Generation Frequency of Rebound Shock Waves from Bubble Collapses in Cavitation Jet

K. Nishibayashi, J. Wang, and A. Abe

Abstract In this paper, a method using cavitation jet is proposed to remove marine creatures adhered to the body of a ship. The flow with the cavitation jet is produced using a high-pressure pump and cavitation nozzle with an orifice plate. Rebound shock waves are expected to be continuously generated in the cavitation jet flow. In order to observe the behaviors of the rebound shock waves, experiments are carried out using the Schlieren method in a water tank. From the results of the visualization, it is found the generation frequency of the rebound shock wave reaches its peak at a close position to the nozzle exit. The behaviors of the rebound shock waves are also investigated under the influence of a wall boundary beside a cavitation jet. The results show that the position where the maximum generation frequency is obtained is at several ten times of an orifice diameter from the nozzle exit, and the generation frequency decreases due to the effect of the wall boundary.

1 Introduction

Recently, the importance of marine transportation has been rising in global economic activities, and there is no room for doubt that the Japanese economy is not maintained without ship transportation [1]. Considering the navigation cost of marine transportation, the fuel costs occupy half of the total running cost. Therefore, in the maritime economic field, reduction of fuel costs directly improve operating costs of ship [2]. In order to reduce fuel consumption, especially it is important to decrease drag on the hull in sea. One of the causes of drag generation

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is marine creatures adhered to the hull. In addition, marine creatures carried by ships cause marine environmental hazard in the whole world. Therefore, ship's body should be always kept clean without adhesion of marine creatures. As one of the preventative measures, special paints are used, but perfect prevention is not expected, and chemical paints have potential risks to marine environment [3]. In fact, ships sometimes need to remove marine creatures from the hull. Generally, the cleaning is operated by sandblast in periodic maintenance on shore. Furthermore, note that dust of sandblast has a bad risk for human health [4].

It is well known that cavitating water jet is effective on cleaning and it has actually been used. It is thought that high cleaning effects are caused by micro-water jet and shock pressures generated from collapse of cavitation bubbles. Water jet is generated by a high-pressure pump and has extremely high energy per unit area [5]. Due to the use of water, there is no problem about dust generation. There is a lot of previous study of water jet behavior; however, the research on the characteristics of the cavitating water jet has not been sufficiently examined yet.

In this paper, in order to establish a method using cavitation jet to remove marine creatures from ship's body surface, the behavior of cavitation jet in water is considered experimentally. Bubbles discharged from a cavitation nozzle are collapsed by ambient pressure. Using cavitation jet, rebound shock waves and micro-jets are probably applied to cleaning of wall. Therefore, effective underwater cleaning may be expected by finding of appropriate conditions. In the experiments, a high-velocity water jet flow with cavitation is generated using a plunger pump and a cavitation nozzle with an orifice plate. Behaviors of cavitation flow discharged from a cavitation nozzle are observed by Schlieren method in a water tank. The generation frequencies of the rebound shock wave are investigated using optical images. Furthermore, we also discuss on the generation of rebound shock waves under the different conditions of the wall boundary beside the cavitation jet.

2 Experimental

Figure 1 shows a schematic of the experimental setup for observation of the cavitation jet flow. The system consisted of a stainless-made cavitation nozzle, a triplex plunger pumps (AJP-1700VGQ, Ryobi Limited), and a water tank with

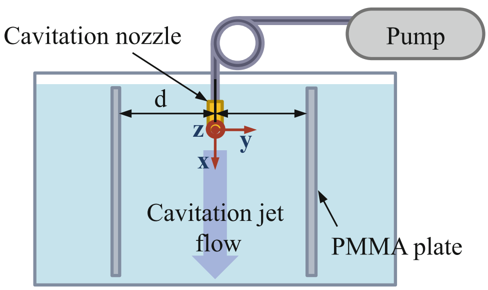

Fig. 1 Schematic of experimental setup for cavitation jet observation

450 mm (width) × 600 mm (length) × 450 mm (height). The dimensions of the cavitation nozzle were 30 mm in diameter and 130 mm in length that was vertically positioned toward the bottom in the water tank. Inside the cavitation nozzle, there was a stainless orifice plate of 15 mm in diameter and 2 mm in thickness with a 1-mm diameter orifice. To accelerate and pressurize water flow, the nozzle was connected to the pump. In the experiment, the applied pressure of the pump was 8.4 MPa. When the high-pressure water flow from the pump passed through the nozzle, the region of negative pressure was generated at the exit of the orifice plate, so that cavitation bubbles were discharged from the nozzle exit. As shown in Fig. 1, PMMA boards were set in the water tank as wall boundaries beside the cavitation jet. The cavitation jet flows were observed with a high-speed camera (HX-3, NAC Image Technology Inc.) using Schlieren method. The frame rate of the camera was 100 kfps and exposure time was 300 ns.

3 Results and Discussion

Figure 2 shows sequential images of the cavitation jet flow. The nozzle exit was on the right side of the images. The shadow of the cavitation jet flow stretches out long and thin from the nozzle exit to the left side. The maximum diameter of the shadow of cavitation cloud was measured about 15 mm from the image. In Figs. 2b and c, rebound shock waves, generated by the motion of cavitation cloud, were continuously observed at a position of about 40 mm from the nozzle exit. Following that, the rebound shock waves were generated at about 30 mm in Figs. 2d–f.

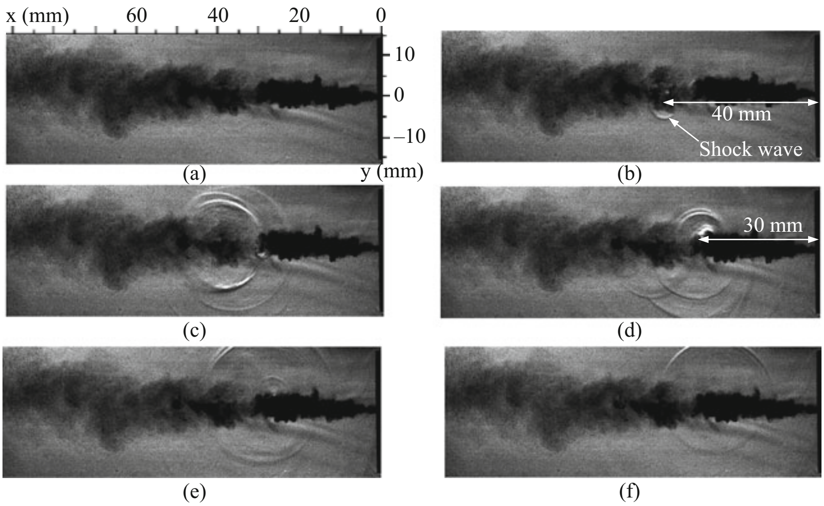

Fig. 2 Sequential observation of rebound underwater shock waves generated in cavitation jet. (**a**) 0 μs, (**b**) 10 μs, (**c**) 20 μs, (**d**) 30 μs, (**f**) 50 μs

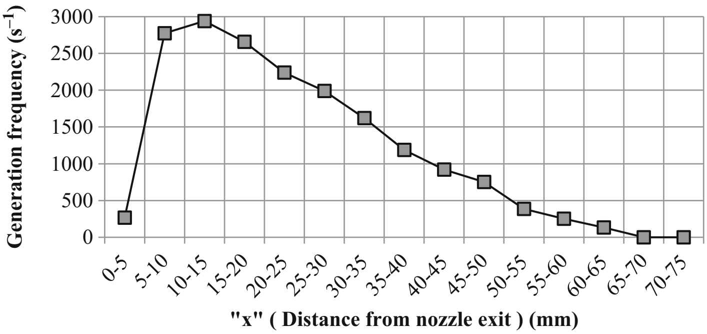

Fig. 3 Distributions of generation frequency along the x-axis

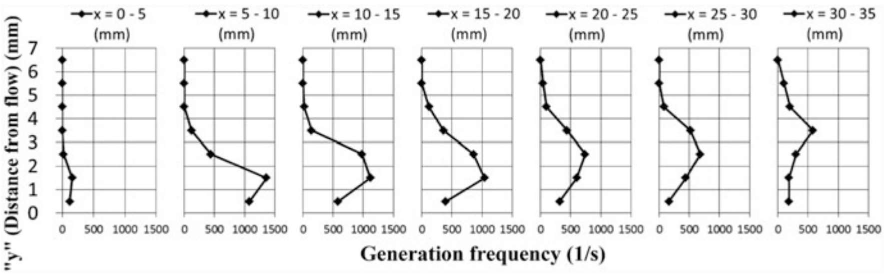

Fig. 4 Distributions of generation frequency along the y-axis

Fig. 3 shows the relationship between generation frequency and observation area along the x-axis defined in Fig. 1. The ordinate is the generation frequency of rebound shock waves, and the abscissa is the measured area of every 5 mm from the nozzle exit. The result shows that the peak value of the generation frequency appeared in the area of 10 mm to 15 mm distance from the nozzle exit. This phenomenon is closely related to the velocity of the cavitation jet flow. According to the principle of the nozzle flow, the flow velocity from the nozzle exit is assumed to be a constant value in the region within about 10-mm distance from the nozzle exit, and the flow velocity suddenly decreases beyond the boundary of around 10 mm from the exit [6]. The pressure increments with those velocity changes cause the beginning of motion of cavitation bubbles, so that a large number of rebound shock waves are generated in this area. From the position of 10 mm, the generation frequency decreases because the velocity of the flow gradually decreases with increase of x. As a result, the generation of the rebound shock wave is affected by the state of the water flow around the cavitation jet. Therefore, the experimental visualization of the rebound shock waves was carried out using a wall boundary beside the cavitation jet.

Figure 4 shows the change of the generation frequency of rebound shock wave along the y-axis defined in Fig. 1. The peak value of generation frequency reaches around 1400 s^{-1} at the $x = 5$–10-mm area. After that, the peak values decrease with

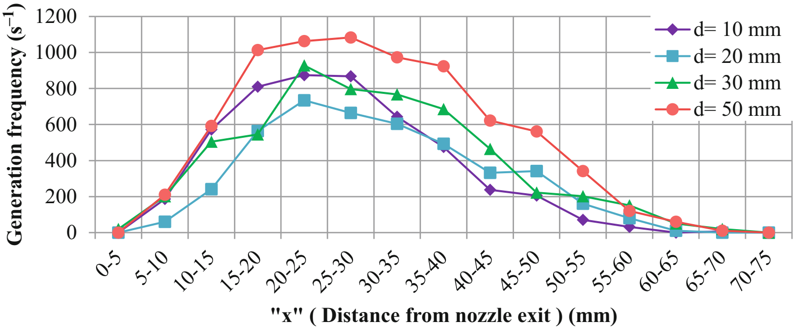

Fig. 5 Distributions of generation frequency along the x-axis setting up a wall boundary beside the cavitation jet

increase of x, and the position of the peak value moves to the y-direction, i.e., the position of peak value of generation frequency goes away from the x-axis along the downstream. In addition, the distributions of generation frequency gradually become gentle. The change in the flow velocity around the center axis of jet is considered to be small at the position more than 10 mm apart from the exit, so that it is hard to make the rebound of cavitation bubble. On the other hand, the peak value of the generation frequency tends to move outward with the distance from the nozzle exit because the cross section of jet increases with the flow dissipation.

Figure 5 shows distributions of generation frequency along the x-axis setting up a PMMA plate as a wall boundary beside the cavitation jet. The curves indicated by the symbols, diamonds, squares, triangles, and circles, are the results obtained when the distances between the wall and the central axis of the cavitation jet were 10 mm, 20 mm, 30 mm, and 50 mm, respectively. Comparing with Fig. 3, all peak values of the generation frequencies are obviously small, and the measurement areas corresponding to the peak frequencies are from 20 mm to 30 mm away from the nozzle exit. We consider that the spread of the cavitation flow is controlled not to be wide by a wall boundary near the jet, so that the pressure change with flow velocity becomes gradual; therefore, the generation number of the rebound shock wave decreases. In addition, in the measurement area of 20 mm to 50 mm, there is a tendency that the generation frequency changes with the position of the wall boundary. However, we can also see that the generation frequency distribution becomes relatively large and out of the tendency in the case of $d = 10$ mm. When the position of the wall boundary closes to the cavitation jet, the flow along wall boundary is formed by Coanda effect, and some conditions of cavitation collapse may be satisfied.

Figure 6 shows distributions of generation frequency along the y-axis setting up a wall boundary beside the cavitation jet. The values of generation frequency in this figure mean the sum of generation frequencies measured within $x = 70$. The solid circles and triangles represent the results obtained with 50-mm and 10-mm distances between the PMMA plate and the central axis of the jet. The total number

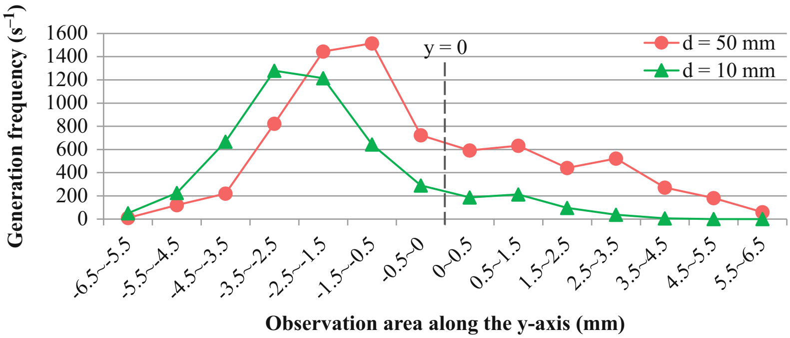

Fig. 6 Distributions of the sum of the generation frequencies measured within $x = 70$ along the y-axis setting up a wall boundary beside the cavitation jet: ● 50 mm, ▲ 10 mm

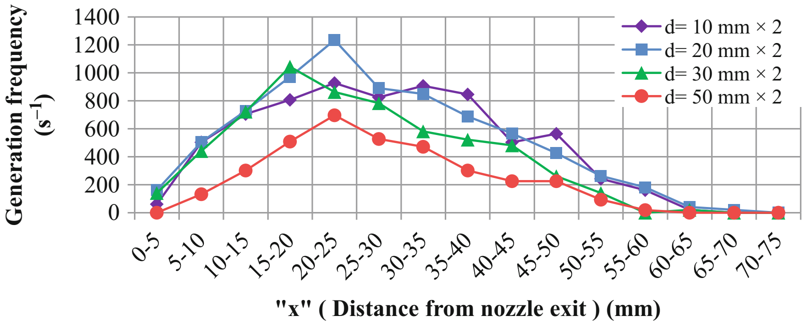

Fig. 7 Distributions of generation frequency along the x-axis setting up two wall boundaries

of generation frequencies of rebound shock waves in the left area is larger than that in the right area due to small changes of the flow velocity near the wall boundary. This tendency becomes remarkable with decrease of distance between a wall and cavitation flow.

Figure 7 shows distributions of generation frequency along the x-axis setting up wall boundaries at both sides of the cavitation jet. The solid diamond, squares, triangles, and circles indicate the results obtained with 10 × 2 mm, 20 × 2 mm, 30 × 2 mm, and 50 × 2 mm of distances between the two wall boundaries, respectively. From the figure, it is found that the generation frequency increases with decrease of the distance between two wall boundaries except the case of 10 × 2 mm. We consider that this phenomenon is concerned with the convection of the water between the wall and jet, and the convection in the wide space develops easier than that in the narrow space. The cavitation flow does not spread out due to the convection generated between two walls; as a result deceleration of the jet-flow velocity hardly generates so that motion of cavitation bubbles is also inactive. Therefore, it is assumed that the relationship between generation frequency and distance between walls of Fig. 7 shows the opposite relation to that of Fig. 5.

4 Conclusions

In this paper, behavior of a cavitation jet in water was investigated as an effective cleaning technique for marine creatures adhered to the hull. Rebound shock waves and micro-jets generated by the collapse of cavitation cloud were expected to remove these marine creatures. In the experiments, cavitation clouds were generated using a cavitation nozzle. The rebound shock waves generated in the jet flow were observed using the Schlieren method. In addition, a wall boundary was set up beside the cavitation jet. From optical images, the generation frequencies of the rebound shock wave were analyzed along the x- and y-axis of the flow. As a result, it was found that the generation frequency achieved its peak at a close position to the nozzle exit without a wall boundary. Furthermore, the position of the peak value in the y-direction moved toward the outer of flow with the distance of the x-direction. These results suggested that the collapse of cavitation is closely related to the change in the flow velocity. In the case of setting a wall boundary, the peak of generation frequency appeared far away from the nozzle exit. Using a wall boundary, the generation frequency increased with the distance between the wall and flow. For wall boundaries setting up at both sides of the jet, the generation frequency increased with decrease of the distance. It was thought that these phenomena were concerned with the convection of the flow between the wall and cavitation jet.

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References

1. Nippon Yusen Kabushiki Kaisha NYK Report Business Management Strategy, 2014
2. W. Simon, Tributyltin pollution on a global scale, An overview of relevant and recent research: Impacts and issues, WWF Living Planet Report, 2006
3. N. Alert, *Request for Assistance in Preventing Silicosis and Deaths From Sandblasting.* (DHHS (NIOSH) Publication, 1992), pp. 92–102
4. M. Szymczak, S. Tavoularis, A. Fahim, M. Vijay, Flow visualization of Cavitating, high-speed, submerged water jets. J. Eng. Ind. **113**(4), 485–489 (1991)
5. A. Guha, R.M. Barron, R. Balachandar, An experimental and numerical study of water jet cleaning process. J. Mater. Process. Technol. **211**(4), 610–618 (2011)
6. S. Sivakumar, R. Sangras, V. Raghavan, Characteristics of turbulent round jets in its potential-Core Region. J Mech Aeros Indus Mech Manuf Eng **6**(1) (2012)