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Ship's Maneuverability in Strong Wind

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Abstract : *This paper deals with effect of wind forces and moment acting on the training ship SAE NURI. The results of drift angle and counter rudder angle due to wind effect are calculated by using the static equilibrium method especially with nonlinear mathematical expression, and then the critical wind velocity is found out. The given results can be applied directly to T/S SAE NURI in handling under the wind condition and used for merchant ships as a referential tool.*

Key words : *Ship's maneuverability, Drift angle, Critical wind velocity.*

1. Introduction

When a vessel is navigated by sailors, it is difficult for them to determine all the environmental effects especially the influence of wind forces and moment because the ship course is unfixed and the sphere of ship's activity is always changed. It is helpful for navigators if they are able to specify the critical wind velocity at certain direction, then base on ship's particulars and maneuverable characteristics the counter rudder angle or power of thrusters would be given out to maintain ship's course or maneuver it. Relative wind speed and direction measured on board ship are usually by cup anemometer and weather vane mounted at some convenient position above the bridge therefore we can use these values to compare with results in this study by using calculated table or graphs.

Many studies and papers relate to effect of wind to ship's maneuverability have been published, Hasegawa and Im (2002) introduced comparison method in which wind forces and moment were compared with rudder and thrusters forces and moment respectively. D. Hara (2006) calculated ship motion under the wind pressure using the simulation without giving out the value of critical wind velocity. More recently, Lee (2007) used linear mathematical expression and equilibrium equation to calculated critical wind velocity. This research was successful as the effects of the wind to ship maneuvering were clearly verified but these results seem not to be satisfied due to the simple linear equations using by author.

In this study, we used non-linear method to calculate the critical wind velocity so that the result would be more reasonable and correct in comparison with some previous published researches, the combination of using both rudder and bow thruster was also mentioned. This paper deals with effect of wind forces and moment acting on the training ship SAE NURI, the results of drift angle and counter rudder angle due to wind effect are calculated by using the static equilibrium method. The given results in this study can be applied directly to T/S SAE NURI in handling under the wind condition and used for merchant ships as a referential tool or utilized as educational materials.

2. Mathematical ship model

In this study, the training ship SAE NURI was adopted as a ship model; principal particulars are given in Table 1, general arrangement and axes coordinates of ship model of the ship are produced in Fig. 1 and Fig. 2 below:

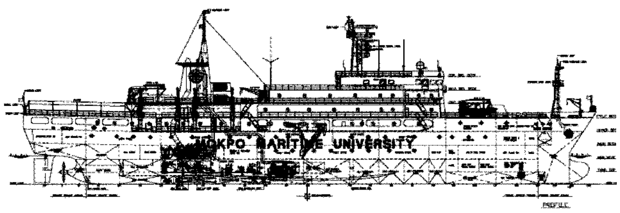

Fig. 1 General arrangement of ship model

In general, the equation for ship's maneuvering motion can be expressed by the coupling motion of surge, sway and yaw. Then, the coordinate systems can be shown as Figure 2. Let O-x0y0z0 be the earth-fixed coordinate and G-xyz be the body-fixed coordinate system.

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Table 1 Principal particulars of the T/S ship

Type	*Training ship*
LOA	*103[m]*
Lpp	*94[m]*
Width	*15.6[m]*
Draft	*5.4[m]*
Thruster (bow)	*49000N*
Transverse Projected area	*183.3[m²]*
Lateral Projected area	*1053.7[m²]*

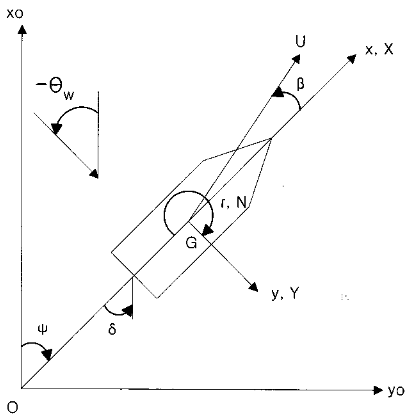

Fig. 2 Coordinate systems

According to Katsuro Kijima (2000), the equation of ship maneuvering motion is introduced as follow:

$$(m'+m'_x)(\frac{L}{U})(\frac{\dot{U}}{U}\cos\beta-\dot{\beta}\sin\beta)+(m'+m'_y)r'\sin\beta=X' \quad (1)$$

$$(m'+m'_y)(\frac{L}{U})(\frac{\dot{U}}{U}\sin\beta+\dot{\beta}\cos\beta)+(m'+m'_x)r'\cos\beta=Y' \quad (2)$$

$$(I'_{zz}+J'_{zz})(\frac{L}{U})(\frac{\dot{U}}{L}r'+\frac{U}{L}\dot{r}')=N' \quad (3)$$

Where X', Y' are the non-dimensional external forces in the x and y direction, respectively. N' is non-dimensional moment about z-axis through the center of gravity of ship. As the MMG model expression, the non-dimensional external forces and moment acting on a ship can be written as follows:

$$X' = X'_H + X'_P + X'_R + X'_W + X'_t \quad (4)$$

$$Y' = Y'_H + Y'_R + Y'_W + Y'_t \quad (5)$$

$$N' = N'_H +' N'_R + N'_W + N'_t \quad (6)$$

Where the subscriptions: H, P, W, R, and t represent the hull, propeller, wind, rudder and thruster components respectively. The hydrodynamic forces acting on the hull are expressed in the form of non-linear terms, hydrodynamic force coefficients were obtained from a research by Kijima and hydrodynamic forces were also calculated by non-linear equations:

$$X'_H = X'_{\beta r}\frac{rL}{U}\sin\beta + X'_{uu}\cos^2\beta \quad (7)$$

$$Y'_H=Y'_\beta\beta+Y'_r\frac{rL}{U}+Y'_{\beta\beta}\beta|\beta|+Y'_{rr}\frac{rL}{U}\left|\frac{rL}{U}\right|+Y'_{\beta\beta r}\beta^2\frac{rL}{U}+Y'_{\beta rr}\beta\frac{r^2L^2}{U^2} \quad (8)$$

$$N'_H=N'_\beta\beta+N'_r\frac{rL}{U}+N'_{\beta\beta}\beta|\beta|+N'_{rr}\frac{rL}{U}\left|\frac{rL}{U}\right|+N'_{\beta\beta r}\beta^2\frac{rL}{U}+N'_{\beta rr}\beta\frac{r^2L^2}{U^2} \quad (9)$$

The hydrodynamic forces and angular moment generated by the rudder angle can be expressed by considering the rudder's normal force and the rudder angle as follow:

$$X_R = -(1 - t_R)\ F_N \sin\delta \quad (10)$$

$$Y_R = -(1 + a_H)\ F_N \cos\delta \quad (11)$$

$$N_R = -(x_R - a_H x_H)\ F_N \cos\delta \quad (12)$$

where, F_N is rudder normal force acting on rudder,

$$F_N = \frac{1}{2}\rho A_R U_R^2 f_\alpha \sin\alpha_R \quad (13)$$

And on the simply way, propeller thrust can be described in term of longitudinal force of propeller:

$$X_P = (1-tP)T \quad (14)$$

$$T = \rho D^4 n^2 K_T(J) \quad (15)$$

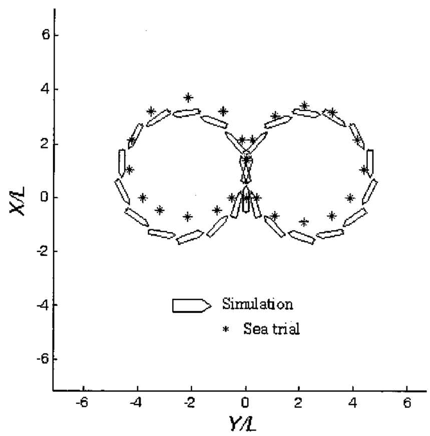

Fig. 3 Turning circle test (σ = ±35⁰)

Fig. 3 shows the result for simulation of turing circle test comparing with sea trial result to verify the ship mathematical model. Sea trial test was conducted in conditions: sea state 5, wind velocity 10kts, wind direction when taking starboard turn was 15^0 off starboard side, port turn was 20^0 off port side at full load condition and simulation was carried out without disturbances.

As we already knew, wind forces and moment acting on ship's hull and superstructure mostly depend on the vessel's type and shape. Those parameters are represented by the coefficients of wind forces and moment. There are several methods to determine the coefficients of wind forces and moment. For wind model adopted, the Isherwood model (1972) is chosen and steady wind is considered, the curves for coefficients of wind forces and moment are given in Fig. 4 below:

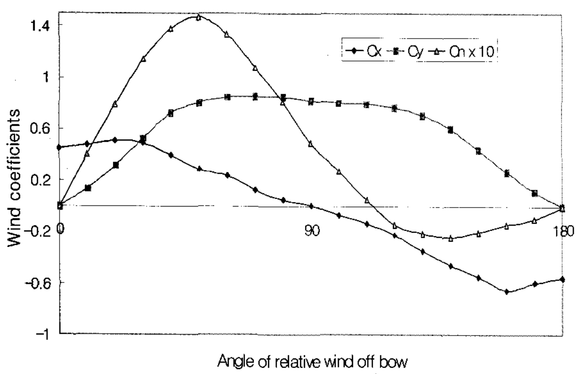

Fig. 4 Coefficients of wind force and moment

Then, wind forces and moment are expressed as follow:

$$X_W = \frac{1}{2} C_x \rho A_T U_W^2 \tag{16}$$

$$Y_W = \frac{1}{2} C_y \rho A_L U_W^2 \tag{17}$$

$$N_W = \frac{1}{2} C_n \rho A_T L_{OA} U_W^2 \tag{18}$$

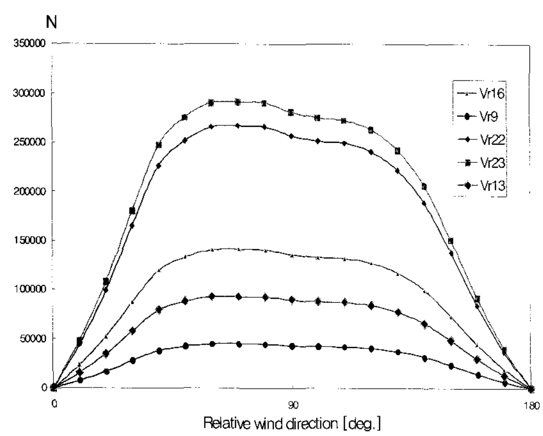

Fig. 5 Curves for wind side forces

The results for wind side force at equations (17) are shown in Fig. 5 and Fig. 6 displays the curves for wind-induced yawing moment at equation (18).

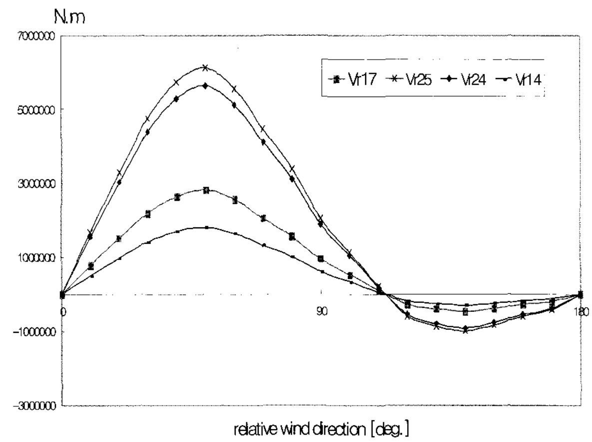

Fig. 6 Curves for wind-induced yawing moment

In the last step, the maximum of turning moment due to the side thruster is calculated according to the equation (19).

$$Tt = Tb \times Db \tag{19}$$

where *Tb* is output of bow thruster, *Db* is distance between center of ship and bow.

3. Critical wind calculation

With the relative wind on or abaft the port beam, all ships require starboard helm and vice versa. As the speed is reduced, the ship will come up into the wind if the rudder angle is held in constant. The closest approach to the wind as speed is reduced with full rudder on constitutes a critical wind angle. This angle is maximized by having the lateral center of area of the above-water parts ahead of the lateral center of area of the below-water parts. If the above-water lateral center of area is far behind that of the hull, especially if the rudder effectiveness is low, the critical angle will become very small and the ship will actively seek the wind. In other words, critical wind velocity, that is, the wind velocity below which the ship can maintain its present course using its counter rudder angle and thruster.

3.1 Counter rudder angle and drift angle

To calculate the critical wind velocity, equilibrium equations are suggested as H. Yasukawa's method (2003), it means that when the ship can maintain her course or ship can keep its position in one fixed point, total the external forces and moments acting on ship are equilateral and the sum of those forces and moments must be zero, respectively as follow:

$$0 = Y'_H(\beta) - (1 + a_H)F'_N(\beta,\delta)\cos\delta + Y'_W(U_W,\theta_W) \quad (20)$$

$$0 = N'_H(\beta) - (x'_R + a_H x'_H)F'_N(\beta,\delta)\cos\delta + N'_W(U_W,\theta_W) \quad (21)$$

from equations (20), (21) with $F'_N\cos\delta$ is annulled we have:

$$(Y'_H + Y'_W)(x'_R + a_H x'_H) - (N'_H + N'_W)(1 + a_H) = 0 \quad (22)$$

In case of using equilibrium equation, it means that the ship making only advance equally movement without turning motion so that the yaw rate of ship r in expressions (7), (8), (9) must be equaled with zero ($r = 0$), substitute those hydrodynamic coefficients into equation (22) we can get the following:

$$[(1 + a_H)\,N'_{\beta\beta} - (x'_R + a_H x'_H)\,Y'_{\beta\beta}]\,\beta^2 + [(x'_R + a_H x'_H)\,Y'_\beta - (1 + a_H)\,N'_\beta]\,\beta + [(x'_R + a_H x'_H)\,Y'_W - (1 + a_H)\,N'_W] = 0 \quad (23)$$

Solve equation (23) with $\theta_W = 0 - 180$ deg. and ratio speed of wind and ships' speed U_W/U, drift angle β and counter rudder δ were calculated, these values are expressed in Fig. 7 and Fig. 8.

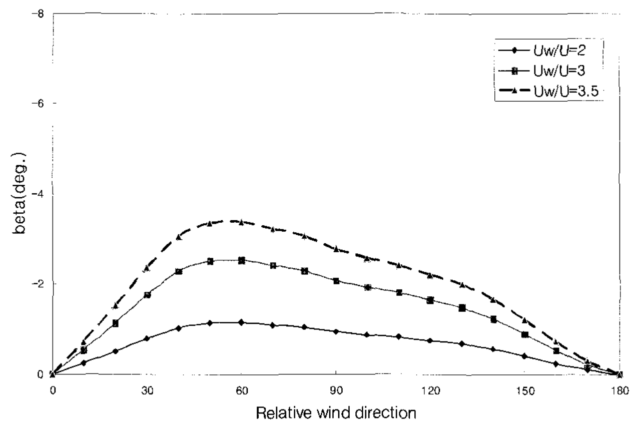

Fig. 7 Variation of drift angle due to relative wind velocity and direction

In this case, the ship speed is 7m/s and the ratios of wind relative velocity to ship speed (U_W/U) = 2, 3, 3.5 ……in succession, substitute these values to equation (17) then counter rudder angles are gained.

$$\delta = \frac{\arcsin\left\{2\dfrac{(Y'_H + Y'_W)LdU^2}{(1 + a_H)A_R U_R^2 f_\alpha} + \sin\gamma\beta\right\} + \gamma\beta}{2} \quad (24)$$

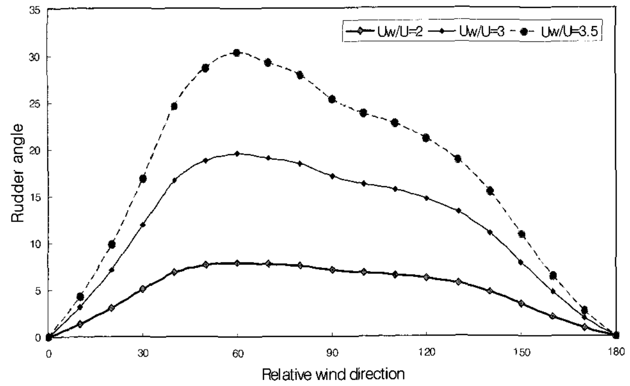

Fig. 8 Counter rudder angle due to relative wind

Base on Fig. 8 it is easy to find that with each value of wind velocity and direction, the counter rudder angle will be equaled in vertical axis of graph or users can interpolate if the velocity is in odd number. For example if the ratio of wind velocity and ship speed is 3.5 (Uw/U =3.5) with relative direction about 60^0 then the counter rudder angle should be 30^0 positive. It can be similarly done with Fig. 7 when the users want to find out the drift angle caused by wind in certain wind direction and value of relative velocity, for example, if wind velocity is 3.5 times greater than ship speed at direction of 60^0 it would make the ship drifting at angle of almost 5^0.

3.2 Critical wind velocity

There is one more problem that with fixed rudder angle in advance how critical wind velocity (U_W/U) and drift angle β are computed, deal with this matter, we consider the set of equations (17), (18) with δ is fixed then critical wind velocity (U_W/U) and drift angle β are calculated as follow:

$$\beta = \frac{(AY'_\beta - N'_\beta) + \sqrt{(AY'_\beta - N'_\beta)^2 - 4(N'_{\beta\beta} - AY'_{\beta\beta})(AY'_R(\delta) + N'_R(\delta))}}{2(N'_{\beta\beta} - AY'_{\beta\beta})} \quad (25)$$

and,

$$\frac{U_W}{U} = \sqrt{\frac{Y'_R(\delta) - Y'_\beta\beta - Y'_{\beta\beta}}{A_1}} \quad (26)$$

where $A_1 = \dfrac{\rho_A A_L C_y}{\rho L d}$, $A = \dfrac{L_{OA} C_n}{L C_y}$

Solved these expressions with fixed δ = *20, 35* deg., θ_W = *0-180* deg. then we gained results which are displayed by Fig. 9 and Fig. 10 below:

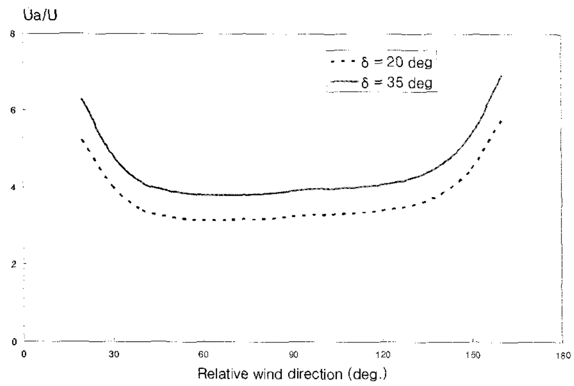

Fig. 9 Critical wind velocity with fixed rudder angle

When we take a look at Fig. 9, the model ship kept her course to one fixed point under the wind effect without any deviation by using rudder, the critical wind velocity in the vertical axis is equaled with each rudder angle value and depended on the relative wind direction. For example, in case θw ~ *120* deg. δ = *15* deg. so Uw/U = *3.5*, compare with present ship speed, it is easily to find out the critical wind velocity. It can be done similarly to verify with such critical wind velocity, how drift angle is in Fig. 10. In fact, the results of β, Uw/U should be printed in table for detail but when looking at these figures, the users have a general view and the change of these value is recognized without difficultly.

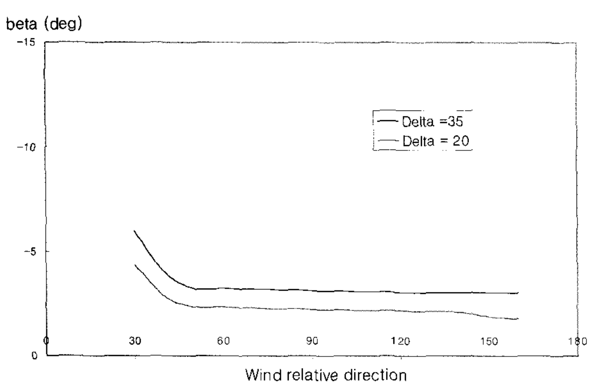

Fig. 10 Variation of drift angle due to relative wind velocity and direction with fixed rudder angle

When calculating the hydrodynamic forces and moment, due to complicated equations, some researchers only used the first element but omitted the other elements in hull forces and moment computing, it means that these results seemed to be approximate, for example the equations used by Lee (2007).

In this study, non-linear expressions (such as equation 20) were used to compute hydrodynamic forces and moment so that the critical wind velocity is much more detail and seems to be satisfied.

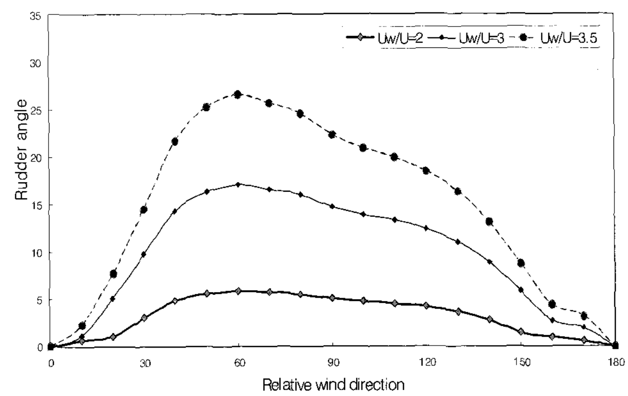

Fig. 11 Combination with bow thruster

When the vessel enter port areas or congested waters, the ship speed would be kept in certain reasonably value, for SAE NURI model, if her speed is less than 5 knots bow thruster should be used due to strong wind. The maximum output of bow thruster is 49KN (Table 1) and the calculation of moment was displayed in equation (19). The effective combination between rudder and bow thruster is shown in Fig. 11. We can easily recognize that with the assistance of bow thruster the value of counter rudder angle would be reduced about 20% by having a comparison with the result in Fig. 8.

4. Conclusion

In this paper, the results of drift angle and counter rudder angle due to wind effect were calculated by using the static equilibrium method to study the effect of strong wind to ship's maneuverability. Non-linear method was used to find out critical wind velocity in certain direction, it means that these results would be more satisfied than some data was published before, the combination of using both rudder and bow thruster was also mentioned in this study. The calculous result tables and figures lead to the following conclusions

(1) At normal operating speed (7m/s), when wind velocities are 14, 21, 24m/s and relative wind direction is 60 deg., the drift angle BETA are: 1.2, 2.5, 3.7 deg.

(2) The critical wind velocities at relative direction of 60 degree at fixed rudder angle 20, 35 degree are 25, 29m/s.

(3) With assistance of bow thruster when ship maneuvered at low speed, the value of counter rudder angle reduced around 20%.

The given results in this study could be applied directly to T/S SAE NURI in handling under the wind condition and used for merchant ships as a referential tool or utilized as educational materials.

However, more simulations should be carried out to verify these results when vessels are navigated under strong wind in open sea and in port areas. These works will be considered in the future.

List of used symbols

L : Ship length
U : Ship speed
dm : Mean draft
ρ : Density of fluid
A_T : Transverse projected area
A_L : Lateral projected area
U_W : Relative wind speed
Cx : Fore and aft wind force coefficient
Cy : Lateral wind force coefficient
Cn : Yaw moment coefficient
F_N : Rudder normal force
t_R : Coefficient for additional drag
a_H : Ratio of additional lateral force
x_H : Distance from the center of gravity of ship to the center of additional lateral force
x_R : Distance from the center of gravity of ship to the center of lateral force
A_R : Rudder area
U_R : Effective relative inflow velocity of rudder
α_R : Effective relative inflow angle
f_α : Rudder normal force coefficient derivative

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