Human handling characteristics on ship’s motion in restricted condition

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Abstract

The Ship Maneuvering Simulator is easy to make setting any ships and environments, So, it has been utilized widely such as training, research, developing apparatuses, and so on.

In Japan, the ship-maneuvering simulator has been utilized in the evaluation of restricted waters, such as safety navigation in harbor and traffic route and so on. When we discuss about them, considerable conditions are large variety that are kinds of ship, current, wind and so on. However, the navigational environment have to be adopted the ship’s behavior, so it is required to know the standard ship-handling and the mean results by human control.

In our study, through the investigation, experiments and discussing, we grasped the standard ship-handling and developed numerical simulation that can expresses the mean results by human control to any ships and environment. So, we can predict ship’s position, ship’s heading, ship’s speed, rate of turn, and so on. In this paper, human factor is defined as the standard ship-handling and results by human control.

1 Introduction

First of all, we consider the way to express human control of steering rudder in section 2. In second step of this paper, we explain the experiments using ship maneuvering simulator in order to obtain the human characteristics of control on steering rudder and propeller revolution in section 3. In section 4, the control laws on the deceleration of ship’s speed are indicated. At last, comparing the result of numerical simulation applied proposed human control laws with one of simulator experiments, we verify the accuracy of control laws and human characteristics in section 5.
2 Human control

Firstly, the characteristics of human control were discussed referring Prof. Kobayashi’s paper. In this paper, in order to evaluate the safety navigational environment, the result of the numerical simulation was utilized as the index. Its numerical simulation was applied optimum control law. Its formula shows below (1).

In this formula, Rudder angle is decided by the combination of the lateral deviation, deviation angle and rate of turn. The Constant $K_1$, $K_2$, $K_3$ can be estimated by solving optimum regulator. This formula can express the result of maneuvers using the maximum of ship’s maneuverability.

$$\delta = K_1 \cdot y_t + K_2 \cdot \psi_e + K_3 \cdot \psi_e / v$$ (1)

Where
- $\delta$ : rudder angle (degree)
- $y_t$ : lateral deviation (m)
- $\psi_e$ : deviation angle (degree)
- $\psi_e$ : rate of turn (degree/sec.)
- $v$ : present ship's speed (m/s)

$K_1$, $K_2$, $K_3$ : Constant

Adopting formula (1), we compared the results of human control with the results of numerical simulation applied the optimum control law. Fig.1 shows the trajectory every 2 minutes. Left figure shows trajectory controlled by the optimum control law. Right one shows trajectory controlled by human. As a result, we can see small difference in maintaining course, however we can see big difference altering course point marked by circle.

![Fig.1 The comparison between optimum control and human control](image1)

![Fig.2 The condition of parallel shift maneuver](image2)
Considering results, we decided to adopt mentioned formula (1) and estimate human characteristics indicated as K1, K2, and K3.

3 Investigation of human factor

3.1 Human factor on steering rudder

We examined the control law on steering rudder referring formula (1). The way to examine the control law on steering rudder is to estimate human characteristics indicated as K1, K2, and K3. In order to estimate them, we have to obtain the data to analysis in the wide range. If the data to analysis are small range, the error of analysis will be large and estimated human characteristics will express ship's behavior in restricted condition. Therefore, in order to obtain the data to analysis in the wide range, we considered the experiment of parallel shift Maneuver.

Fig.2 shows the condition of parallel shift maneuver. In this figure, 3 routes are indicated with leading buoy and the intervals of each route are 200m. In this setting condition, ship's operators have to shift 200m in parallel. The shift distances must be changed corresponding to ship's length (Lpp). In circle area, we can see that the ship is heading for the next line. In this condition, variables in control law on steering rudder become large. So, ship's operators must maneuver to make lateral deviation smaller accurately using transit buoy. Through this experiment, we can obtain the data to analysis in wide range.

In our simulator, the mathematical model of this ship maneuverability is referred to the report of SR175 (Ship Research Project No.175 in Japan). This model can be estimated to increase and decrease ship's speed, it can estimate the speed reduction caused by turning and by operating rudder. In this paper, all of ship's mathematical model are estimated by same method as mentioned above. So, the experiments of handling the ship were carried out. After experiment, analyzing the results using method of least squares, we obtained human characteristics. And then, numerical simulations applied them were carried out.

Fig.3 indicates trajectory in wind condition being calm. 5 colored thin lines indicated trajectory by human control in Ship Maneuvering Simulator. The type of ship is VLCC. The shape of ship indicates every 1 minutes trajectory by numerical simulation applied human characteristics indicated as K1, K2, K3. We can see that numerical simulation pass through the mean position of human control and the numerical simulation can express the results of average human control. And we found that the average deviation of numerical simulation applied human characteristics were almost same value as one of human control. As the results, we confirmed that control law on steering rudder and human characteristics could express the average results by human control. And, we found that human characteristics can be gotten through parallel shift maneuver.
3.2 Normalization of human factor on steering rudder in any kind of ships

Furthermore, we carried out the parallel shift maneuver in any kind of ships. Table 1 indicates the principles of ship’s dimension.

<table>
<thead>
<tr>
<th></th>
<th>Cargo Ship</th>
<th>Car Ferry</th>
<th>Container (Panamax)</th>
<th>Container (Over Panamax)</th>
<th>VLCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lpp(m)</td>
<td>109.42</td>
<td>151.13</td>
<td>200.0</td>
<td>261.0</td>
<td>313.0</td>
</tr>
<tr>
<td>Breadth(m)</td>
<td>18.5</td>
<td>23.0</td>
<td>27.6</td>
<td>32.3</td>
<td>56.6</td>
</tr>
<tr>
<td>Depth(m)</td>
<td>7.8</td>
<td>13.61</td>
<td>14.0</td>
<td>21.5</td>
<td>28.7</td>
</tr>
<tr>
<td>T'</td>
<td>0.9</td>
<td>2.95</td>
<td>2.95</td>
<td>1.8</td>
<td>2.17</td>
</tr>
<tr>
<td>K'</td>
<td>1.2</td>
<td>1.6</td>
<td>1.6</td>
<td>1.05</td>
<td>0.93</td>
</tr>
<tr>
<td>Speed (Teleg.)</td>
<td>12kt (N/H)</td>
<td>12kt (H/H)</td>
<td>12kt (F/H)</td>
<td>12kt (H/H)</td>
<td>12kt</td>
</tr>
</tbody>
</table>

Through discussing, we have grasped human characteristics can be normalized by ship characteristics and human constants. Ship characteristics are composed of time constant T, gain K and Length of ship. And human constants are indicated as same value in every ship. These relations are expressed as formula (2), (3) and (4).

Fig. 4 indicates $K_\phi$ and K2 (Human Constant of Heading Deviation) as typical example of human constants. In both figure, horizontal axis indicates type
of ship, vertical axis indicates $K_2$ in upper figure and $K_\psi$ (Human Constant of Heading Deviation) in lower figure. 5 lines and marks indicate results of analysis every ship operator with different marks. Upper figure indicates every value of $K_2$ before normalizing. Lower figure indicates every value of $K_\psi$ after normalizing. Comparing between them, we can see $K_\psi$ are same values roughly corresponding to changing the type of ship using our normalizing factor. The difference can be considered as personality. The other constants are mostly same as this figure. Considering results, every human constant can be estimated by normalizing by proposed methods.

$$K_1 = K_\gamma \cdot \left( \frac{T'}{K'} \right) \cdot \left( \frac{1}{Lpp} \right)$$  \hspace{1cm} (2) \\
$$K_2 = K_\psi \cdot \left( \frac{T'}{K'} \right)$$  \hspace{1cm} (3) \\
$$K_3 = K_\psi \cdot \left( \frac{T'}{K'} \right) \cdot (Lpp)$$  \hspace{1cm} (4)

Where

$T'$: Time Constant \\
$K'$: Gain \\
$Lpp$ : Ship's Length \\
$K_\gamma, K_\psi, K_\psi$ : Human Constants

3.3 Human factor on deceleration of ship's speed

It is well known that ship's operator decelerate ship's speed corresponding to remaining distance using Eng. Telegraph. So, we examined the way to decelerate ship's speed from 15 ship's operators.

Table 2 is the typical example of control plan on deceleration of ship's speed using the engine telegraph. The type of ship is 200m container ship described as Table 1.

Through examining, we obtained that the control plan was composed of the relation among remaining distance, ship's speed and propeller revolution.
Table 2 The operation plan of engine control
(Contanier ship Lpp:200m)

<table>
<thead>
<tr>
<th>Distance to the destination</th>
<th>Speed</th>
<th>Engine Telegraph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 5 miles</td>
<td>12kt</td>
<td>F/AH</td>
</tr>
<tr>
<td>Before 4 miles</td>
<td>12kt</td>
<td>H/AH</td>
</tr>
<tr>
<td>Before 3 miles</td>
<td>10kt</td>
<td>S/AH</td>
</tr>
<tr>
<td>Before 2 miles</td>
<td>8kt</td>
<td>DS/AH</td>
</tr>
<tr>
<td>Before 1 mile</td>
<td>6kt</td>
<td>Stop</td>
</tr>
</tbody>
</table>

In order to confirm the standard deceleration of ship's speed, we carried out experiments on deceleration of ship speed using simulator.

Fig.5 indicates an example of route setting. The ship's operators are required to make speed zero at the destination marked by a cross, under following the route including altering course. The total distance is 5 miles, the width of route is 700m, the buoys are indicated every 1 mile. Based on engine telegraph control plan mentioned above, the initial ship's speed of experiment is 12knots. The variable conditions are 4 kinds of wind force (calm, East 5,10,15m/s), 2 kinds of altering course angle (15,30deg.), 2 kinds of remaining distance after point at altering course (1and 2miles, this distance is called "Dist2" in following).

Fig.6 shows the change of ship's speed and propeller revolution to remaining distance. The horizontal axis indicates remaining distance. The vertical axis indicates ship's speed, propeller revolution and the position of Engine Telegraph. The solid line indicates the change of ship's speed. The broken line indicates the change of propeller revolution. In circle A, we can see that ship's operator decelerate ship's speed referring to the control plan mentioned above.

Decelerating ship's speed, it becomes difficult to maintain ship's heading.
and position gradually using rudder. In this situation, ship's operator performs to increase propeller revolution in the short time. This operation doesn't make the speed up. This performance is called the boosting (circle B).

When remaining distance becomes less than 1 mile, ship's operator will perform to make ship stop by operating propeller revolution astern. And more, in this phase ship's operator make propeller revolution astern and ahead repeatedly to maintain ship's position (circle C).

Considering the way on deceleration of ship's speed from the viewpoint of the propeller revolution control, it can be divided into before and after controlling propeller revolution astern. After using propeller revolution astern, the motion of ship will be small because of low speed. Therefore, the most important is to estimate the motion of ship before controlling propeller revolution astern. And we decided to estimate the control law before controlling propeller revolution astern.

We assumed that the control laws on the deceleration of ship's speed in fairway are composed of 3 items:
1. the control law on steering rudder
2. the control law on propeller revolution
3. the control law on the boosting

The control law on steering rudder has been already explained. And we obtained the human characteristics. So, in next chapter, we go on the deceleration.

4 Estimation on the control law on the deceleration of ship's speed

4.1 The control law on propeller revolution

Referring the ship's operator's control plan, the control law on propeller revolution is assumed by using the relations among the Propeller revolution, remaining distance and present ship's speed. The formula shows below (5).

\[ n = K_x \cdot x + T_v \cdot v \]  

Where
- \( n \): propeller revolution (r.p.m)
- \( v \): present ship's speed (m/s)
- \( x \): remaining distance (m)
- \( T_v \): constant of human characteristics
- \( K_x \): constant of human characteristics

The timing of commencing to decelerate is estimated by averaging remaining distance in experiment result.

On the timing of commencing to control propeller revolution astern, we found that if the present speed is high corresponding to remaining distance, the timing will be early and If the present speed is low, the timing will be late.

Fig.7 shows the timing of commencing to control propeller revolution astern. The horizontal axis indicates the remaining distance. The vertical axis
4.2 The control law on the boosting

The timing of commencing to perform the boosting is when the present ship’s speed is not expected to make rudder effective. So, we investigated the relation between ship’s heading and lateral deviation when performing the boosting.

Fig.8 shows the timing of performing the boosting. The horizontal axis indicates the lateral deviation. The vertical axis indicates the heading deviation. This solid line shows as the condition when performing the boosting.

Formula (7) expressed The timing of commencing to perform the boosting.

And control law on propeller revolution during the boosting is estimated by the relations between lateral deviation and heading deviation. Formula (8) shows its relations.
Fig. 8 The estimation on the timing of commencing to perform the boosting revolution

\[ A_1 |\psi_e| + A_2 |y_e| + A_3 > 0 \]  

(7)

\[ n = K_4 |\psi_e| + K_5 |y_e| \]  

(8)

Where

- \( n \) : propeller revolution (r.p.m)
- \( \psi_e \) : heading deviation (degree)
- \( y_e \) : lateral deviation (m)
- \( A_1, A_2, A_3 \) : constant of human characteristics
- \( K_4, K_5 \) : constant of human characteristics

5 Discussion

In above section, we proposed the control law before controlling propeller revolution astern. And through the experiments using ship maneuvering simulator, we obtained human characteristics in every control law.

The numerical simulation applied proposed formula referring human characteristics were carried out.

Fig. 9 shows the change of ship speed to remaining distance by human control in simulator experiment and numerical simulation applied human characteristics. The horizontal axis indicates the remaining distance and the vertical axis indicates the ship's speed, fine lines indicate the results by simulator experiment controlled by human, solid line indicates the change of speed estimated by numerical simulation applied human characteristics. The numerical simulation shows the mean value of simulator experiments.
As results of the other conditions being same as this figure, it is confirmed that estimated control laws and human characteristics show good agreements. Fig.10 shows both trajectories. Solid line indicate trajectory by human control, the shape of ship indicate trajectory by numerical simulation. The ends of trajectory indicate the point where operated propeller revolution astern.

The numerical simulation shows good agreement with that by human control.

As results of the other conditions being same as this figure, it is confirmed that estimated control laws and human characteristics show good agreements.

6 Conclusion

Main points on this paper are summarized as follows.

1. The control law on steering rudder can be expressed by formula (1). The human characteristics can be obtained from the experiment of the Parallel Shift Maneuver.

2. The human characteristics can be normalized using ship's characteristics and human constants. The ship's characteristics are composed by time constant T, gain K, length of ship. And, human constants are same value in every ship. These relations are expressed by formula (2), (3) and (4).

3. The control law on propeller revolution can be expressed by formula (5). And the timing of commencing to control propeller revolution astern can be expressed by formula (6).

4. The timing of commencing to perform the boosting can be expressed by formula (7). And the control law on propeller revolution during the boosting can be expressed by formula (8).

5. All of proposed control laws and human characteristics can estimate the contents of operation and ship's movement by human control.