# ROLL MOTION CHARACTERISTICS OF SHIP WITH LARGE BREADTH AND DRAUGHT RATIO IN FOLLOWING WAVES

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## SUMMARY

Since the International Maritime Organization decided to revise its intact stability criteria from deterministic based criteria to be performance based one, some researches regarding the ship performance in waves have been conducted by several researches. One of the dangerous condition reccomended to be included in the criteria was the stability of ships in following waves especially for ship with small coefficient for vertical well-sidedness. Ships with large breadth and draught ratio tends to have large the coefficient for well-sidedness. However large roll angle may occur when the ships operate in large significant wave height. The forward speed also could have significant effect on the roll motion characteristics due to time spend of ship in a certain position relative to the wave.

This paper discusses effect of restoring arm variation due to waves characteristics and ship speed on roll motion of ships with large breadth and draught ratio in following waves. The waves characteristics is modelled based on the Beaufort scale and the forward speed is estimated by changing the propeller revolution from 6 rps to 15 rps. The results of numerical simulation and discussions show that amplitude of roll motion significantly affected by variation of the waterline area of the ship in sugging and hogging condition. The large roll angle can be avoided by increasing the forward speed with considering the other dangerous condition such as pure loss of stability and broaching.

## NOMENCLATURE

| | |
|---|---|
| $A_{11}$ | Added mass in surge motion |
| $A_{44}$ | Added inertia of roll motion |
| $B_L$ | Linear damping coefficient of roll ($s^{-1}$) |
| $B_N$ | Nonlinear damping coefficient of roll ($rad^{-1}$) |
| $B(x)$ | Breadth of ship section (m) |
| $D$ | Propeller diameter (m) |
| $GZ_S$ | Righting arm in calm water (m) |
| $GZ_W$ | Righting arm in wave (m) |
| $J$ | Advance coefficient |
| $K_T(J)$ | Trust coefficient |
| $M_W$ | Roll excitation moment (N.m) |
| $P$ | Propeller pitch |
| $R(u)$ | Ship resistance (N) |
| $S(\omega,\chi)$ | Wave spectrum |
| $T(n;u)$ | Propeller trust (N) |
| $V_A$ | Advance velocity (m $s^{-1}$) |
| $W$ | Ship weight (N) |
| $X_W$ | Wave force in surge (N) |
| $Z$ | Number of propeller blade |
| $d(x)$ | Draught of ship section (m) |
| $k$ | Wave number |
| $n$ | Propeller revolution (rps) |
| $t_p$ | Trust deduction factor |
| $u$ | Surge velocity (m $s^{-1}$) |
| $\varsigma_w$ | Wave amplitude (m) |
| $\xi_G$ | Position of gravity in global axis (m) |
| $\phi$ | Roll angle (rad) |
| $\chi$ | Heading angle from wave direction (deg) |
| $\lambda$ | Wave length (m) |
| $\rho$ | Density of water (kg $m^{-3}$) |
| $\psi$ | Wave phase angle (rad) |

## 1. INTRODUCTION

The International Maritime Organization (IMO) decided to revise its intact stability criteria because the current criterion is not applicable to the current ships topology. The present criterion was statistically developed based on the ships topology four decades ago. The criterion is also very difficult to revise because it’s prescriptive nature. Therefore some delegations in IMO proposedthat the new generation of the criteria should be developed in performance based one. The criteria may easily be revised following the evolution of the ship topology. Nevertheless thetested ships should comply with the old criteria.

The new intact stability criterion therefore is separated into two parts namely the old one and the performance based criteria which will be developed. The IMO has agreed that the performance based criteria should be divided into four stages for each dangerous condition may occur in seaways as shown in Figure 1.

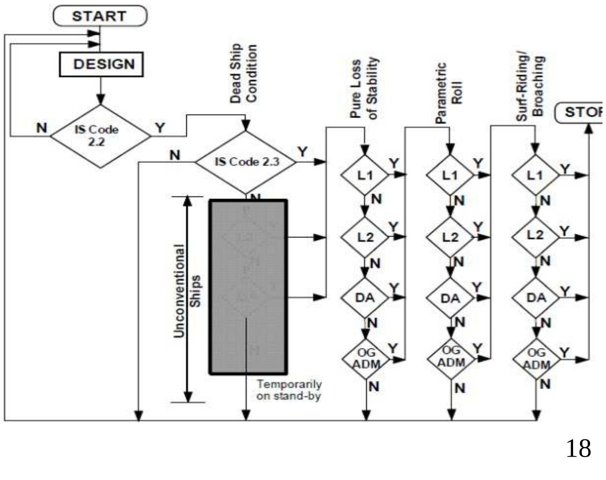

Figure 1. Framework of the new generation of intact stability criteria

For the dead ship condition, the tested ship should comply with the weather criterion in the current criteria. For the others dangerous conditions such as pure loss of stability in following waves, the new criteria is divided into four stages. Belenky, et. al. [1] proposed the total coefficient of vertical wall-sidedness or the variability of hull shape from the maximum dimension over the range of draft as the stage one criteria or vulnerability level 1. Based on 17 tested ships, they propose the range of total coefficient for vertical wall-sidedness of 0.75 to 0.80.Kubo, et. al., [2] proposed the metacentric height estimated using the transver moment of inertia of flat waterplan at the worst water level as the vulnerability crtieria level one. The metacentric height should be positive in such waterline level. For the vulnerability level 2, Belenky, et. al., [1] proposed the duration time of the metacentric height (GM) below the critical value or the significant duration of GM to be negative. The time duration of roll angle exceeds a certain angle is also may be considered as the vulnerability criteria level 2.Bulian[3] proposed a probabilistic approach as the vulnerability criteria level 2. He proposes an analytical method to estimate the probability of GM below the critical value using Gaussian process assumption for the variation of the metacentric height in waves.

The direct assessment of ships performance as the third stage criteria needs a set numerical simulation tools with capability to investigated occurrence of pure loss of stability for several possible sea state in seaways. Umedaet. al[4] proposed mathematic model of roll motion in following waves coupled with the surge motion. The mathematic model was validated with model experiment of past ro-ro passenger ship with good agreement. If the tested ships cannot comply with the three performance criteria level, an operation guidance is necessary as the criteria level four.

Based on the vulnerability level 1 and level 2 proposed by Belenkyet. al. [1], the righting arm variation significantly depends on wave characteristics, ship speed and wave direction relative to the ship. The righting arm variation increases due to increase of the wave height as shown by Umedaet. al. [4].For ships with small coefficient for vertical wall-sidedness, the GM value could be negative when the wave crests on the midship section. The midship section may stay in the wave crests for long duration of time in the ship speed similar with the wave celerity. As a result, the ship may loss her stability or suffering large roll angle due to the negative metacentric height.

Ships with large ratio of breadth and draught usually have coefficient for vertical wall-sidedness larger than 0.75 therefore possibility of the righting or the GM value to be negative when the midship section in the wave crest is very small. The velocity of ships with large ratio breadth and draught is usually slow so that the ship cannot stay in the wave crest for long time duration because the wave will pass the ship with shorter duration of time. Even capsizing dangerous due to pure loss of stability does not identify but the ship may suffering large roll angle due to significant variation of the righting arm especially when operating in rough seas. Therefore a direct simulation is necessary in order to identify roll motion characteristics of ship with large ratio of breadth and draught in following waves.

This paper discusses the roll motion characteristics of ship with large ratio of breadth and draught in following waves. The roll motion characteristics will be identified using numerical simulation. Results of the numerical simulation are used to analysis effect of significant wave height on the roll motion. Effect of time duration for the midship section in the wave crest to the variation of GM value and roll angle can also be investigated by variating the forward speed. This is important in order to provide operation guidance to avoid large roll angle when the ships operate in following waves.

## 2. MATHEMATIC MODELLING OF ROLL MOTION IN FOLLOWING WAVES

Umedaet. al. [4] proposed a coupled of roll and surge motions equation to estimate roll motion of ships in following waves. The couple motions have been validated with model experiment with good agreement. The couple equations of roll and surge motions mathematically are written as follows:

$$(W + A_{11})\dot{u} - R(u) + T(n,u) = X_w(\xi_G/\lambda, \chi) \qquad (1)$$

$$(I_{xx} + A_{44})\ddot{\phi} + B_L\dot{\phi} + B_N\dot{\phi} + W\big(GZ_s(\phi) + GZ_w(\phi,t)\big) = M_w(\chi,t) \qquad (2)$$

There motion equations are developed based on the following coordinate system.

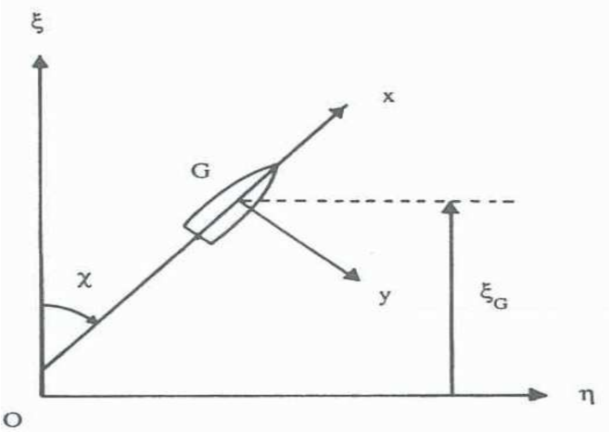

Figure 2. Ordinate system for modelling ship motion in following and quartering seas.

The propeller trust as a function of propeller revolution and surge velocity is estimated using the following equation:

$$T(n,u) = \big(1 - t_p\big)\rho n^2 D^4 K_T(J) \qquad (3)$$

where the thrust coefficient of propeller is estimated using the polynomial equation as shown in equation (4).

$$\mathrm{K}_T(J) = \sum_{n=1}^{39} C_n(J)^{S_n}\left({}^{P}/_{D}\right)^{t_n}\left({}^{A_E}/_{A_0}\right)^{u_n}(Z)^{v_n} \qquad (4)$$

Value of each coefficient in the equation (4) is estimated based on statistical data of B Series propeller as a function of advance velocity [5]. Therefore, the coefficient thrust of propeller can be estimated for variation of ship velocity so that it can be modelled as polynomial equation in order to obtain propeller thrust in a certain ship velocity using the equation (3).

Surge wave force in the equation (1) may be estimated using the method developed by Umeda and Renilson [6] as follows:

$$X_w(\xi_G/\lambda, \chi) = \rho g \varsigma_w k\, cos\chi \int_{AE}^{FE} C_1(x)\, S(x) e^{-\frac{kd(x)}{2}} \times \sin k(\xi_G + x\, cos\chi)\, dx \qquad (5)$$

Coefficient $C_1$ in this equation for each ship section may be estimated using the following equation [7]:

$$C_1(x) = \frac{\sin(k\ \sin\chi . B(x)/2)}{k\ \sin\chi . B(x)/2} \qquad (6)$$

If the surge velocity has been estimated using the equation (1), the ship position relative to the wave can be estimated. Based on this ship position, the restoring arm in calm water and wave may be estimated, respectively. Finally the roll angle can be obtained by solving the equation (2).

## 3. SHIP DATA AND METHODOLOGY

The ship data use in this paper is a ro-ro ferry 600 GT operating as intern island transportation in Indonesia. This ship is designed and built by national shipyard. The main dimension and ratio of main dimension as well as her body plan respectively are shown in Table 1 and Figure 3 as follow.

Table 1. Principle dimension of a ro-ro ferry 600 GT

| Items | | Values |
|---|---|---|
| Length between perpendicular (Lbp) | m | 40.00 |
| Breadth (B) | m | 12.00 |
| Draught (T) | m | 2.15 |
| Height (H) | m | 3.20 |
| Linear damping coefficient ($B_L$) | $s^{-1}$ | 0.008 |
| Nonlinear damping coefficient ($B_N$) | $rad^{-1}$ | 0.0005 |
| B/T | - | 5.58 |
| H/T | - | 1.49 |
| L/B | - | 3.33 |
| L/H | - | 12.5 |

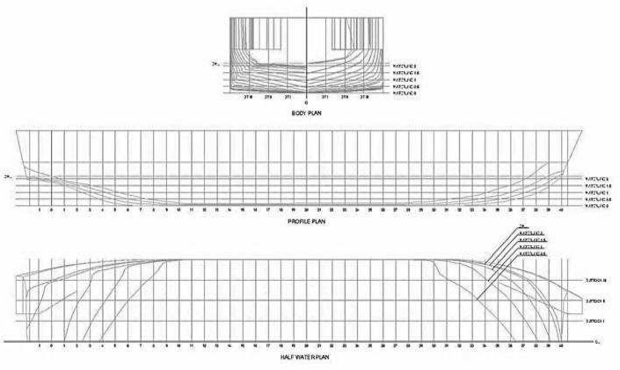

Figure 3. Body plan of subject ship

Characteristics hydrodynamics such as added inertia is estimated by using the strip theory. The roll damping coefficient both linear and nonlinear is estimated by using Ikeda semi empirical method. The surge wave force and the restoring arm in waves are estimated using irregular waves with wave length the same as the ship length. In order to model irregular waves, the ITTC wave spectrum is used and the effective wave profile is modelled by using the Grim effective wave [8]. The wave elevation based on the Grim effective wave can be written as the following equation:

$$\hat{\zeta}_{eff}(x,t) = a(t) + \zeta_{eff}(t)\cos\frac{2\pi}{L}x \qquad (7)$$

where:

$$a(t) = \sqrt{2S\,(\omega,\chi)d\omega d\chi}F_A\cos(\omega t - kx\cos\chi + \psi)$$

$$\zeta_{eff} = \sqrt{2S\,(\omega,\chi)d\omega d\chi}F_C\cos(\omega t - kx\cos\chi + \psi)$$

$$F_A = \frac{\sin Q}{Q}$$

$$F_C = \frac{2Q\sin Q}{(\pi^2 - Q^2)}$$

$$Q = \frac{\omega^2\lambda}{2g\cos\chi}$$

In order to obtain effect of some variable on pure loss of stability in following and quartering waves such the wave height, the wave direction and ship velocity, numerical simulation in time domain is conducted with several different values of those variables. The ship velocity is determined by changing the propeller revolution with assumption that the power and the propeller characteristic are constant. This means that alteration of ship velocity only due to variation of the propeller revolution.

The range of ship velocity used for estimating the resistance is 6 – 15 knots. Based on the estimation results, polynomial equation of ship resistance as a function of ship velocity may be developed. Relationship between the ship velocity and ship resistance is shown in Figure 4 and its polynomial equation shown in the equation (8).

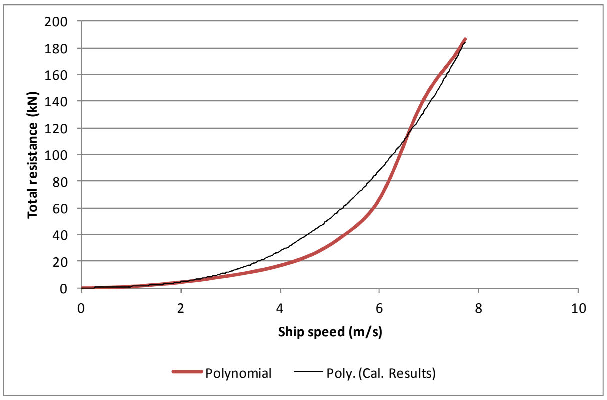

Figure 4. Ship resistance as function of ship velocity

$$R(u) = 0.3904u^3 + 0.6525u \qquad (8)$$

Using the equation (4) for the same variation of ship velocity as the estimation of ship resistance, the thrust coefficient as function of advance velocity can be estimated. Here, the number of propeller blade, propeller diameter and aspect ratio of propeller are assumed to be constant. Variation of ship velocity occurs due to alteration of the propeller revolution will result in difference thrust coefficient. The thrust coefficient for propeller revolution of 9.0 revolutions per second in several advance velocities is shown in Figure 5. The polynomial equation of the thrust coefficient as function of advance velocity is shown in the equation (9).

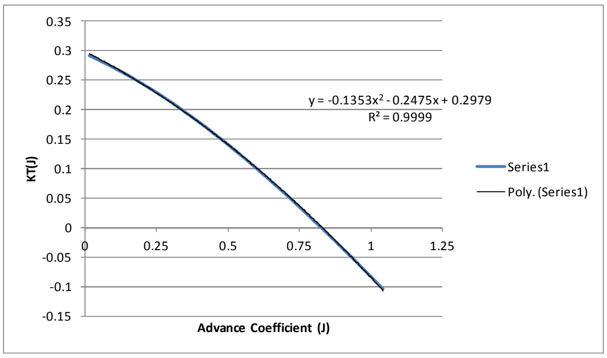

Figure 5. Thrust coefficient of propeller as function of advance velocity

$$K_T(J) = -0.1353J^2 - 0.2475J + 0.2979 \qquad (9)$$

where

$$J = \frac{V_A}{nD}$$

In order to obtain roll motion response, the equation (1) and (2) are solved in time domain using the second order Runga-Kutta method. The restoring arm in wave is calculated by considering the static trim with pressure due to both calm water and Froud-Krylov forces. The subject ship is assumed to have an initial heel angle due to cargo shift on car deck. This condition is possible to occur in Indoensianro-ro ferry especially when the ship operates in rough weather.

In order to investigate the roll motion characteristics in following seas, numerical calculation are conducted for wave condition of Beauport scale 3 – 6 as the most environment condition possible to occur on the route of the subject ship. The ship speed is simulated by changing the propeller revolution from 6 – 15 rps. The wave direction relative to the ship is assumed to be constant of 0 degree (following waves).

## 4. RESULTS AND DISCUSSIONS

Results of numerical simulation for different significant wave height and the propeller revolution of 9.0 rpsis shown in Figure 6. Here the time duration of simulation is 1800 seconds.

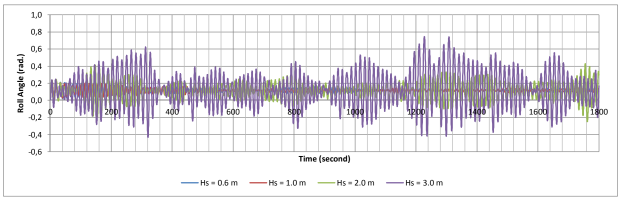

Fig. 6 Roll motion for different significant wave height with propeller revolution of 9.0 rps

Figure 6 shows that the maximum amplitude of roll motion increases when the significant wave height increases. This is because the variation of restoring arm in wave increases when the significant wave height increases. Even the average of vertical wall-sidedness coefficient is larger than 0.75 and the metacentric height in hogging condition for all significant wave heights is positive, the restoring arm variation may be significant due to significantly changes of ship body above the maximum draught especially both after peak and forepeak. Variation of restoring arm for significant wave height of 2.0 meters is shown in Figure 7. The alteration of the restoring arm variation for each significant wave height is smaller compared with the restoring variation of the container ship using by IMO as sample ship in the developing of the new generation intact stability criteria [1]. The large roll angle here may be also caused by small damping coefficientt of roll motion.

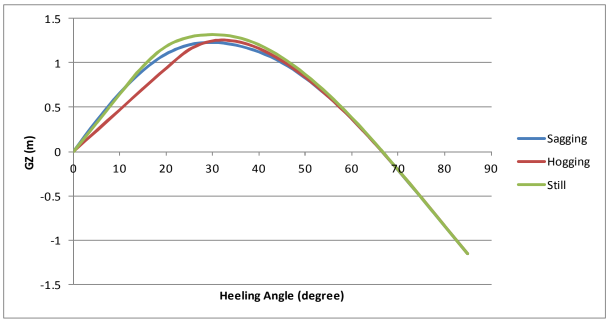

Figure 7. The restoring arm in calm water and wave. The

significant wave height is 2.0 meters.

Figure 8 shows variation of the metacentric height for three different significant wave height. The amplitude of the metacentric height variation also increases when the significant wave height increases. The inertia of waterline area increases due to increase of the significant wave height when the ship in sugging condition. When the ship in hogging condition the momen of inertia decreases due to increase of the significant wave height. Therefore the maximum and the minimum amplitude of the metacentric height tends to increase when the significant wave height increases. This means that the roll motion in following seas depends on the significant wave height and the hull form of the ship. This results conform with the previous result conducted by Belenky et. al [1]. Even the restoring arm is still positive when the ship in hogging condition but the large variation may induce dangerous condition for ship in following waves.

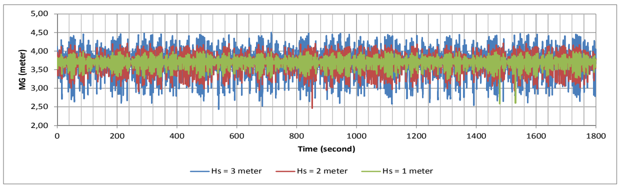

Fig. 8Variation of metacentric height in wave

Figure 9 shows effect of ship forward speed on the roll motion in following waves. Here the significant wave heigth was 2.0 meters and the time duration of 1800 seconds. The roll angle tends to decreases when the ship forward speed increases. The forward speed affect time of ship spend on a certain posisition to the wave. The restoring arm tends to be constant on the time and the roll angle tends to be smaller.

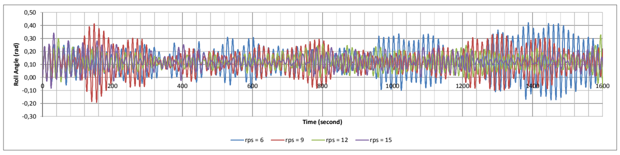

Fig. 9 Roll motion for significant wave height of 2.0 meters and the mean wave period of 5.5 seconds

Figure 10 show the simulation results of the metacentric variation for four differenct forward speed with the simulation time of 1800 seconds. The metacentric vatiation tends to increases when the forward speed increases. The periode of the variation also increases due to higher forward speed. This means that the periode of the exciting moment becomes longer and the roll angle tends to be decreases when the forward speed increases.

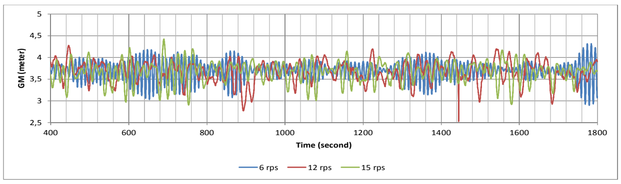

Fig. 10 Roll motion for significant wave height of 2.0 meters and the mean wave period of 5.5 seconds

This results show that the large roll angle in following seas can be avoided by increasing the forward speed. However in cases of negative metacentric height when the ship in hogging condition, the longer duration in a certain position in waves may induce another dangerous condition due to pure loss stability as shown by Belenky et. al. [1]. When the wave length is more than one and half of the ship length, another dangerous condition may also occurs such as surf-riding followed by broaching [9]. Therefore an advance study should be conducted focusing on the others dangerous condition may occur when the ship operating in following waves.

## 5. CONCLUSIONS

Numerical simulation of roll motio in following seas using two degree of freedom mathematic model. The mathematic model is roll motion coupled with surge motion has been conducted. The simulation was conducted for four different significant wave hegiht based on the Beaufort scale with different forward speed. Based on the simulation results and discussion some conclussions can be remarked as follows:

1. Roll angle significanlty depends on the alteration of the waterline characteristic when the ship position relative to the wave in sugging and hogging conditions. When the difference of waterline area between sungging and hongging condition increases the roll angle tends to increases because the restoring arm variation as the main factor induce roll motion in following seas also increases.
2. Roll angle depends on the periode of righting arm variation. The restoring arm tends to be constant on the time spent by the ship in a ceratain position in waves. As a result the roll angle decreases when the periode of restoring arm variation increases.
3. An advance research is neccessary to conduct regarding the effect of forward speed especially when the wave length is longer than one and half of the ship length because another dangerous condition may occur for ships operate in following waves. In cases of negative metacentric height when the ship in hogging condition, pure loss of stability is the other dangerous condition should be investigated for ship with higher forward speed.

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