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Experimental Investigation of Bow Slamming on a Ship: The Effect of Weight and Impact Angle

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Abstract

The impact pressure induced by slamming can imply physical damage on a ship. The high probability of the slamming impact is on the bow part in the actual sea state. In this present study, the slamming induced pressure on the bow flare of a ship have been investigated through the experiment. The experiment was schemed by the dropping test based on free-falling body in the wave tank, wherein the bow of the ship model was inclined in several impact angles 0° to 30° to the free-water surface. To measure slamming impact pressure acting on the bow flare, the piezoelectric sensors S1, S2, S3, S4 were attached to the bow section and installed on a computer. As the obtained results, the impact pressure on bow flare occurred in a short time duration caused by slamming. The discrepancy of the peak impact pressure between ship model weight of 2.42 kg and 7.29 kg for the impact angle 0° is 70.36% S1, 69.52% S2, 68.97% S3, and 68.34% S4. For the relative impact angle of 30°, the discrepancy is 67.02% S1, 65.73% S2, 58.51% S3, and 48.21% S4. The tendency of the peak pressure coefficient at the sequenced impact points S1, S2, S3, S4 is similar for all impact angles 0°, 10°, 20°, and 30°. The peak pressure coefficient due to the full load condition is highest in the nearest bottom part, and the peak pressure coefficients due to the lightship condition highest in the nearest bottom part caused by the small impact angle.

1. Introduction

When a ship sailing in waves is sometimes experiencing slamming events. Slamming is a phenomenon that indicates nonlinear interaction between ship hull and wave within the water entry process and results short duration of high force and pressure and dynamic response. The effect of this phenomenon can imply damage, capsizing, or sinking. Therefore, the characteristics of ship slamming should be investigated, and then the investigation results are the considerations in obtaining proper ship hull form and construction designs.

Subjected to the study of slamming impact, von Karman [1] and Wagner [2] had firstly conducted, hereinafter the enormous number of studies subjected to the slamming impacts and its effects on a ship has been carried out by using numerical and experimental methods. The following, some related studies in the last decade have been presented. The investigations of slamming induced pressure and load in two-dimensional (2D) ship model section have been developed by using the finite element software ABAQUS [3], explicit FEM code LS-DYNA [4], finite element code ABAQUS [5], combined strip theory, and smoothed particle hydrodynamics (SPH) approach [6], the boundary element method (BEM) code and FLUENT code [7], 2D generalized Wagner model [8], the moving particle semi-implicit (MPS) method involving Prandtl's mixing length method and the$k$-epsilon method [9]. Although the 2D approach has sufficient results, however, it is still not relevant in the reality of the slamming problem. Also, this becomes less appropriate if the results are validated using the experimental results.

The slamming investigations using the three-dimensional section have also been carried out by using some methods such as the Wagner approach and the boundary element method (BEM) [10], the coupled model of 3D Rankine panel model, 3D FEM, and 2D GWM [8], the 3D time-domain nonlinear hydroelastic method [11], seakeeping code and simplified method [12], momentum impact method and dam-breaking method [13]. Those studies have shown high accurate results by the developed numerical method, and then these results have been validated with the experimental results.

On the other hand, few experimental methods have shown satisfaction by using the elastic body. In these studies, the experiment devices to accomplish a ship's body entering the water had been introduced. The wedge model was driven by using an actuator programmed to execute triangular wave trains [14]. The Slingshot Impact Testing System (SITS) was designed to study experimentally slamming loads [15]. The drop tower and the sliding trolley connected to the parallel fixture was designed [16]. The oil pressure actuator system was designed for the injection of heavy steel wedges with the safety device [17]. However, those experiment devices that were used possibly affect a result, and it is a possible difference compared with the free-fall test.

The water entry of a floating body is interested in being studied regarding the slamming loads acting on a floating body. The dropping test of a ship model with a free-fall approach is the most appropriate way to describe the water entry of a floating body and slamming event. However, this method needs a specialized technique and proper measurement device to obtain accurate results. Therefore, the consideration of the experiment equipment and experimental design is an appropriate way. Nevertheless, an experimental investigation remains to be needed to interpret and enrich physical understanding from the resultant nonlinear interaction between ship and wave-induced slamming impact.

In this present study, the impact pressure resulted through dropping test by free fall way of a ship model has been investigated to characterize the effect of the relative impact angle and the model weight on bow slamming. The ship's bow angles to the water-free surface have been considered from 0° to 30°, and four sensor devices have been attached to the bow flare surface of the ship model. By characterizing bow slamming through the experimental investigation, the bow slamming of a ship in waves could be interpreted.

2. Methods

The ship slamming is described by an impact resulting from contact between a ship's body and free surface after lifting upward on a wave. By this description, the dropping test of a ship model has been conducted to obtain an impact pressure caused by slamming. Also, the influence of the weight and bow impact angle of the ship were investigated in this experiment. The weights of the ship model were considered 2.42 kg and 7.29 kg, and they were respectively defined as the lightship and full loading conditions.

The experiment was performed at wave tank, Ship Hydrodynamics Laboratory, Naval Architecture Department, Hasanuddin University, Indonesia. The size of the wave tank length is 20 m, the width is 1.5 m, and the depth is 1.3 m. The ship type that was used in the experiment is a container. The lines plan of the ship is shown in Figure 1. The ship model scale is 1:75, and it was made of fiberglass, as shown in Figure 1. The scale of the ship model considered the size of the wave tank. The main dimensions of the actual ship and model are provided in Table 1. In the bow part, the pressure sensors were attached to capture the slamming induced pressure. The experimental details are discussed accordingly of the ship model, experiment scheme, experiment equipment, and device.

Table 1. the Main Particulars of the Actual Ship and Model

Dimension	Actual (m)	Model (m)
Length overall, LoA	74.49	0.993
Length waterline, LwL	72.40	0.965
Length between perpendiculars, LbP	67.70	0.929
Breadth, B	11.50	0.153
Depth, H	7.20	0.096
Draft, T	6.00	0.080

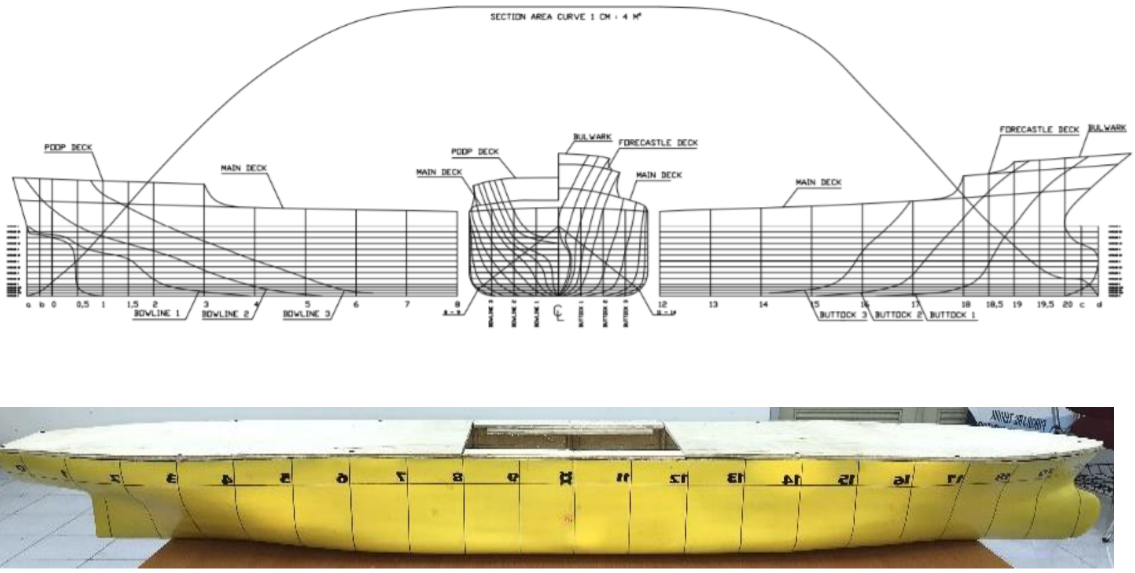


Figure 1. the Ship Lines Plan and Ship Model

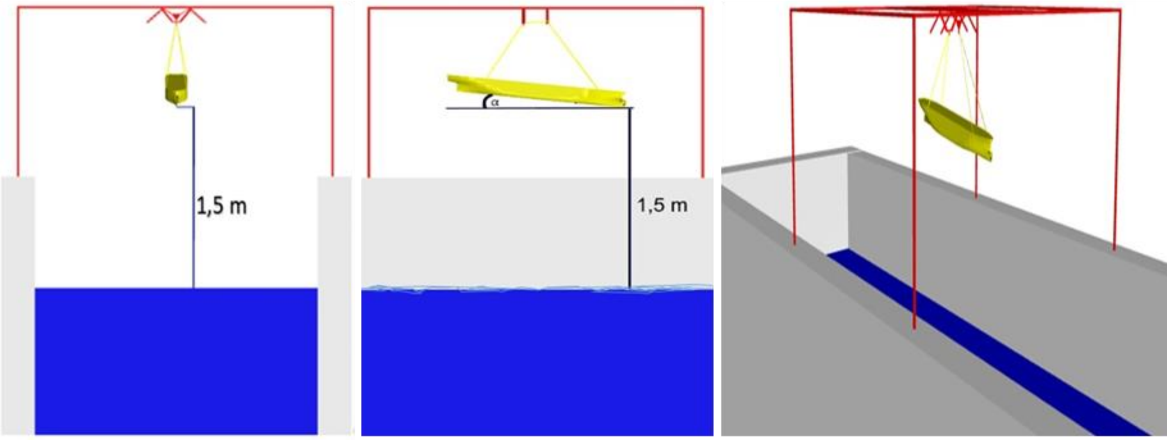


Figure 2. the Experimental Scheme of The Dropping Test

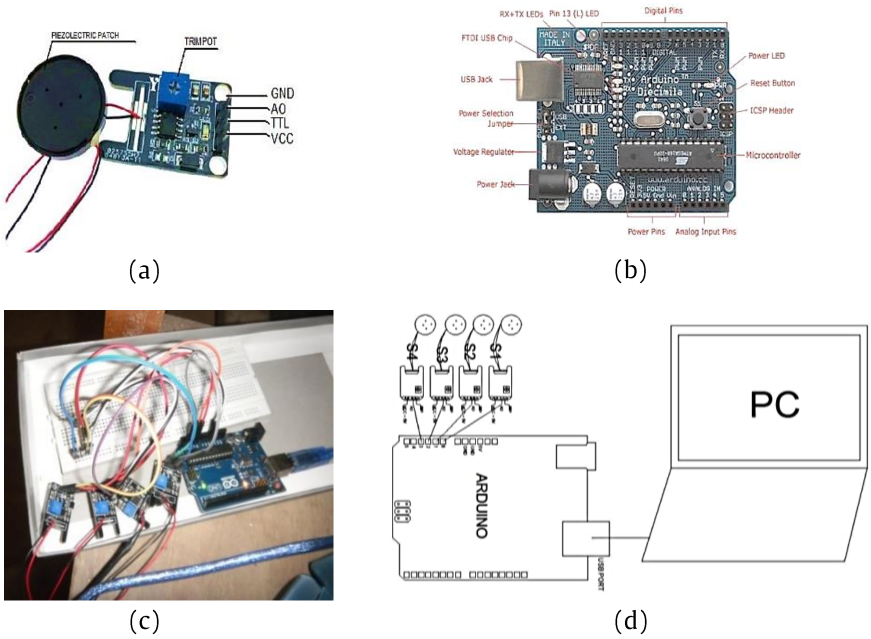


Figure 3. the Installation of the Pressure Sensor Device; (a) Piezoelectric Knock Sensor, (b) Arduino Mega, (c) Breadboard, (d) Block Diagram

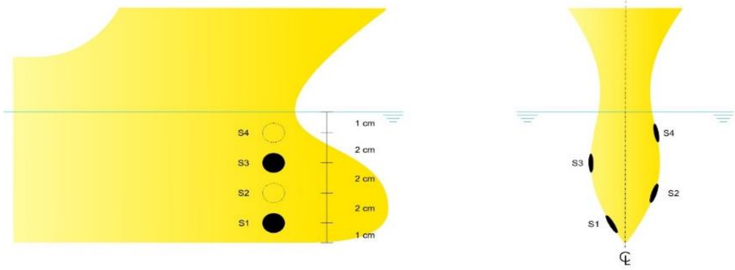


Figure 4. the Illustration of Piezoelectric Knock Sensors Attached Vertically in Bow Flare of The Model

The experimental method is the dropping test with free fall way. For dropping a ship model, the dropping tower as experiment equipment was constructed above the wave tank construction. The ship model was hung using a rope in the dropping tower. The distance between the ship model in the dropping tower and the water-free surface in the wave tank was considered 1.5 m for reaching a relative impact angle on the bow part after dropping a ship model. The bow angle of the ship model was fixed from 0° to 30° to the water-free surface.

In the dropping tower, the bow angle of the ship model is adjusted and kept by using two ropes that are tied on the rear and middle part of the ship model connected to the dropping tower. Then, the bow angle is maintained until reaching the water-free surface. Also, two ropes are needed for tying the starboard and portside of the ship model connected to the dropping tower to avoid a heeling condition of the ship model, and they are freely released during the dropping process. The ship model with the proper condition regarding the expected bow angel is dropped to the water-free surface by cutting simultaneously two ropes on the dropping tower. The experiment scheme, dropping test by free fall entry, is illustrated in Figure 2. The time during the dropping process, from the beginning of the dropping the ship model until hitting the water-free surface, is recorded using a camera.

The sensor device that was used is a piezoelectric knock sensor installed with the Arduino Mega. It is used for measuring impact pressure due to slamming. The piezoelectric knock sensors are connected to the breadboard and Arduino mega, and then they are installed on a computer. The block diagram of the device installation is shown in Figure 3. There are four pressure sensors S1, S2, S3, S4, that ware attached vertically to the bow part of the ship model, as shown in Figure 4. The position of the sensor has a distance vertically on the bow flare. By the vertical position of the impact point, the influence of the impact point on the bow flare vertically toward pressure distribution due to slamming can be obtained.

The output of the piezoelectric knock sensor is a digital number in a voltage unit (volt). Then, it is calibrated by using a force measurement device. By pressing the piezoelectric knock sensor, force N working on the sensor is shown in the measurement device. Then, the impact pressure (Pa) is defined by multiplying the digital number with force per digital number which is divided by the section area of the piezoelectric knock sensor.

3. Results and Discussion

In this present study, the dropping test of the ship model was carried out successfully, and the experimental data were obtained. Then, the obtained results have been discussed accordingly. Figure 5 shows examples of the snapshots of the ship model during the dropping test. The bow of the ship in both impact angle hit the water free surface. In the case of the weight of ship model 2.42 kg, the vertical velocity of the ship after dropping the ship model until reaching the water-free surface in both impact angles 0° and 10° is about 0.40 m/sec. Based on Figure 5, the water splashing occurred, and then the characteristics of the water splashing for both cases seemed similar. In other cases, the ship bow with the impact angles of 20° and 30° was suddenly lifted upward after the entry process, and then the ship capsized. This occurrence happened in a relatively short duration. Furthermore, the ship model with bow angles 30° experienced an occurrence of the wet deck during entering the water free surface. Regardless, the slamming induced impact pressure on the occurrence was still measured.

The time histories of the impact pressure in each model weight for the weight model of 2.42 kg and 7.29 kg are shown in Figure 6. In the hydrostatic conditions, for the weight model of 2.42 kg, the pressure is acting only at impact points S1 and S2, and each impact pressure is less than 20 Pa.

ts = 0 *sec* ts = 0.42 *sec* ts = 0.45 *sec* ts = 0.50 *sec*

a). Bow Angle 0°

ts = 0 sec ts = 0.40 sec ts = 0.44 sec ts = 0.50 sec

b). Bow Angle 10°

Figure 5. the Snapshots of the Model Within the Dropping Test; a). Bow Angle 0°, b). Bow Angle 10°

In the dropping test, the peak pressure at impact points *S1*, *S2*, *S3*, *S4*, for the impact angle 0°, is 253.298 Pa, 235.673 Pa, 212.048 Pa, 189.611 Pa, respectively. As the influence in increasing the impact angle, the peak pressure decreases. Also, the vertical position of the impact point in the bow flare affects impact pressure. When the impact point is reached by water impact increasing from baseline to the impact point again, the impact pressure also decreases. This impact behavior is the same as in other cases. Furthermore, the other cases are shown in Figure 6a and Table 2.

Meanwhile, the peak pressure at impact points (*S1*, *S2*, *S3*, *S4*) for the impact angle 0° and the model weight 7.29 kg as shown in Table 2 are 853.298 Pa, 773.298 Pa, 683.298 Pa, 599.611 Pa, respectively. Figure 6b shows the time histories of the impact pressure at each impact point in increasing the impact angle. The impact pressure decreases steeply in a short duration for all impact angles after reaching the peak pressure. The vertical velocity is about 0.28 m/sec.

As the comparison results, the discrepancy of the peak impact pressure between ship model weight of 2.42 kg and 7.29 kg for the impact angle 0° is 70.36% *S1*, 69.52% *S2*, 68.97% *S3*, and 68.34% *S4*. For the relative impact angle of 30°, the discrepancy is 67.02% *S1*, 65.73% *S2*, 58.51% *S3*, and 48.21% *S4*. However, the dropping test for the relative impact angles 20° and 30° experienced a bow diving phenomenon, and then the ship model did not return to its hydrostatic condition.

The tendency of peak pressure in increasing the impact angle is similar for all impact points, as shown in Figure 7. For the ship model weight 2.42 kg, the peak pressure decreases relatively small magnitude from the impact angle 0° to 10°, and then it tends to decrease steeply with the significant value from 10° to 30°. For the peak pressure from the impact point to another impact point, the discrepancy of the peak pressure is relative in the same value from S1 to S2 along increasing impact angle; however, it is different from S2 to S3 and S4 as shown in Figure 7a. On the other hand, the peak pressure for the ship model weight 7.29 kg decreases relatively with the same value in each increasing impact angle as shown in Figure 7b.

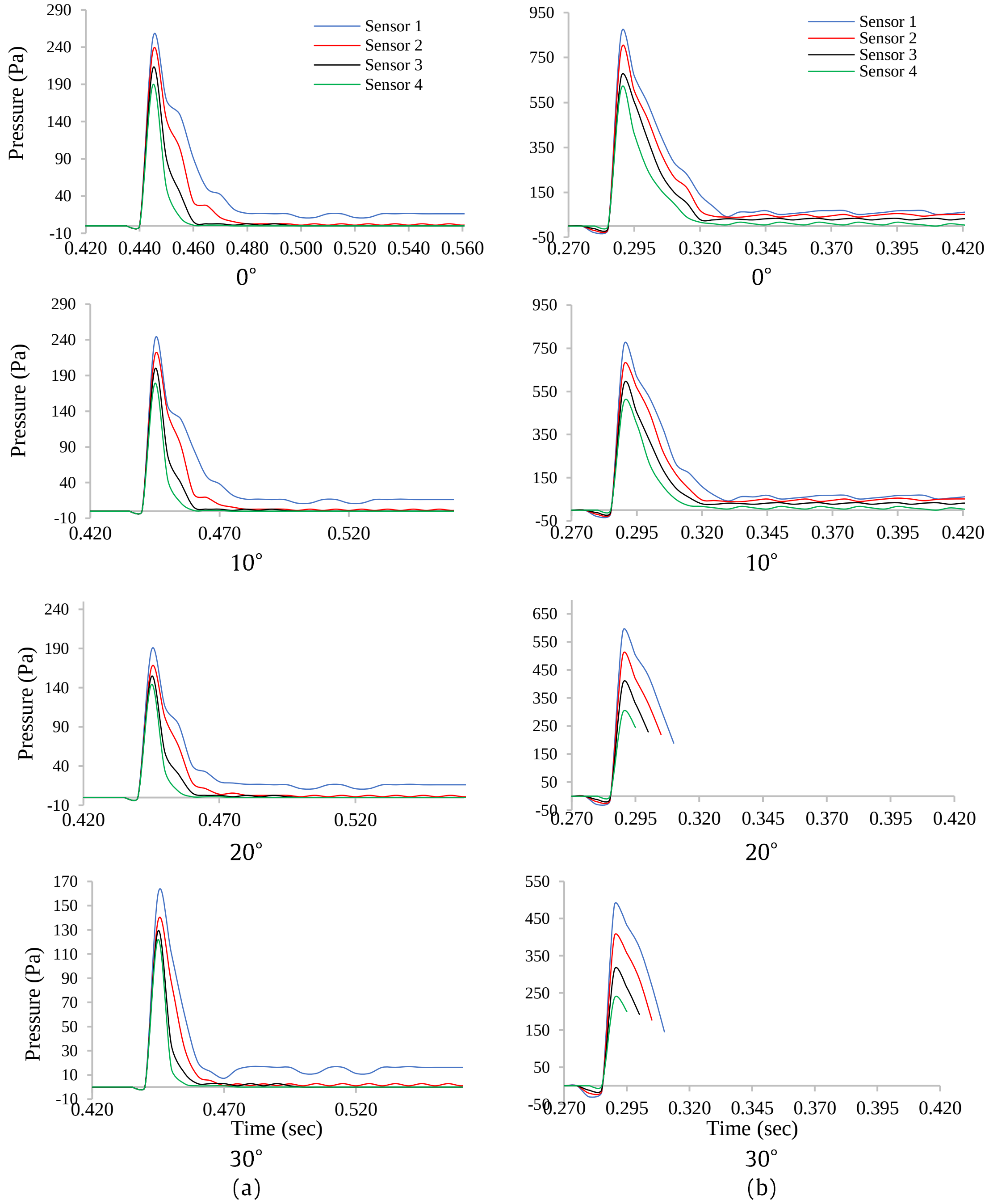
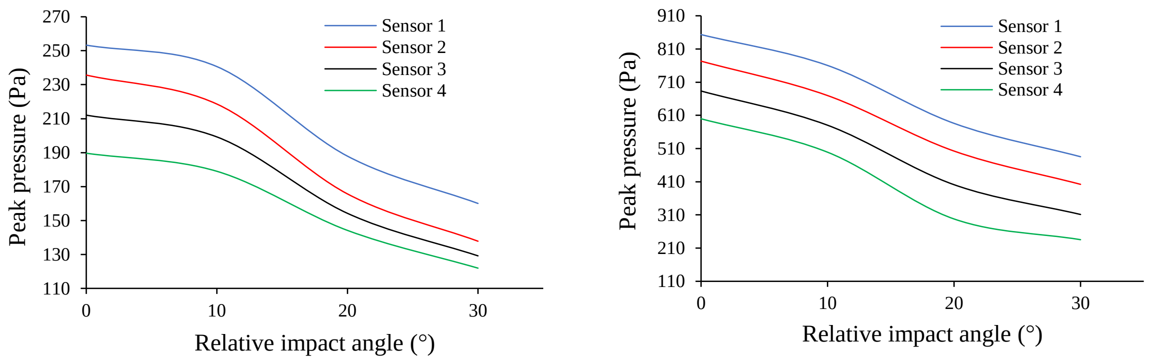


Figure 6. the Time Histories of the Impact Pressure for Model Weight at Sensor Point and Relative Impact Angles; (a). Model Weight 2.42 Kg, (b). Model Weight 7.29 Kg

Table 2. the Peak Pressure at Impact Point

Model weight (kg)	Relative impact angle (°)	Peak pressure (Pa)			
		S1	S2	S3	S4
2.42	0	253.298	235.673	212.048	189.611
	10	240.673	218.611	199.245	179.312
	20	187.925	165.676	154.239	144.167
	30	160.051	137.802	129.177	121.928
7.29	0	853.298	773.298	683.298	599.611
	10	760.333	669.611	580.245	499.303
	20	585.877	502.412	401.111	297.881
	30	485.288	411.143	311.312	235.411

The impact pressure in association with the impact velocity and impact point position on the bow flare, the impact pressure can be characterized by using the coefficient of the peak pressure. The peak pressure coefficient Cp is defined by $P_{max}/0.5\rho V_i^2$, where Pmax is the peak pressure, ρ is the water density, and Vi is the impact velocity reaching the impact point after hitting the free-water surface. The vertical velocity of the ship model to the free-water surface generates the impact velocity reaching the impact point within bow entry. The impact velocity is obtained in a short time. The impact velocity for the model weight 2.42 kg in reaching the impact points S1, S2, S3, S4 are obtained 0.007 cm/sec, 0.020 m/sec, 0.033 cm/sec, and 0.047 m/sec, respectively. For the ship model weight 7.29 kg, the impact velocity at S1, S2, S3, S4 is 0.01 m/sec, 10.015 m/sec, 0.017 m/sec and 0.018 m/sec, respectively. Figure 8 shows the peak pressure coefficient at impact points for each impact angle. The tendency of the peak pressure coefficient at the sequenced impact points S1, S2, S3, S4 is similar for all impact angles 0°, 10°, 20°, and 30°. The peak pressure coefficient tends to decrease acting on bow flare in increasing the bow immersed (vertical impact point). However, the peak pressure coefficient decreases steeply and gradually in a small discrepancy from the body immersed 0.01 m to 0.03 m. In the comparison result of the peak pressure coefficients, the peak pressure coefficient for the impact angle 0° and ship model weight 7.29 kg is highest in increasing bow immersed.



(a) Model weight 2.42 kg (b) Model weight 7.29 kg

Figure 7. the Tendency of Peak Pressure due to Model Weight in Increasing the Relative Impact Angle

The overall result of the peak pressure coefficient for the model weight 7.29 kg, as shown in Figure 8b is higher than the ship model weight of 2.42 kg, as shown in Figure 8a. Based on Figure 8, the peak pressure coefficients due to the ship model weight of 7.29 kg in the impact point S1 (nearest bottom part) are higher than 1.0 for all impact angles, and there are two peak pressure coefficients due to the weight of 2.42 kg in the impact point S1 (nearest bottom part) are higher than 1.00 given by the impact angle 0° and 10°. The peak pressure coefficient higher than 1.0 indicates that a ship suffers high impact pressure, and this condition can be a ship that leads possible to damage.

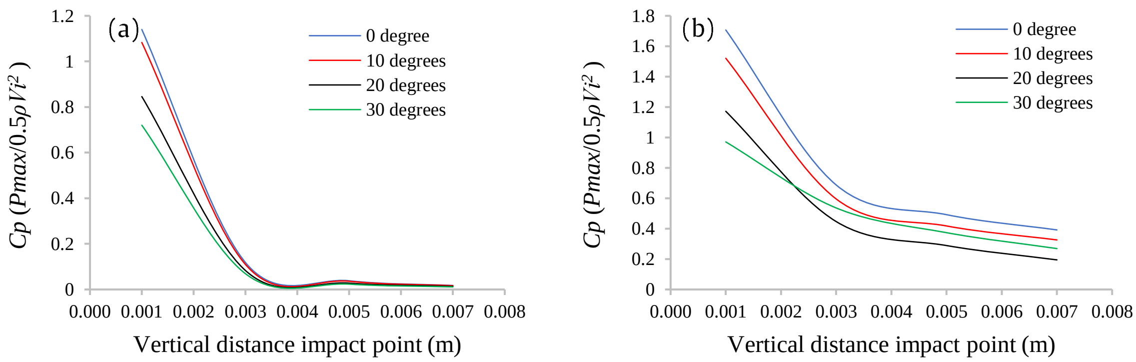


Figure 8. the Peak Pressure Coefficient in Vertical Distance Impact Point Influenced by the Model Weight; (a) 2.42 Kg, (b) 7.29 Kg

Based on the discussion above, this present result emphasizes a notable finding that a ship in slamming conditions experiences the dynamic responses of the high impact pressure in the bottom and bow part with a small impact angle. The ship with full loading condition and a small impact angle in the slamming event is also induced by the high peak impact pressure and leads to the most vulnerable damage. Therefore, the ship with full load conditions in slamming conditions has to be an attention to the ship navigation. In addition, the ship experiences water on deck, and the bow diving phenomenon possible occurs when the impact angle becomes larger. Regardless, the bottom and bow parts of a ship should be designed properly to reduce impact pressure due to slamming conditions.

4. Conclusion

The influence of the impact angle in the slamming event, the peak pressure decreases in increasing the impact angle. Also, the vertical position of the impact point in the bow flare affects impact pressure induced by slamming. The impact pressure decreases steeply in a short duration after reaching the peak pressure. The tendency of peak pressure in increasing the impact angle is similar to acting on the bow flare.

Regarding the effect of ship weight, the peak pressure decreases relatively small value due to the small impact angle. It tends to decrease steeply with the significant value by the high impact angle. The discrepancy of the peak pressure is relative in the same value acting on the nearest bottom part along increasing impact angle, and it is different on the high bow part.

In increasing the ship's weight, the peak pressure decreases relatively with the same value in each increasing impact angle of the bow flare to free-water surface.

The tendency of the peak pressure coefficient in the immersed bow flare is similar for any impact angle of the bow flare. The peak pressure coefficient tends to decrease acting on bow flare in increasing the immersed bow flare. However, the peak pressure coefficient decreases steeply and gradually in a small discrepancy from the immersed bow flare in the nearest bottom part.

The peak pressure coefficient due to the full load condition is highest in the nearest bottom part. However, the peak pressure coefficients due to the lightship condition highest in the nearest bottom part caused by the small impact angle. The highest peak pressure coefficient in the nearest bottom part indicates the ship bow suffers high impact pressure, and this condition can be a ship bow that leads possible to damage.

This present result emphasizes a notable finding that a ship in slamming conditions experiences the dynamic responses of the high impact pressure in the bottom and bow part with a small impact angle. Moreover, the ship experiences water on deck, and the bow diving phenomenon possible occurs when the impact angle becomes larger. Regardless, the bottom and bow parts of a ship should be designed properly to reduce impact pressure due to slamming conditions.

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