Effect of Fin Area and Control Methods on Reduction of Roll Motion with Fin Stabilizers

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In recent year, a fin stabilizer has been widely used as a hull stability instrument for a patrol boat, defence ship, car ferry and passenger ship.

This paper presents some investigations on the influence of the fin area and the control method on the reduction of roll with the fin stabilizer in view of full scale test results. In order to select the optimum fin area, it is important to use not only empirical wave slope capacity, but simulation including rolling probability based on hull motion theory as design criteria. The rolling reduction performance by PID control method is decreased under the condition of long periodic wave. This problem however can be solved by newly developed fuzzy control method.

1. Introduction

A fin stabilizer is a hull stability equipment for reduction of hull rolling by using the generating lift of the fins extended to the both sides of a hull. This technology was invented by Dr. Shintaro Motora in 1922, thereafter it was succeeded to U.K. and put to practical use.1)2) In Japan the fixed type fin stabilizers (fins are fixed as extended) have been initially installed on defence ships and patrol boats for the purpose of safe taking off and landing of a helicopter. In recent years a retractable type fin stabilizer has been adopted in many cases on car ferries and passenger ships from viewpoint of improvement of habitability and prevention of cargo collapse. (Fig. 1)

However the roll reduction performance of the fin stabilizer on an actual ship is complicatedly affected by external sea conditions, hull parameters in duding hull principal particulars and electrical and mechanical parameters of the fin stabilizer itself, therefore there are problems which is difficult to be clearly evaluated. Those lead to how to select the optimum fin area in the design stage of the fin stabilizer.

In this paper study and considerations are made on the method of selecting the fin area and on the latest fin control method based on the data of roll obtained by the sea trial.

2. Criteria for rolling reduction performance

The fin stabilizer is, as shown in Fig. 2, installed around midship and a pair of fin on both sides is made tilted in the reverse direction mutually by oil pressure based on the electric signals through the control unit from the roll motion sensor. The lift is generated by tilting the fins and the velocity of sea water flowing into the fins and it acts as Yighting couple of the hull, resulting in reduction of roll. (Fig. 3)

In general the wave slope capacity Owsc is widely used as the criteria for evaluation of the roll reduction performance by the fin stabilizer.3) This is defined as
The wave slope capacity can be verified in sea trial, etc. and can evaluate the static stability capacity of the fin.

In addition, roll damping coefficient \( R_r \) is used as the criteria for the roll reduction performance. This coefficient can synthetically evaluate the roll reduction performance including the dynamic characteristics of the control system, hydraulic system and driving system. This method is that the fins are actuated in calm sea and rolling is forcibly given to the hull in advance, thereafter the tests are carried out in case of natural roll damping with ship's own stability after stopping actuation of the fins and in case of forced roll damping by actuation of the fins. Fig. 4 shows the example of rolling angle measurements in case of natural damping and in case of forced damping in the sea trial. Based on these measurement results, natural damping coefficient \( C_n \) and forced damping coefficient \( C_s \) are obtained from the equations (2) and (3) and rolling magnification \( M_{fr} \) in case of actuation of the fins and rolling magnification \( M_{fn} \) in case of non-actuation of the fins can be calculated from the equation (4). As shown in Fig. 5, the hull roll characteristics can be obtained using the rolling magnification on the basis of different encounter wave period (or wave frequency). The roll reduction ratio \( R_r \), as shown in the equation (5), is estimated as the functions of \( M_{fr} \) and can be used as the criteria of the rolling reduction performance including response of the total fin stabilizer system.

Natural damping coefficient

\[
C_n = \frac{1}{2\pi} \zeta_n \frac{\phi_{n} + \phi_{n+1}}{\phi_{n+2} + \phi_{n+3}} (2)
\]

Forced damping coefficient

\[
C_s = \frac{1}{\zeta_s} \frac{\phi'_n}{\phi'_{n+1}} (3)
\]

For \( \phi_n \sim \phi_{n+3} \) and \( \phi'_n \sim \phi'_{n+1} \) refer to Fig. 4.

Rolling magnification

\[
M_{fr}, f_n = \frac{1}{\sqrt{1 + (\frac{\omega}{\omega_h})^2} + \left(2C_{n} - \frac{\omega}{\omega_h}\right)^2}} (4)
\]

where, \( M_{fr} \): Rolling magnification in actuation of fin stabilizer
\( M_{fn} \): Rolling magnification in non-actuation of fin stabilizer
\( \omega \): Wave angular frequency
\( T \): Wave frequency
\( \omega_h \): Hull natural angular frequency
\( T_n \): Hull natural rolling period

Roll reduction ratio

\[
R_r = \frac{M_{fn} - M_{fr}}{M_{fn}} (5)
\]

3. Optimization of fin area

When hull rolling is reduced by using the fin stabilizer, an important point is how to select the optimum fin area. In general with increase in the fin area lift increases, but drag generated in the fin in-
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creases by increase in lift, resulting in decrease in ship speed. Moreover, from the viewpoint of the installing space, the manufacturing cost, etc. of the fin stabilizer, it is required to select the fin stabilizer having larger roll reduction performance with the smallest possible area.

In this paper some investigations on the method of selecting the optimum fin area including the existing methods are described making reference to the sea trial results.

3.1 Method of selecting fin area based on wave slope capacity

As a standard of selecting the fin area in the simplest method, the following method is available: as shown in Fig. 6, the empirical wave slope capacity $c_L$ to be required for individual ships is obtained and the fin area satisfying the above wave slope capacity is selected, that is, the said fin area can be calculated by the following equation (6).

$$ A_r = \frac{\Delta \cdot GM \cdot \sin \theta_{sc}}{\rho \cdot c_L \cdot V^2 \cdot L} \quad (6) $$

where, $ho$: Density of sea water
$C_L$: Lift coefficient of fin
$V$: Ship speed

However when this method is used it is within the range of possibility that the large fin area to roll the ship having the original stability in rolling due to large displacement and metacentric height is proportionally calculated, resulting in selecting the larger fin area than it needs. Therefore as the first step for optimization of the fin area selection, the relation between the wave slope capacity and the roll damping coefficient obtained by the sea trial has been examined and the data have been sorted as shown in Fig. 7. In general it is expected that the roll damping coefficient is similarly increased with increase in the wave slope capacity, but as a result of the sea trial, it was found that the constant relation between the both was not necessarily found and the roll damping coefficient was within a range of 60 to 800° irrespective of the magnitude of the wave slope capacity. Fig. 8 shows the sorted relation of the wave slope capacity and the forced damping coefficient obtained by the sea trial. In Fig. 8 also, it is found that the forced damping coefficients are greatly dispersed and the relation between the forced damping coefficient and the wave slope capacity cannot be clearly defined.

As above, in the sea trial, constant relation of the roll damping coefficient and the forced damping coefficient with the wave slope capacity is not shown. The reason for this is considered to be that hull response by the external forces and fin stabilizer response4) (response from detection of the hull roll to lift generation by actuation of the fin stabilizer) have greater influence on the hull rolling reduction performance than the wave slope capacity. From the above it can be understood that it is not necessarily proper to use only the existing.
wave slope capacity method in order to select the optimum fin area.

![Diagram](image1)

**Fig. 6 Method of selecting fin area based on wave slope capacity**

![Graph](image2)

**Fig. 7 Relation between wave slope capacity and roll damping coefficient in sea trial**

### 3.2 Method of selecting fin area based on hull motion calculation

In order to understand the roll reduction performance of the fin stabilizer in waves, it was found that it was required to particularly consider the hull response by the external forces. In the procedure for calculation of the hull motion in waves⁶) the theoretical calculation based on the strip method was put into practical use. Validity of this theoretical calculation can be evaluated by the tank test and the sea trial. The calculation in the condition of installing the fin stabilizer will add the hydrodynamic force generated by the fin as an external force acting on the hull in the hull motion equation and the calculation conditions as shown in Fig. 9 are established. In selecting the fin area based on the hull motion calculation, simulation of the hull roll with a computer is carried out assuming the fin area and combining various conditions shown in Fig.9.

It is very important to presume exactly the natural rolling period and the natural damping coefficient of the hull in particular. The natural rolling period Tₙ is shown by the following equation as functions of coefficient Cₓ relating to radius of gyration of ship, ship breadth B and metacentric height GM.

\[
T_n = C_x \cdot \frac{B}{\sqrt{GM}}
\]

(7)

In Fig. 10 the sea trial results are plotted to raise the accuracy in presuming the natural rolling period. It can be understood by Fig. 10 that the natural rolling periods

![Graph](image3)

**Fig. 8 Relation between wave slope capacity and forced damping coefficient in sea trial**

![Table](image4)

**Fig. 9 Conditions of hull motion calculation in design of fin stabilizer**
Then, it is important to estimate the fin hydrodynamic characteristics, that is, the lift coefficient, in the calculation conditions in Fig. 9, but as for the lift coefficient and the lift curve slope for fin angle, various data in relation to the sectional shape of the fin have been announced. In the method of selecting the fin area based on the hull motion calculation a simulation is carried out in order to obtain the fin lift by combining the angles of incidence added that is changed with the passage of time by the mechanical angle of the fin and the hull motion (especially heaving) and by using the actual fin angle that is hydrodynamically effective. Consequently, even if cavitation is not generated at the mechanical fin angle, the lift may possibly be decreased due to cavitation generated at the effectively actual fin angle. Therefore the lift characteristics test in a cavitation tank as shown in Fig. 12 becomes important.

### 3.3 Example of fin area selection

#### 3.3.1 Example of fin area selection based on wave slope capacity

The wave slope capacity is empirically determined by type of ship. In case of this car ferry it is presumed to be around 5°. When the fin area of one side is calculated by the equation (6) using this value, \( A_f = 7.0 \text{m}^2 \) is obtained.

#### 3.3.2 Example of fin area selection based on hull motion calculation

Sections of the sea on the Pacific coast that are the operational route of this ship (Kanto - Kyushu) correspond to E08 and E09N according to the sections of the sea along the coast of Japan shown in Fig. 13. It is reported that in these regions of the sea conditions of wave height of less than 2.75 m (wave period of 6 to 7 sec) account for over 80% of a year. Therefore the stabilizer for this ship was determined to be studied in the conditions of wave height of 3 m and wave period of 6.7 sec.

As mentioned above, in the method of selecting the fin area based on the hull motion calculation,
simulation with a computer is carried out by assuming the fin area in advance and combining various calculation conditions. In this example the rolling simulation results in the all directional waves under the assumption of the fin area of 5.0m² and 7.0m² are described.

Fig. 14 shows the significant roll angles in non-actuation and actuation of the fin stabilizer with the fin area of 5.0m² and 7.0m² respectively by varying the wave direction such as head wave from bow, beam wave and following wave. From Fig. 14 it is found that hull roll becomes maximum in the vicinity of following wave of 50° where the encounter wave period is the most approximate to the hull natural period. The significant roll angles in the vicinity of following wave of 50° show around 5.5° in non-actuation of the fin stabilizer, around 2.2° in actuation of the one having the fin area of 5.0m² and around 1.5° in actuation of the one having the fin area of 7.0m². On the other hand, it is found that there is almost no difference between in case of the fin area of 5.0m² and in case of the fin area of 7.0m² in beam wave of 90°.

Fig. 15 shows the calculation results of roll excessive probability, using the statistical procedure in the sea conditions of wave height of 3m and following wave of 60°. It is found by Fig. 15 that probability of exceeding the significant roll angle of 30° is around 60% in non-actuation of the fin stabilizer, around 130° in actuation of the fin stabilizer with the fin area of 5.0m² and around 170° in actuation of the fin stabilizer with the fin area of 7.0m². When the specification requires the roll angle of less than 5° that is commonly used, it can be understood that even if 5.0m² is adopted instead of 7.0m² selected by the wave slope capacity, the fin has the sufficient roll reduction performance.

4. Roll reduction performance and control method of fin stabilizer

In general the PID control method is employed in the fin stabilizer and the control is made by proportioning the fin angle $P$ to the rolling angle $\phi$, the rolling angular velocity $\dot{\phi}$ and the rolling angular acceleration $\ddot{\phi}$.

The lift $F$ generated by the fin is expressed by the following equation.

$$ F = \rho \cdot A_f \cdot L \cdot V^2 \cdot \frac{dC_l}{d\beta} $$

Excessive probability, using the statistical procedure in the sea conditions of wave height of 3m and following wave of 60°. It is found by Fig. 15 that probability of exceeding the significant roll angle of 30° is around 60% in non-actuation of the fin stabilizer, around 130° in actuation of the fin stabilizer with the fin area of 5.0m² and around 170° in actuation of the fin stabilizer with the fin area of 7.0m². When the specification requires the roll angle of less than 5° that is commonly used, it can be understood that even if 5.0m² is adopted instead of 7.0m² selected by the wave slope capacity, the fin has the sufficient roll reduction performance.
where, \( I \): Moment of inertia of ship 
\( C \): Roll damping coefficient 
\( \theta \omega \): Wave slope angle 
\( \rho \): Density of sea water 
\( A_f \): Fin area 
\( L \): Arm length of moment 
\( V \): Ship speed 
\( \frac{dC_f}{d\beta} \): Fin lift curve slope 
\( K_1, K_2, K_3 \): Proportional gain

Setting up the proportional gains \( K_1, K_2 \) and \( K_3 \) in the equation (9) is important to improve the roll reduction performance \( C_e \) of the fin. In the PID control method usually the rolling angular velocity gain \( K_1 \) is set up at a maximum, then the angular acceleration gain \( K_2 \) is set up, and finally the angular gain \( K_3 \) is set up, taking account of the irregular wave.

However, when the wave period \( T \) becomes longer than the natural rolling period \( T_n \) as shown in Fig. 16, that is, \( T_n < 1.0 \) or less, the roll reduction performance decreases when the PID control method is used. In other words, when the long periodic wave are encountered, or the encounter wave period becomes longer as same as following wave, the hull floats on the large wave and is greatly heeled. The authors have developed the fuzzy control method and put it to practical use as the measures for the above.9)10) This method varies automatically the control gains depending on the sea conditions. Heel of the hull is decreased by raising angular gain \( K_3 \) against long periodic wave and by introducing the concept of attitude control. As above, the fuzzy control method can improve the roll reduction performance of the fin stabilizer against long periodic wave. Fig. 17 shows the tank test results in case of the PID control method and the fuzzy control method in the condition of comparatively long periodic encounter wave. It can be recognized that in the fuzzy control method the fins are actuated with larger angle compared with the PID control method and the hull rolling angle is decreased.

The fuzzy control method is employed on ten vessels in service and the excellent results are shown.

5. Conclusion

Study has been made on the relation of the hull roll reduction performance, the fin area and the control method of the fin stabilizer based on the sea trial data. As a result the following have been understood.

(1) Hull response by the external force has great influence on the hull roll reduction performance.

(2) In the simulation of the hull motion it becomes possible to combine variously the wave conditions, the fin conditions, etc., and rolling angle and roll excessive probability of all directional waves can be estimated.

(3) The existing PID control method can not show the sufficient roll reduction performance when the ship floats on long periodic wave. However the

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\[
\begin{align*}
\text{Fuzzy control (an example)} \\
\text{PID control} \\
\text{Without fin}
\end{align*}
\]
fuzzy control method developed by the authors can automatically vary the control gains corresponding to the wave conditions and improve the roll reduction performance against all periodic waves.

In conclusion special thanks are given to the valuable external support the authors have had to date, particularly from Kyushu Yusen Co., Ltd. for whose cooperation in the onboard tests of the fin stabilizer.

References

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