A STUDY ON CRITICAL WIND VELOCITY OF A RO-RO PASSENGER SHIP EQUIPPED WITH SIDE THRUSTERS IN A PORT

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ABSTRACT

In this study, critical wind velocity of a Ro-Ro passenger ship equipped with side thrusters are examined. Two different methods were developed to identify the critical wind velocity. One is based on static equilibrium. The other is numerical maneuvering simulation of the ship in a port. Wind forces and moment were compared with forces and moment acting on a ship caused by side thrusters or rudder angle. Furthermore numerical maneuvering simulation in a port was also developed to confirm the calculation results. This paper may offer a more efficient way to estimate critical wind velocity of a ship equipped with side thrusters in a certain port.

KEY WORDS: Critical wind velocity, maneuvering simulation, safety in a port.

INTRODUCTION

This paper deals with critical wind velocity of a Ro-Ro passenger ship equipped with side thrusters. Two different methods were developed to identify critical wind velocity. One is based on static equilibrium of forces and moment acting on a ship. Wind forces and moment were calculated by Isherwood empirical method (Isherwood, 1973). The other is numerical maneuvering simulation of the ship in a port. In the existing studies (S.Inoue et al 1973, Y.Yoshimura 1985, A. Tanaka et al 1980, J.Takashina 1986), critical wind velocity was usually expressed by a graph called a control boundary that explains the relationship between wind-to-ship speed ratio and relative wind angle. Also other studies (Martin 1980) indicated that the ratio of ship drift speed to wind speed is approximately proportional to the square root of the rudder angle and of the ratio of effective rudder area to above-water lateral area. They usually considered ship's speed or effective rudder area to calculate critical wind velocity and they dealt with equilibrium equations of steady motion of a ship or simulation method. However a ship's motion in a port are very unsteady and its speed is almost near zero. In addition, when the ship is maneuvered in a port, a different maneuvering pattern, for example keeping its position in one fixed point, is considerably required for the safety. Therefore there are some limitations in calculating their critical wind velocity using only the existing methods when they are operated in a port.

In this paper, wind forces and moment were compared with forces and moment acting on a ship caused by side thrusters or rudder angle to identify critical wind velocity. Furthermore numerical maneuvering simulation in a port was also developed to confirm the calculation results. This paper may offer a more efficient way to estimate critical wind velocity of a ship equipped with side thrusters in a certain port and can also be applied to a basis for investigating the cause of running aground accidents in a port due to strong wind.

MATHEMATICAL SHIP MODEL

A 132 meter Ro-Ro ship was adopted as a model, of which axes coordinates are depicted in Fig. 1. Particulars of the ship are presented in Table 1. The maneuvering of a ship is usually described in the form of the modular mathematical model, in which the total hydrodynamic forces and angular moment are split into separate parts. Consequently, the ship's dynamical behavior can be described by the equations of motions for three degrees of freedom as follows:

$$(m+m_x)\dot{u}-(m+m_y)vr=X_H+X_P+X_R+X_W+X_t \quad (1)$$

$$(m+m_y)\dot{v}+(m+m_x)ur=Y_H+Y_R+Y_W+Y_t \quad (2)$$

$$(I_{zz}+J_{zz})\dot{r}=N_H+N_R+N_W+N_t \quad (3)$$

where; X_H, Y_H, N_H : Hydrodynamic forces and angular moment acting on a hull, X_R, Y_R, N_R : Hydrodynamic forces and angular moment due to the rudder, X_P : Hydrodynamic forces due to the propeller, X_W, Y_W, N_W : Hydrodynamic forces due to wind, X_t, Y_t, N_t : Hydrodynamic forces and moment due to thruster

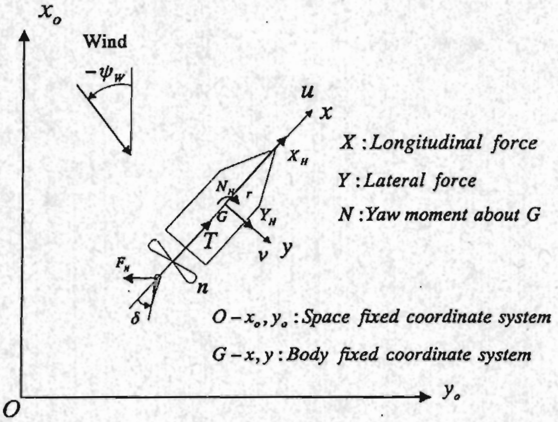

Fig.1 Coordinate System.

The hydrodynamic forces acting on the hull are those acting during maneuvering and usually are expressed in the form of a combination of linear and non-linear terms. Hydrodynamics force coefficients was obtained from a research by Hirano (M.Hirano et al 1984). Added masses and added inertial moment are calculated from the chart of motora (S. Motora 1969). 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 follows:

$$X_R=-(1-t_R)F_N\sin\delta \quad (4)$$

$$Y_R=-(1-a_R)F_N\cos\delta \quad (5)$$

$$N_R=-(x_R+a_Hx_H)F_N\cos\delta \quad (6)$$

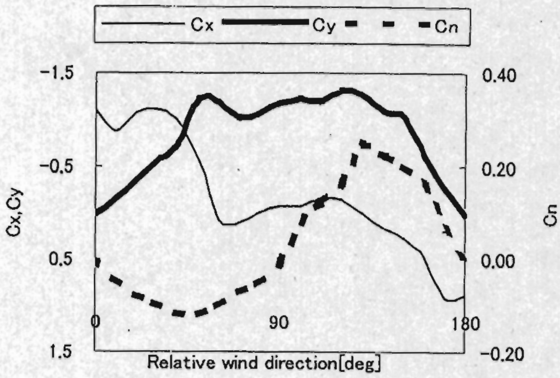

Fig. 2 Coefficient curves for wind force and wind-induced yawing moment.

Table 1 Principal Particulars of the ship.

Type	Ro-Ro
Loa	132.92[m]
Lpp	123[m]
Width	23[m]
Height	7.4[m]
Draft	5.45[m]
Thruster(bow)	117600[$kg\cdot m/s^2$]
Thruster(stern)	117600[$kg\cdot m/s^2$]

Propeller thrust can be described simply in terms of the longitudinal force of the propeller.

$$X_P=(1-t_P)T \quad (7)$$

$$T=\rho D^4n^2K_T(J) \quad (8)$$

T: Propeller thrust force, t_P: Effective thrust deduction factor, D : Propeller diameter, K_T : Thrust coefficient, J : Advance of propeller

As the ship's motion is relatively slow in a port, the influence of environmental disturbances such as wind and current on automatic berthing control is significant. For wind model adopted, the Isherwood model (Isherwood 1973) is chosen and steady wind is considered. The curves for coefficient of wind forces and wind-induced moment are given in the Fig. 2 and theirs expression are;

$$X_W=C_x\frac{1}{2}\rho V_r^2A_T \quad (9)$$

$$Y_W = C_y \frac{1}{2} \rho V_r^2 A_L \tag{10}$$

$$N_W = C_n \frac{1}{2} \rho V_r^2 A_L L_{OA} \tag{11}$$

where V_r : Wind speed relative to ship. Cx, Cy, Cn: Coefficient for wind force and wind-induced yawing moment

Table 2 Calculation results.

Vr (Vd= 120°)	10.1	10.2	10.3
Yw	−170853	−174371	−177880
Nw	2860414	2919244	2978083
Tb		57790.6	58956.8
Ts		107064	118923
Yt		174371.4	177879.8
Nt		−2919244	−2978083

Vr (Vd=130°)	9.6	9.7	9.8
Yw	−151077	−154183	−157290
Nw	3885308	3965198	4045097
Tb		37308.6	38063.2
Ts		116874.8	119226.8
Yt		154183.4	157290
Nt		−3965198	−4045097

Vd = Relative Wind Direction

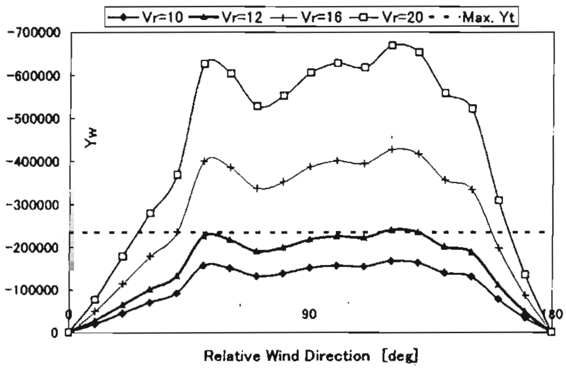

Fig. 3 Curves for wind side forces according to velocity and the maximum of thruster side force.

CRITICAL WIND VELOCITY

Equilibrium equation method concerning the thruster is examined to identify the critical wind velocity in a port. Critical wind velocity, that is, the wind velocity below which the ship can maintain its present one-point-fixed position using its thruster, is examined. In addition, wind velocity for keeping ship's course or making turns under wind is also examined. Finally ship's maneuvering simulation is carried out to confirm the results of calculation.

-KEEPING SHIP IN ONE FIXED POINT

The ship adopted in this paper has two side thrusters in the bow and stern respectively. Curves of side force due to wind is explicated in Fig. 3 with which we can identify how much the output of the thruster will be required to counteract hydrodynamic forces and moment due to wind. As shown in that figure, comparison between hydrodynamic force due to wind and side thruster indicate that critical wind velocity is about 12m/s. However when relative wind direction is set on about 130deg, since all power of the thruster is used for preventing the ship's lateral deviation, turning moment will occur. Then the ship makes a turn due to the wind. The middle of Fig.5 shows these results.

In second step, the moment due to wind is considered. Maximum of turning moment due to the side thrusters is calculated as $11801160 N \cdot m$ according to the Equation (11).

$$Tb \times Db + Ts \times Ds = Tt \tag{11}$$

where Tb,Ts is the output of the bow thruster and stern thruster, Db, Ds is the distance between the center of ship and bow and astern thruster respectively, Tt is the total thruster moment.

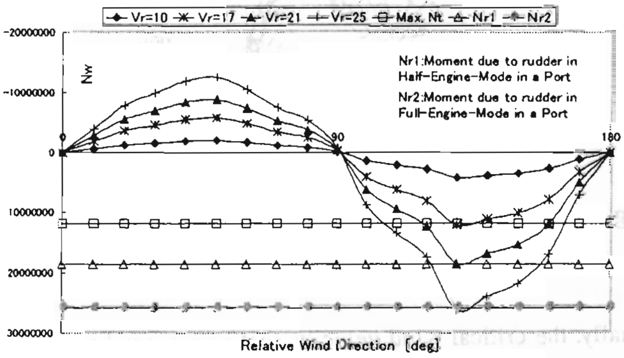

Fig. 4 Curves for wind-induced yawing moment according to velocity and the maximum of thruster moment.

When this Tt, calculated by Eq. (11), is compared with wind moment in Fig. 4, it is easy to find that the line of maximum moment by thruster meet with another line that indicates wind-induced moment calculated with 17m/s of wind relative velocity. Therefore the critical wind velocity to counteract this wind-induced moment is calculated as

17.0m/s of velocity with 130deg of relative wind direction. However when simulation is carried out as shown at the top of Fig.5, it is found that even if the turning moment is counteracted by the output of thrusters, wind side force causes lateral deviation to the ship. Therefore it is found that it is almost impossible to keep the ship in a fixed one position under 17.0m/s of wind.

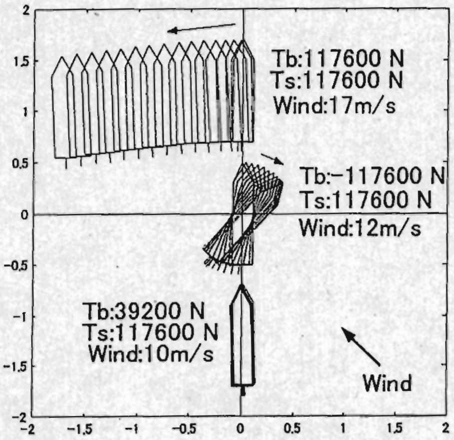

Fig. 5 Hovering test under wind using side thrusters.

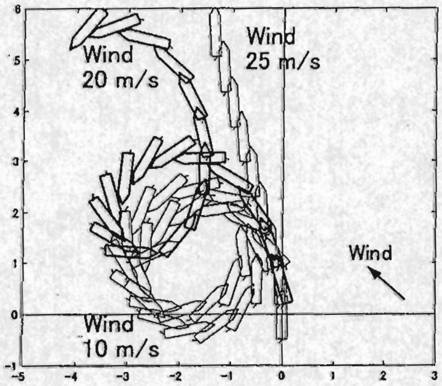

Fig. 6 Turning test with maximum rudder angle under three different wind velocities.

Finally, the critical wind velocity, that is, the wind velocity below which the ship can be keep its position on one fixed point, will be considered. Keeping the ship in one fixed point is one of important maneuvering modes in a port, because if the ship can keep its position at a desired point without its lateral deviation or turning due to wind, we can assume that the ship is safe for berthing operation.

To calculate the critical wind velocity, some equations are suggested such as Eqs. 12 and 13. When wind side force and wind moment are given, which can be calculated according to the wind velocity, the output of the thrusters can be obtained by the Eqs. 12 and 13. The calculation result for Tb and Ts, satisfying both of equations 12 and 13, will be the output of the thruster with which the ship can keep its position on one fixed point without its turning. As the wind velocity continues to grow, more powerful thruster output is required to counteract the wind and the thruster will reach to its maximum capacity to counteract the wind as a result. Therefore the critical wind velocity is easily obtained reading the wind velocity when the output of thruster reaches its maximum.

$$Tb + Ts = Y_{W,} \quad (Tb - Ts)Ds = N_W \tag{12}$$

$$Y_t + Y_W = 0, \quad N_t + N_W = 0 \tag{13}$$

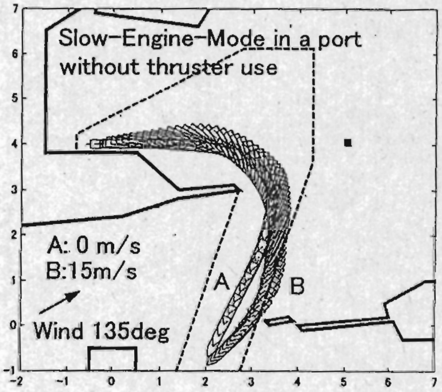

Fig. 7 Maneuvering with a slow-engine-mode in a port .

Table 2 shows the results of these calculations. Since the effect of the wind on a ship is considered to be more severe when its direction is about 120deg or 130deg, the calculation is taken with 120deg or 130deg of wind direction. According to the table, when the wind comes from 120deg at 10.2m/s of velocity, the output of the thrusters, which are required to counteract the hydrodynamic force and moment due to wind, are given as 57790.6 N (bow) and 107064 N (stern). They are within of the thruster's maximum capacity. On the other hands, when the wind comes from 120deg at 10.3m/s of velocity, the output of the side thruster are given as 58956.8 N (bow) and 118923 N (stern), which excesses their maximum capacity. It means that the critical wind velocity is 10.2m/s when the wind comes from a 120deg direction.

In addition, when the wind comes from 130deg at 9.8m/s of velocity, the output of the thrusters are given as 38063.2N (bow) and 119227 N (stern), which excess their maximum capacity. Therefore it is easy to understand that the critical wind velocity, when the wind comes from 130deg of direction, will be 9.7m/s. To confirm these calculation results, simulation is carried out and its result is given at the bottom of Fig. 5. As shown in the figure, the ship shows its ability to keep its present position on one fixed point just using its thrusters.

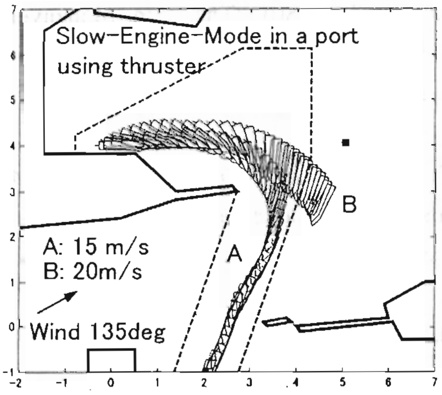

Fig. 8 Maneuvering with a slow-engine-mode in a port and thruster use.

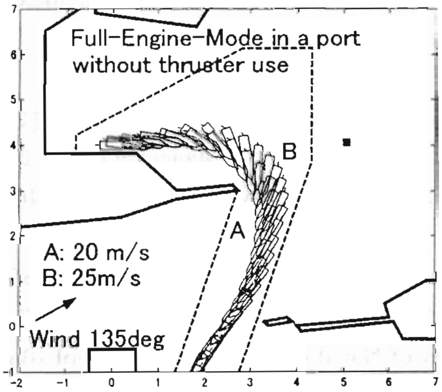

Fig. 9 Maneuvering with a full-engine-mode in a port.

-KEEPING COURSE AND TURNING

The existing research dealt with the relationship between wind-to-ship speed ratio and relative wind angle to consider the critical wind velocity. One of them is a turning test, where a ship makes a turn with maximum rudder angle under strong wind. Another method is an oblique test, where the ship proceeds straight with some attitude of rudder angle under wind. These methods are also examined in this paper.

At first, the critical wind velocity is considered when the ship turns with maximum rudder angle under strong wind. Two kinds of ship's speed, that is half-engine-mode and full-engine-mode in a port, are considered. When we compare moment due to rudder angle, which can be calculated by the equation (6), with wind moment in Fig. 4, the critical wind velocity can be obtained as 21.0m/s in half-engine-mode and about 25.0m/s in full-engine-mode respectively. Some of the results, when ship speed is given as full-engine-mode in a port, are explained in Fig. 6. In the figure, the ship runs with maximum rudder angle using full-engine-mode. When the wind velocity is set on 10m/s, the ship showed stability in its turning circle, however when increased to 20m/s, it is found that the ship encountered deviation due to wind effect. The third case showed that the ship proceeded oblique under a wind velocity of 25m/s, since the rudder-induced moment in that time is almost the same as the wind-induced moment.

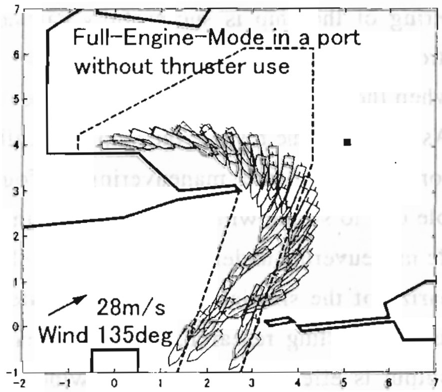

Fig. 10 Maneuvering cases ended in failure under strong wind.

SIMULATION FOR CRITICAL WIND VELOCITY

In the previous section, critical wind velocity, that is, the wind velocity below which the ship can keep its position in one fixed point using its side thruster, was examined. And critical wind velocity, below which the ship can make a turn under wind, also was examined. However the maneuvering of a ship in a port, particularly when the ship is under berthing operation, requires frequent handling of the rudder and engine. In addition, the characteristics of a port including geographical features may affect on the estimation of critical wind velocity in the port. Considering these facts, an imaginary port is designed and maneuvering simulations in the port are carried out to suggest one of tools, which can help us estimate the critical wind velocity in a certain port area.

For the first step, one scenario is taken where the ship leaves off a berth using slow-engine-mode in a port and additional thruster handling. The Fig. 7 showed that the ship is deviated from a routine due to 15m/s of wind effect, while safe maneuvering is possible when the wind velocity is set on zero. The Fig. 8 showed that the use of the thruster made possible safe maneuvering of her course under 15m/s of wind velocity. And another simulation result in that figure shows that keeping course is almost impossible under 20m/s of wind velocity even when its thruster is used.

The second scenario is also taken with a case in which the ship uses maximum engine power in a port and the handling of its thruster is not considered. The results are given in Figs. 9 and 10. Simulation results, obtained under 20m/s and 25m/s of wind velocity without thruster, are given in the Fig. 9. It is easy to find that general maneuvering of the ship is successfully carried out even under strong winds. The Fig. 10 also shows simulation results when the wind velocity is set to a higher velocity of 28m/s. As shown in the results, the ship is usually deviated to its port side and safe maneuvering is found almost impossible due to strong wind. It was almost impossible to make safe maneuvering under 28m/s of wind velocity.

A summarize of the simulation results indicates the same results as the existing research, that is increasing of the engine output is effective to overcome wind effect under strong wind. Moreover it was found that the maneuvering simulation in a port can be one of the tools to estimate the critical wind velocity particularly in a certain port.

CONCLUSION REMARKS

In this paper, the critical wind velocity in a port, particularly when the ship is maneuvered in a port, was examined. The critical wind velocity for keeping a ship in one fixed point was calculated through the handling of its thruster. Finally maneuvering simulation was used to calculate the critical wind velocity in an imaginary port. This paper may offer a more efficient way to estimate critical wind velocity of a ship equipped with side thrusters in a certain port and can also be applied to a basis for investigating the cause of marine accidents such as running aground accidents in a port due to strong wind.

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