The Effect of Bulbous Bow on the Probability of Slamming on Hull (Case Study on Container vessel 4200 DWT)

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Abstract. One of the environmental factors that influence the probability of a ship accident is the wave height. Extreme wave height can cause the bow of the ship crashing on the surface of the sea water (slamming). Slamming can cause local buckling and deformation on the ship's bottom plate at the bow. At certain conditions the slamming can cause damage to the ship's bow structure. This research discussed the effect of using bulbous bow on slamming probability on 4200 DWT container vessel. The analysis was carried out at 1.5 - 3 meter wave height conditions, according to the wave height conditions on this ship's shipping route in Makassar Strait. The geometrical dimension is LPR = 2.116 m, BB = 2.805 m and ZB = 2,42 m. The analysis of the motion response of the ship is carried out on two types of motion heaving and pitching. In maximum draft conditions, 5.5 meters and speed 11.9 knots (6.12 m/s) and a heading angle of 180°. The next step is calculation of response spectrum by multiplying the wave spectrum with RAO. From the analysis, known that higher wave produced greater response of heaving and pitching motion. And also higher wave produced higher relative bow motion spectrum. The probability of slamming of 4200 DWT ships with bulbous bow is smaller than without bulbous bow. At a certain wave height (2-3 meters) indicates that the bulbous bow reduces the slamming probability approximately 17-49%. The intensity slamming per hour of 4200 DWT ships with bulbous bow is smaller than without bulbous bow. It is indicates that the bulbous bow reduces the slamming intensity per hour approximately 24-45%.

1. Introduction
One of the environmental factors that influence the probability of a ship accident is the wave height. Extreme wave height can cause the bow of the ship crashing on the surface of the sea water (slamming). Slamming caused extremely high loads to ship structure. Small or medium slamming was known to be the cause of local buckling and deformation on the bottom plate of the ship's bow. For example in July 2013, a container ship accident occurred at Banggai Sea, Central Sulawesi, Indonesia. This ship accident happened because the ship was hit by the waves, which caused damage to the ship’s bow structure so that the ship sank. The slamming effect caused by the wave on the bow of the ship, can be reduced by installing bulbous bow on the ship [8]. Bulbous bow interfering the waves coming from the bow, so the wave energy around the hull will be reduced and the slamming effect can be minimized. [9] In this study discuss the effect of bulbous bow to the probability of slamming on the hull of container vessel 4200 DWT. Initially this ship was designed without a bulbous bow. This ship sails in Makassar Strait waters. The wave height in Makassar Strait is about 1-3 meters, so the ship is vulnerable to slamming. In this study the design of the bow of ship model was changed by adding
elliptical bulbous bow. Then the designed hull is analyzed to get the probability of slamming. The analysis was carried out at 1.5-3 meters wave height conditions, in accordance with the wave height conditions on this ship route in the Makassar Strait. The analysis also carried out on the ship’s hull without bulbous bow as a comparison of slamming probability.

2. Theory

2.1. Geometry of Bulbous Bow

Bulbous bow dimensions are based on the Linear Form Coefficients parameters as shown in the figure1 [4]:

To determine the dimensions of the bulbous bow using equations 1, 2 and 3

Breadth Coefficients \( C_{BB} \): \( \frac{B_{PR}}{B} \) (1)

Length Coefficients \( C_{LPR} \): \( \frac{L_{PRT}}{L_{PP}} \) (2)

Height Coefficients \( C_{ZB} \): \( \frac{Z_B}{T_{FT}} \) (3)

Where:

LPR is length of bulbous bow from fore perpendicular
BB is breadth of bulbous bow at the fore perpendicular
ZB is height of bulbous bow from baseline.

The linear form coefficients shown on the table 1 as follows:

| Table 1. Linear Form Coefficients |
|-----------------------------------|
| (source: KRACHT, Design Of Bulbous Bow) [4] |
| Min | Max | Used |
|-----|-----|------|
| \( C_{BB} \) | 0.17 | 0.20 | 0.17 |
| \( C_{LPR} \) | 0.018 | 0.031 | 0.023 |
| \( C_{ZB} \) | 0.26 | 0.55 | 0.44 |

2.2. Sea keeping Criteria

The results of sea keeping calculations are evaluated according to the standard of sea keeping criteria. In this study, the probability of slamming as sea keeping criteria is refers to the Nordfoks 1987 criteria, as per shown in Table 2. [10].
Table 2. Probability of Slamming criteria (source: Nordfoks 1987)

| Criteria               | Merchant Ship | Naval Vessels | Fast Small Craft |
|------------------------|---------------|---------------|------------------|
| Slamming (Probability) | 0,03 (L ≤ 100 m) | 0,01 (L ≥ 300 m) | 0,03             | 0,03             |

2.3. Response Amplitude Operator (RAO)

The response of ship movements to regular waves is expressed in RAO (Response Amplitude Operator). RAO is the ratio between the amplitude of the ship's motion (both translational and rotational) to the amplitude of the wave at a certain frequency. The ship motion response to random waves described by the response spectrum. Response spectrum is obtained by multiplying the wave spectrum ($S_\zeta$) by $RAO^2$ as per shown in Equation (6). [10]

$$RAO = \frac{z_0}{\xi_0} \text{ (m/m)} \quad (4)$$

$$RAO = \frac{\theta_0}{\kappa_0} \text{ (deg/m)} \quad (5)$$

$$S_\zeta = RAO^2 S_\zeta(\omega) \quad (6)$$

2.4. Wave Spectrum

In this study, wave spectrum is based on Bret Schneider or ITTC as per shown at Equation 7. Significant of wave height ($H_s$) depend on the type of waters at ship route. [10] [11]

$$S(\omega_w) = \frac{0.0001 g^2}{\omega_w^5} e^{-3.11/H_s \omega_w^4} \quad (7)$$

Due to the influence of the speed of the ship and the incident wave angle, so the frequency of incident wave ($\omega_w$) will turn into encountering wave frequency ($\omega_e$). Equations 8 and 9 used to calculate the frequency and spectrum of encounter waves. [10]

$$\omega_e = \omega_w - \frac{\omega_w^2 V}{g} \cos \mu \quad (8)$$

$$S(\omega_e) = S(\omega_w) \frac{1}{\sqrt{1 - \left(\frac{4 V \omega_w}{g}\right) \cos \mu}} \quad (9)$$

where:

- $\omega_e$ = encountering wave frequency (rad/s)
- $\omega_w$ = wave frequency (rad/s)
- $V$ = ship speed (m/s)
- $g$ = gravity (9.81 m/s²)

2.5. Vertical Relative Motion

According to Dynamic of Marine Vehicles by Bhattacharyya (1978), the vertical motion of the ship was formulated as follows: [10] [11]

$$z_b = z + \xi \cos \theta \quad (10)$$

Based on the equation 2.10, we get the coupled Heaving and Pitching equation as follows:

$$z_b = z_a \cos (\omega_e t + \xi) \cos (\omega_e t + \xi \theta) \quad (11)$$

where:

- $z_b$ = combined relative motion
\((z_b)\) = amplitude of movement at point b
\[= z^2 + (\xi \theta)^2 + 2z \xi \theta \cos (\varepsilon + \varepsilon_\theta)\]
\(\varepsilon_b\) = motion phase angle at point b
\[= \frac{Z \sin \varepsilon + \Xi \sin \varepsilon \theta}{Z \cos \varepsilon + \Xi \cos \varepsilon \theta}\]

Vertical movements occur at each point along the ship over regular waves. This movement occurs due to a couple movement between the heave and pitch movements. So that allows the difference in movement at each point along the ship. [10]

2.6. Vertical Velocity
According to Dynamic of Marine Vehicles by Bhattacharyya (1978), vertical motion is heave and pitch. Heave and pitch motion are centered on the center of gravity of the ship. The motion of the ship on regular waves will be harmonic. Equation 12 and 13 used to get vertical velocity at any point respect to CG. [11]

\[Z^2 = \omega_e (Z^2_a + \omega_e \Xi_a (\theta) a^2 + 2(Z_{\theta})_a \Xi \cos (\varepsilon_\theta - \varepsilon_\theta))\]  
\[\text{where:}\]
\(Z^2_a\) = heave speed amplitude on CG (m/det)
\((\theta)_{a}\) = the amplitude of the pitch speed in CG (rad/det)
\(\omega_e\) = encountering frequency
\[= \omega_w \{1 - (\omega_w V \cos \mu / g)\}\]
\(\omega_w\) = wave frequency (rad/sec)
\(\mu\) = angle of wave
\(Head\ seas\ \mu = 180^\circ\)
\(following\ seas\ \mu = 0^\circ\)
\((Z)_{\theta}\) = \(\omega_e Z_\theta\) or \((Z)_{\theta}\) = \(\omega_e (Z_{\theta})_{a}\)

2.7. Relative Bow Motion
Equation 14 is used to calculate relative bow motion in regular wave. [11]

\[S_S = S_z + (X \cdot \theta) - S_z\]  
\[\text{where:}\]
\(S_S\) = Spectral density relative bow motion
\(S_z\) = Spectral density response spectrum of heave motion
\(S_\theta\) = Spectral density response spectrum of pitch motion
\(S_{z \theta}\) = Spectral density wave encounter spectrum
\(X\) = CG distance to the bow of the ship (m)

2.8. Slamming Probability
Calculation of the probability of slamming using equation (15)

\[P \{\text{slamming}\} = \exp y\]  
Calculation of slamming intensity using Equation (16)

\[N_w = \frac{1}{2\pi} \sqrt{\frac{2m_0 S}{2m_2 S}} \times P \{\text{slamming}\} \times 3600\]  
\[\text{where:}\]
\[ y = \left( \frac{T^2}{2m_0} \right) + \left( \frac{V_{cr}^2}{2m_2} \right) \]
\[ T = \text{Draft (m)} \]
\[ V_{cr} = \text{velocity threshold} = 0.093 \ (\text{gL})^{1/2} \]
\[ M_{0s} = \text{The area below the 0th moment response spectrum curve} \]
\[ M_{2s} = \text{The area below the 2th moment response spectrum curve} \]

3. Discussion

This ship has Froude Number (Fn) 0.20, it has been eligible for the requirement of using bulbous bow is (Fn) 0.17-0.23. Principal Dimension of the ship is shown in Table 3:

| Principal Dimension |  |
|---------------------|--|
| Loa                 | 98 m |
| Lpp                 | 92 m |
| B                   | 16.5 m |
| H                   | 7.8 m |
| T                   | 5.5 m |
| Vs                  | 11.9 knot |
| DWT                 | 4200 ton |

3.1. Geometry of elliptical bulbous bow

In this study elliptical bulbous bow was chosen, because this type of bulbous bow is commonly used for ships with U-shape hulls such as container vessel. The geometrical dimensions are based on the linear form coefficients (CBB) from Kracht 1978. The geometrical dimension of designed elliptical bulbous bow (A) is:

\[ \text{LPR} = C_{\text{LPR}} \times Lpp = 0.023 \times 92 = 2,116 \text{ m} \]
\[ \text{ZB} = C_{\text{ZB}} \times T_{\text{FT}} = 0.44 \times 5.5 = 2,420 \text{ m} \]
\[ \text{BB} = C_{\text{BB}} \times B = 0.17 \times 16.5 = 2,805 \text{ m}, \text{BB/2} = 1,4025 \text{ m} \]

The detailed geometrical dimension of this elliptical bulbous bow is shown in Figure 2. The analysis also carried out on the ship’s hull without bulbous bow (E) as a comparison of slamming probability. The body plan of the hull without bulbous bow is shown in figure 3.
3.2. Analysis of Motion Response in Regular Waves
Ship motion response was analyzed at maximum draft (5.5 m) and speed 11.9 knots (6.12 m/s) and heading angle 180° on two types of motion, these are heaving and pitching. RAO heaving and RAO pitching graphs are shown in the figures below.

Based on the graphs on figures 4 and 5, the largest RAO heaving at 5.5 m draft occurred on hull without a bulbous bow, the heaving value is 6.781 m/m at 0.4 rad/s frequency. The biggest RAO pitching also occurred on hull without bulbous bow, the pitching value is 7.824 o/m at 0.4 rad/s.
frequency. Whereas in the ship with bulbous bow has a heaving value of 6.949 m/m at 0.4 rad/s frequency, and the pitching value is 6.949 °/m at 0.4 rad/s frequency.

3.3. Wave spectrum
The next step is calculating the wave spectrum at 1.5 m, 2 m, 2.5 m and 3 m wave height. The wave spectrum is transformed into an encounter wave spectrum. Wave spectrum graphs are shown in figures 6 and 7.

![Wave Spectrum Graph](image)

**Figure 6. Wave Spectrum**

![Wave Encounter Spectrum Graph](image)

**Figure 7. Wave Encounter Spectrum**

Figures 6 and 7 shown that the wave spectrum of significantly different wave heights will produce different spectra. The higher significant wave produces greater spectrum.

3.4. Heaving and Pitching Spectrum Response
The next step is calculating the response spectrum, by multiplying the wave spectrum with RAO. Heave and pitch spectrum response graphs are shown in the figures 8 and 9. Figure 8 and 9 shown that the wave height affect to the heaving spectrum responses. The higher wave produced the greater response of the heaving motion. This happens to both hull designed, with and without bulbous bow. Figure 8 and 9 also show that the heaving spectrum response on ships with bulbous bow is smaller than ships without bulbous bow. The heaving spectrum response value on the ship with bulbous bow is 0.2 at an encounter frequency of 0.82 rad/s, while on a ship without bulbous bow the value is 0.3 at the same frequency.
Figure 8. Heave spectrum response of hull with *Bulbous Bow* (A)

![Heave spectrum response of hull with Bulbous Bow (A)](image)

Figure 9. Heave spectrum response of hull without *Bulbous Bow* (E)

![Heave spectrum response of hull without Bulbous Bow (E)](image)

For the response of pitching motion can be shown in the figures 10 and 11. Figure 10 and 11 shown that the wave height also affect to the pitching spectrum responses. The higher wave produced the greater response of the pitching motion.

Figure 10. Pitch spectrum response hull with *Bulbous Bow* (A)

![Pitch spectrum response hull with Bulbous Bow (A)](image)
Figure 10 and 11 also show that the pitching spectrum response on ships with bulbous bow is smaller than ships without bulbous bow. The pitching spectrum response value on the ship with bulbous bow is 0.6 at the encounter frequency of 0.91 rad/s, while on ship without bulbous bow the value is 0.76 at the same frequency.

3.5. Relative Bow Motion (RBM)
After obtaining the response spectrum of the heaving and pitching motion, the next step is calculating the spectra density of relative bow motion. The relative bow motion graphs are shown in figure 12 and 13. Figure 12 and 13 shown that the wave height affect to spectrum of relative bow motion. Higher the wave, produce the higher spectrum of relative bow motion. The spectrum of relative bow motion on ships with bulbous bow is smaller than the spectrum of ships without bulbous bow. spectrum of relative bow motion value on ships with bulbous bow is 28.13 at encounter frequency 1.01 rad/s, at the same frequency the spectrum of relatief bow motion on ship without bulbous bow is 35.81.
The area of relative bow motion spectrum curve is also calculated to be used in calculating the probability and intensity of slamming. The area of the curve is shown in the table 4.

**Table 4. Curve area of Relative bow motion spectrum**

| $H_s$ (m) | Ship with Bulbous Bow (A) | Ship Without Bulbous Bow (E) |
|-----------|--------------------------|-------------------------------|
| 1,5       | 1,345                    | 1,793                         |
| 2         | 4,487                    | 5,283                         |
| 2,5       | 12,825                   | 17,688                        |
| 3         | 28,982                   | 41,816                        |

**3.6. Relative Vertical Velocity Spectrum**

The next step is calculation of the relative vertical velocity spectrum. Relative vertical velocity spectrum is used to determining probability and intensity of slamming. Relative vertical velocity spectrum is obtained by multiplying RAO relative bow motion with the square of the encounter frequency. Relative vertical velocity spectrum of ship with and without bulbous bow is shown in figures 14 and 15.

**Figure 13. Relative Bow Motion hull without Bulbous Bow (E)**

**Figure 14. Relative Velocity Spectrum hull with Bulbous Bow (A)**
Figure 14 and 15 shown that the value of the vertical velocity spectrum increased if the wave getting higher. The relative vertical velocity spectrum value of ship with bulbous bow is smaller than ship without bulbous bow. The relative vertical velocity spectrum value of ships with bulbous bow is 24.59 at an encounter frequency of 1.01 rad/s, while at ship without bulbous bow is 29.89 at the same frequency.

Furthermore, the relative vertical velocity spectrum curve area is calculated to be used in the calculation of probability and intensity of slamming. The curve area is shown in Table 5.

| Hs (m) | Ship with Bulbous Bow (A) | Ship without Bulbous Bow (E) |
|--------|--------------------------|-----------------------------|
| 1.5    | 2.863                    | 3.316                       |
| 2      | 6.271                    | 8.654                       |
| 2.5    | 14.634                   | 16.996                      |
| 3      | 27.006                   | 32.825                      |

3.7. Probability and Intensity of Slamming

The next step is determining the probability of slamming at several wave heights at full load draft (5.5 m). The comparison of slamming probability of ship with and without bulbous bow is shown in the Table 6. The table shows that the probability of slamming of ship with bulbous bow is smaller than ship without bulbous bow. The decrease in the probability of slamming on ships with bulbous bow is ± 17-49%, at 2-3 meters wave height.

| Hs (m) | Probability of Slamming |
|--------|-------------------------|
|        | Ship with Bulbous Bow(A) | Ship Without Bulbous Bow(E) |
| 1.5    | 0.0000                  | 0.0001                       |
| 2      | 0.0182                  | 0.0360                       |
| 2.5    | 0.2340                  | 0.3362                       |
| 3      | 0.5118                  | 0.6167                       |
While the comparison of slamming intensity of ship with and without bulbous bow shown in Table 7. The table shows that the slamming intensity per hour of ship with bulbous bow is smaller than ship without bulbous bow. The decrease in the intensity of slamming on ships with bulbous bow is ± 24-45%, at 2-3 meters wave height.

| Table 7. Intensity of Slamming per hour |
|----------------------------------------|
| Hs (m) | Ship with Bulbous Bow (A) | Ship without Bulbous Bow (E) |
| 1.5    | 0.001                     | 0.027                        |
| 2      | 8.807                     | 16.113                       |
| 2.5    | 125.577                   | 196.581                      |
| 3      | 303.937                   | 398.991                      |

4. Conclusion
From this analysis known that:
1. The probability of slamming of 4200 DWT ships with bulbous bow is smaller than without bulbous bow. At a certain wave height (2-3 meters) indicates that the bulbous bow reduces the slamming probability approximately 17-49%.
2. The intensity slamming per hour of 4200 DWT ships with bulbous bow is smaller than without bulbous bow. It is indicates that the bulbous bow reduces the slamming intensity per hour approximately 24-45%.

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