kΩ], R2 was set to 10 [kΩ], and R3 was set to 0.1 [Ω]. By using this amplifier circuit, it is possible to obtain an output with a maximum current consumption of 0.9 [A] and 300 [Vp-p] with an input signal of up to 9 [Vp-p].

3. Evaluation experiments of developed cleaner

3.1. *Basic property of ultrasonic transducer*

In order to investigate the basic property of the 520-5 PSD transducer, an experiment shown in Fig. 4 was conducted. The test tank has a size of 1650 × 540 × 600 [mm] and the water level at 550 [mm], and an artificial lawn was laid on the wall surface to suppress the influence of echo. The sound pressure was measured using the TC4013 hydrophone, and the hydrophone and transducer were set at a water depth of 250 [mm]. The measured distance L was set to be at 25, 50, 75, 100, 200, 300 [mm], respectively. The frequency of the transducer is set to 50 [kHz], and the input voltage is 50, 150, 200, 250, 300 [Vp-p] at each length.

Figure 5 shows the measurement results of attenuation characteristics for each input voltage. The higher the input voltage, the higher the sound pressure, and the sound pressure decreased as the distance L increased for all input voltages. The sound pressure required to generate cavitation exceeds 0.2 [MPa] when the input voltage is 300 [Vp-p] with L of 25, 50 [mm], and the input voltage is 250, 200 [Vp-p] with the L was 25 [mm].

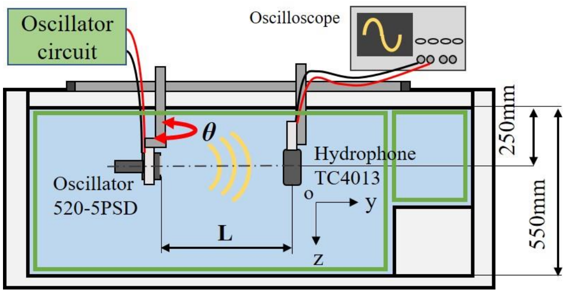


Fig. 4 Arrangement for basic property measurement of the transducer 520-5PSD.

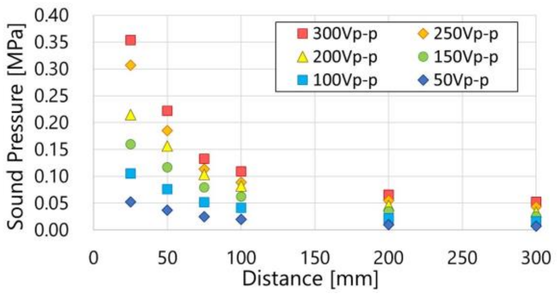


Fig. 5 The relationship between the length L and sound pressure by changing the input voltage.

3.2. *Cavitation using an ultrasonic transducer*

In the experiment in 3.1, it was found that the sound pressure at which cavitation occurs exceeds 0.2 [MPa] when the input voltage is 300, 250, 200 [Vp-p]. In order to verify the cavitation effect using single transducer, an experiment shown in Fig. 6 was carried out. The aluminum foil is fixed to a jig so that the vibration surface of the transducer could be seen vertically. The area of the aluminum foil was 68 x 55 [mm] to secure the diameter of the vibrating surface and the distance to 50 [mm], and colored red to check cavitation effect easier. The installation water depth of the oscillator with the aluminum foil fixed was set to 250 [mm]. The input voltage of the oscillator was 150, 200, 250, 300 [Vp-p], and the transducer was operated for 3 minutes each to qualitatively observe the state of the aluminum foil.

The state of the aluminum foil is shown in Fig. 7. When the input voltage over 200 [Vp-p] was applied, torn holes could be observed, but not in 150 [Vp-p]. The hole lengths generated by the input voltage of 200, 250, 300 [Vp-p] are 14, 24, 33 [mm], respectively, and it can be seen that the higher the input voltage, the larger the holes. It can be seen that the holes were found when the aluminum foil was affected by cavitation and possible to generate sufficiently strong cavitation even with a single oscillator.

From the basic property of the transducer in Fig.5, the sound pressure exceeding 0.2 [MPa] at the measurement point of 25 [mm] occurs with the input voltages of 200, 250, 300 [Vp-p]. From the experimental results in Fig.7, the cavitation occurs when the input voltage was 200, 250, 300 [Vp-p], which shows good agreement.

In this research, an ultrasonic cleaning system with the combined waves using an ultrasonic array is proposed, so that the directivity of the transducer is also important. In order to investigate the directivity of the oscillator, an experiment was conducted with the condition that transducer was fixed with a jig to rotate around the vibration surface, and the distance L was 50, 75, 100 [mm]. The sound pressure was measured with the angles between the y-z plane 0, 15, 30, 45, 60, 75, 90 [deg] with input voltage of 300 [Vp-p], respectively.

Figure 8 shows a directivity of the sound pressure for each angle. It can also be seen that the sound pressure decreased as the angle increased and the sound pressure with the surface angle 30 [deg] becomes half pressure of 0 [deg] (-6 [dB]), which it is almost the same performance as the directivity angle of the transducer specifications. When the system consists of an ultrasonic array with two oscillators, the sound pressure generated by each oscillator should be at least 0.1 [MPa] at a distance of 50 [mm], ± 30 [deg]. At 75 [mm], cavitation will occur within the range of ± 15 [deg].

3.3. *Cavitation using two ultrasonic transducers*

In order to estimate the cavitation strength of an ultrasonic array, the simulations using the property obtained in the previous section were carried out. Figure 9 (a) shows the sound pressure distribution of a single transducer at the input voltage of 300 [Vp-p]. Figures 9 (b) to (d) are the pressure distributions by combined waves when the distance between the centers of the two transducers is 100 [mm] and the relative angles are 30, 60, 90 [deg] and the phase difference was 0 [deg]. From the simulation results, the maximum positions of the combined wave at angles 30, 60, and 90 [deg] were 104, 70, and 47 [mm] and the sound pressure at those positions exceeded 0.2 [MPa], therefore, there is the possibility to generate cavitation by combined waves.

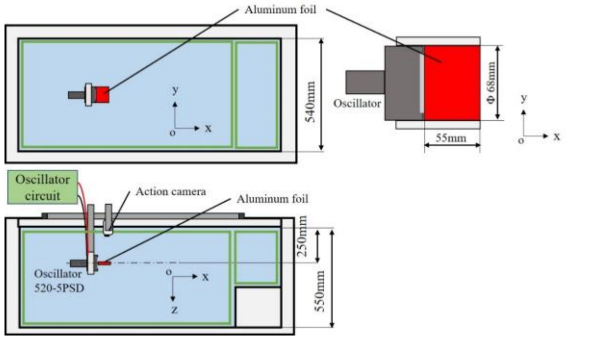
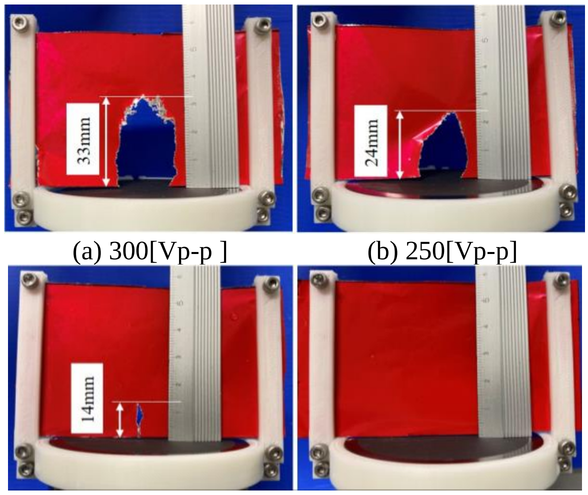


Fig. 6 The cavitation experiment using single transducer.



(a) 300[Vp-p] (b) 250[Vp-p]

(c) 200[Vp-p] (d) 150[Vp-p]

Fig.7 The results of cavitation experiments in the test tank, when the input voltage changes from 150[V] to 300 [V].

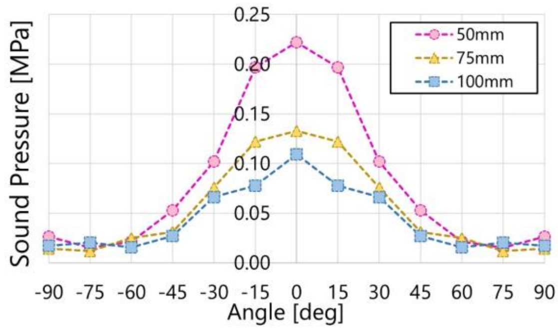
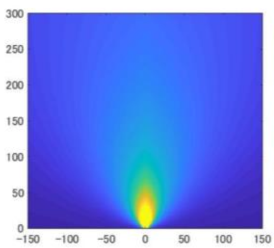


Fig.8 The directivity property of the transducer 520-5PSD with the angle θ from 0 [deg] to +/- 90 [deg]. With the angle of 30 [deg], the pressure becomes half.

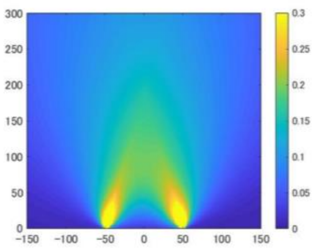
In order to verify cavitation with an ultrasonic array using two oscillators, an experiment was conducted with a configuration as shown in Fig. 10. The two amplifier circuits are used to control the phase of each transducer. The arrangement of the ultrasonic array was such that the distance between the centers of the transducers was constant at 100 [mm], and the angles θ between the oscillators were 30, 60, and 90 [deg], respectively. The distance L along the x-axis from the center of the distance between the centers of the two oscillators was set to be constant at 50, 75, 86, 100, 187 [mm]. The distances 50, 86, 187 [mm] are the focal lengths geometrically determined at the angles 90, 60, 30 [deg], respectively. The sound with the frequency of each oscillator was 50 [kHz] and the input voltage 300 [Vp-p] is used.

Figure 11 shows the results in which the sound pressure distributions of the combined sound waves along x-axis for each angle between transducers 30, 60, 90 [deg], respectively. The phase-adjusted sound pressure was higher than no phase-adjusted. The sound pressure required for cavitation generation exceeded 0.2 [MPa] between 50 and 100 [mm] in the phase-adjusted sound pressure of the three angles.

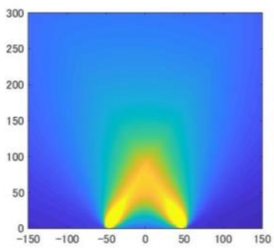
In order to verify the cavitation effect by the ultrasonic array, we conducted an experiment using aluminum fiols. The aluminum foil was fixed so that the vibration surface



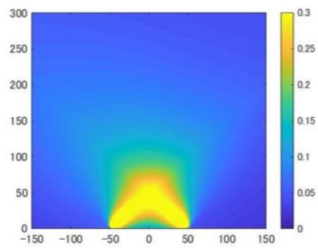
(a) One transducer



(b) Two transducers, 30[deg]



(c) Two transducers, 60[deg]



(d) Two transducers, 90[deg]

Fig. 9 The simulation results are compared using the property obtained from basic experiments.

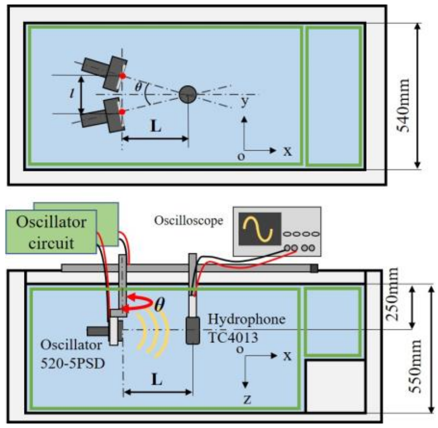
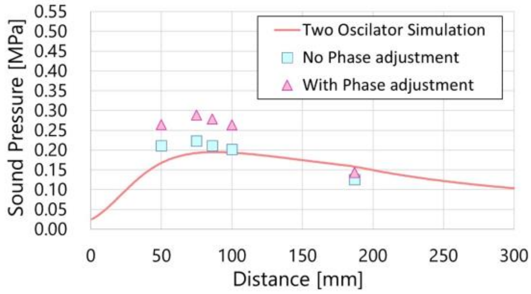
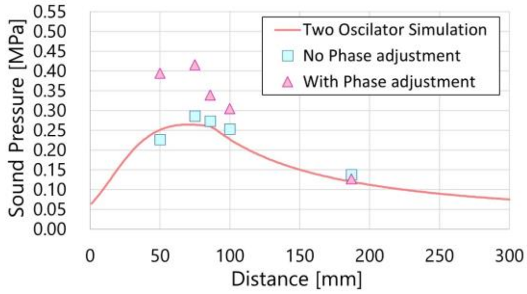


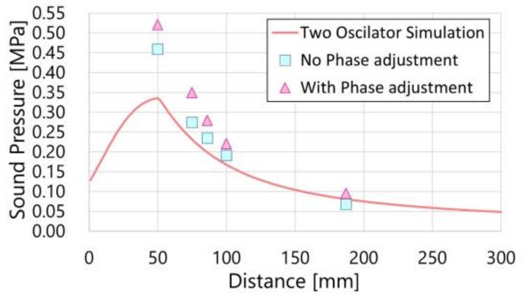
Fig. 10 The experimental setup for the transducer array.



(a) Relative angle: 30 [deg]



(b) Relative angle: 60 [deg]



(c) Relative angle: 90 [deg]

Fig. 11 Experimental results using two transducers with relative angles 30, 60, 90 [deg].

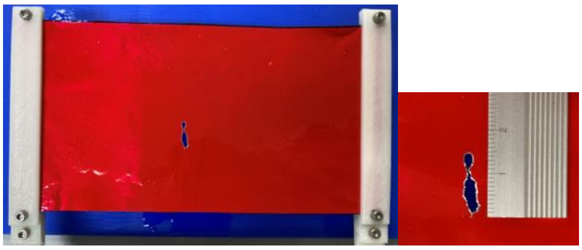


Fig. 12 Cavitation effect using two transducers.

of the oscillator becomes vertically. The area of the aluminum foil was 170 x 100 [mm] so as to cover the arrangement of the two oscillators. The position of the aluminum foil was set 30 [mm] away, the water depth of the aluminum foil was set to 250 [mm], which was the same as the arrangement of the transducers. The arrangement of the transducers was such that the distance between the centers of the transducers was constant at 100 [mm], and the relative angles θ were 30, 60, and 90 [deg], respectively. The input voltage of the oscillator was 300 [Vp-p] and given for 3 minutes.

Figure 12 shows the state of the aluminum foil when the arrangement angle of the oscillator is changed. The holes and cracks were confirmed in the aluminum foil at a position of about 35 [mm] from the center of rotation of the oscillator at all angles. However, since the holes and cracks of 30, 60 [deg] are far from the center of the aluminum foil, it is considered that they were generated by the cavitation effect of a single transducer. The crack of angle 90 [deg] is near the center of the aluminum foil, it is considered that it was generated by the combined wave of the ultrasonic array. The sound pressure of 0.2 [MPa] where cavitation occurs between 50 and 100 [mm] at every angle exceeded 0.2 [MPa], but in this experimental result, there is no holes or cracks.

4. Conclusions

In this paper, we have described the ultrasonic cleaner for the ship hull. The cleaner generates sound waves with sound pressure of 0.2MPa or more required to occur cavitation at the point where sound waves from two transducers overlap. In experimental results, the cleaner occurred cavitation in 50mm away from transducers.

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