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Maneuvering control technology for a ship with twin azimuth thrusters

Controls, Automation, Measurement, Monitoring & Predictive Maintenance

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ABSTRACT

In Japan, the operation of ships with twin azimuth thrusters (without side thrusters), represented by tugboats, is conducted using four levers: two steering levers to control the thrust angle, and two levers to control the main engine rotation speed (including clutch slip). Overseas, it is common to use a pair of integrated levers for controlling the thrust angle and the main engine rotation speed, but the point of individually controlling four control quantities remains the same. Tugboats require forward/backward movement, curves, turning in place, as well as lateral/diagonal movement. Operators, based on abundant experience and advanced navigation skills, use these four levers to achieve these movements. As a result, in Japan, it takes many years of practice to be able to operate a tugboat, with some people taking as long as 10 years. On the other hand, due to the declining birthrate in Japan, there is a labor shortage that is expected to continue, and securing crew members is becoming an issue. Even when personnel can be secured, there are not a few young people who give up halfway because operating is difficult and takes time to learn. Against this backdrop, we have received requests from several domestic tugboat operation companies for a navigation system that can be operated more easily, and we believe there is a need for it. Therefore, our company has been working on the research and development of control technology to realize simple and intuitive operation by consolidating the four control levers into one joystick. The challenges of this technology include the difficulty of balancing control during lateral/diagonal movement and ensuring the immediacy of "counter-steering". Workboats like OSVs typically have side thrusters, making it easy to generate lateral force/hold direction control and sudden reverse thrust during counter-steering. As tugboats do not have side thrusters, implementing these thrust controls is not easy. Therefore, we devised a vector distribution logic to generate lateral force on the hull using only the two azimuth thrusters without using the side thrusters, generate a force that can maintain direction even when subjected to external forces such as fluid force and wind, and quickly generate reverse thrust during counter-steering operation. Currently, we have prototyped a ship control system implementing this technology, confirmed the validity of the logic in a navigation simulator, and installed it on an actual ship (escort tug), and have conducted basic operation at sea, and so far, we have obtained good results. The effects of this technology, as mentioned earlier, include not only shortening the proficiency period of navigation skills by simplifying navigation, but also reducing the burden on crew members by making navigation easier. We believe this will help prevent a decrease in attention due to fatigue and improve the quality of work-life balance.

1 INTRODUCTION

The acceleration of the declining birthrate has become a social issue in Japan. As a result, most industries are suffering from a shortage of manpower, and automation / efficiency improvement are being strongly promoted to compensate for this. Looking at the tugboat industry, operating a tugboat is very challenging and takes a considerable amount of time to train, with some individuals taking up to 10 years to become proficient, and it's not uncommon for young people to quit during the training process. Moreover, it's not easy to replenish personnel due to the shortage of manpower. For these reasons, we, IHI Power Systems Co., Ltd., have received requests from tugboat operation companies for a more straightforward and intuitive navigation system. Therefore, we will discuss our efforts to develop a system that allows for simple and intuitive operation, which we have been working on so far.

2 MAIN SECTION

2.1 Approach to Realize Intuitive Navigation

In Japan, most navigation control systems for two-axis azimuth ships, represented by tugboats, are configured as shown in Fig.1.

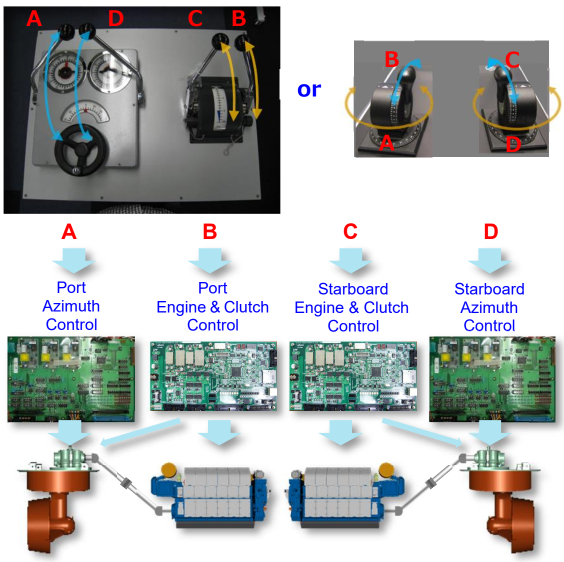


Fig. 1: Conventional system

For control levers, a combination of two levers for individually operating the thruster direction of the port and starboard sides, and two levers for individually controlling the propeller rotation speed of the port and starboard sides (top left in Fig.1) make up the majority. In addition, there are cases where a pair of integrated units, each consisting of a dial for thruster direction operation and a lever for propeller rotation speed operation for one side of the ship (top right in Fig.1), are used. This latter configuration is more common worldwide.

The lower control device consists of the following:

The ZP-Controller, which receives the thruster direction command signal from the lever and controls the direction of the azimuth thruster.

The ME/CL-Controller, which receives the propeller rotation speed command signal from the lever and controls main engine rotation speed and the clutch slip.

Regarding navigating ship, these four levers are skillfully manipulated by operators with advanced lever-handling skills. This requires a considerable amount of expertise cultivated over many years and takes a significant amount of time to master.

Therefore, we developed a system that can be intuitively operated with a single lever, as shown in Fig. 2.

In terms of structure, it consists of a three-dimensional joystick adopted for intuitive operation and an integrated controller, and the lower-level control units are the same.

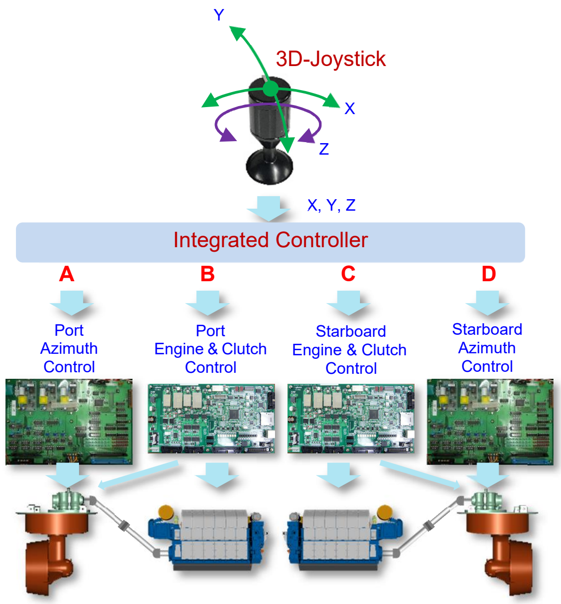


Fig. 2: Newly developed system

A 3D joystick is a 2D joystick (X-Y axis) with the addition of a twisting operation as the Z-axis. The integrated controller outputs command signals to the subordinate control devices based on the operation signals from the 3D joystick. Also, this integrated controller is equipped with software (control logic) to substitute the navigation know-how of skilled operators.

2.2 Ship Operation Function

Two modes of ship operation are provided.

2.2.1 General Navigation Mode

This is a mode used during general navigation, allowing for low to high-speed travel. Tilting the Joystick forward results in forward movement, while tilting it backward results in reverse. The amount of thrust is proportional to the tilt of the Joystick. In addition, by twisting the Joystick in the direction of the turn, it is possible to generate turning force proportional to the amount of twist. (Fig. 3)

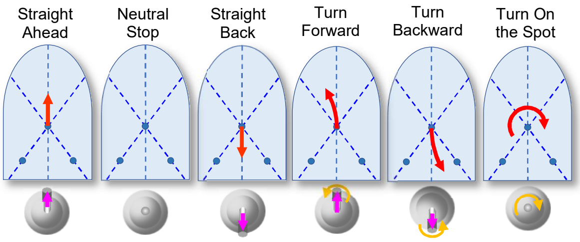


Fig. 3: General navigation mode

2.2.2 Berthing/Unberthing Mode

In the mode where the ship is moved parallel to the direction the Joystick is tilted, the amount of thrust is proportional to the amount of tilt of the Joystick. Also, to adjust/change the direction, a turning force corresponding to the amount of twist can be obtained by performing a twisting operation of the Joystick. Moreover, it is also possible to use the automatic heading control function based on the bow direction/turning-angle-speed feedback signal from the Satellite Compass installed on the ship. (Fig. 4).

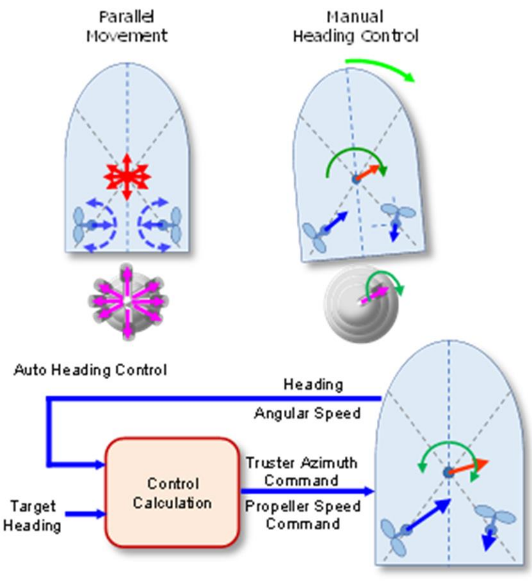


Fig.4: Berthing/Unberthing Mode

2.3 Control Logic

The following describes the navigation control logic implemented in the integrated controller for a two-axis azimuth ship.

2.3.1 Coordinate System

The coordinate system handled by this logic is as shown in Fig.5, where the Y-axis is the straight-ahead direction of the ship, the X-axis is the right lateral direction of the ship, and the Z-axis is the turning direction. The Z-axis takes the Y-axis direction as "0 degrees", with 0 to 180 degrees to the right and 0 to -180 degrees to the left.

Let the center of gravity of the hull be G, and let θ be the angle formed by the Y-axis and the straight line passing through the installation position of the thruster and the center of gravity.

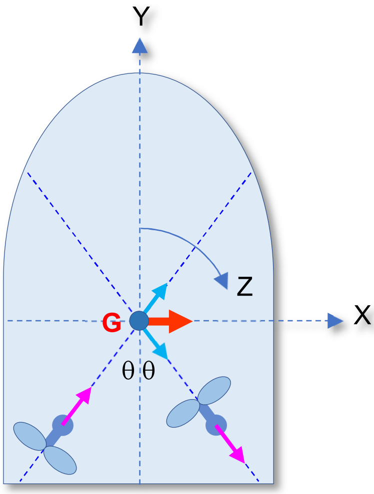


Fig. 5: Coordinate system

2.3.2 Forces Acting on the Hull

The forces acting on the hull include:

1. Thrust from the thrusters

2. External forces

- Fluid force (water resistance)
- Wind force
- Force received from tidal currents and waves
- Reaction force from another ship (in the case of tugboat-operations)

And so on.

In general, the motion of a rigid body is divided into translational motion and rotational motion, and this logic is also treated as divided into the following three elements as shown in the Fig. 6.

a. Thrust in the forward and backward direction F_y

b. Thrust in the left and right direction F_x

c. Yaw moment N around the center of gravity.

2.3.3 Thrust of the thruster acting on the hull of the ship

Assuming the thrust generated by the left and right thrusters are T_L and T_R, and the thruster directions are α and β, the X and Y components of the translational force acting on the center of gravity, F_x and F_y, can be represented as follows:

$F_y = T_L \boldsymbol{cos}\alpha + T_R \boldsymbol{cos}\beta$ .... Eq. 1

$F_x = T_L \boldsymbol{sin}\alpha + T_R \boldsymbol{sin}\beta$ .... Eq. 2

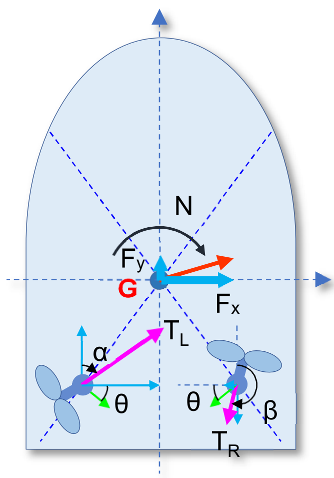


Fig. 6: Thrust acting on the hull

On the other hand, the rotational component of thrust M that contributes to the yawing moment N around the center of gravity is the sum of the green arrows on each side in Fig.6, so it can be expressed as

$M = T_L \boldsymbol{sin}(\alpha-\theta) + T_R \boldsymbol{sin}(\beta+\theta)$ .... Eq. 3

Furthermore, if the distance from the thruster to the center of gravity is denoted as L, the yawing moment N is M*L. However, to simplify the equation, it is treated as the yawing component M.

* Note that in the following formulas, the signs of M and the yaw moment N are treated inversely.

2.3.4 Thrust Vector Allocation

The thrust allocation relationship of the two thrusters can be derived from the previous equation (EQ.1-Eq.3) as,

$\boldsymbol{tan}\beta = (- B \pm \sqrt{(B^2-4AC)}) / 2A$ …………..Eq. 4

$A= F_x \boldsymbol{cos}^2\theta \boldsymbol{cos}\alpha - F_y \boldsymbol{cos}\theta \boldsymbol{sin}\theta \boldsymbol{cos}\alpha$

$-M\boldsymbol{cos}\theta \boldsymbol{cos}\alpha$

$B= -F_x \boldsymbol{cos}\theta \boldsymbol{sin}(\alpha-\theta)+2F_x \boldsymbol{sin}\theta \boldsymbol{cos}\theta \boldsymbol{cos}\alpha$

$-2F_y \boldsymbol{sin}\theta \boldsymbol{cos}\theta \boldsymbol{sin}\alpha+F_y \boldsymbol{sin}\theta \boldsymbol{sin}(\alpha-\theta)$

$-M\boldsymbol{sin}\theta \boldsymbol{cos}\alpha+M\boldsymbol{cos}\theta \boldsymbol{sin}\alpha$

$C=-F_x \boldsymbol{sin}\theta \boldsymbol{sin}(\alpha-\theta)+F_x \boldsymbol{sin}^2\theta \boldsymbol{cos}\alpha$

$-F_y \boldsymbol{sin}^2\theta \boldsymbol{sin}\alpha+M\boldsymbol{sin}\theta \boldsymbol{sin}\alpha$

$T_R =(F_y \boldsymbol{sin}\alpha-F_x \boldsymbol{cos}\alpha)/\boldsymbol{sin}(\alpha-\beta)$ ……….Eq.5

$T_L =(F_x \boldsymbol{cos}\beta-F_y \boldsymbol{sin}\beta)/\boldsymbol{sin}(\alpha-\beta)$ ……….Eq.6

are derived.

Here, if we denote the translational force command according to the amount of tilt of the Joystick as H, and the translational direction command according to the Joystick tilting direction as η, F_x and F_y are represented as shown in Fig.7

$F_x = H\boldsymbol{sin}\eta$ …………………… Eq. 7

$F_y = H\boldsymbol{cos}\eta$ …………………… Eq. 8

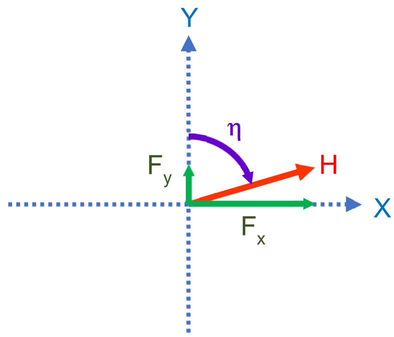


Fig.7: The X and Y component of vector H

Also, the amount of helm command according to the Joystick twist amount, that is the generated yaw component M, is

$M = T_L \boldsymbol{sin}(\alpha-\theta) + T_R \boldsymbol{sin}(\beta+\theta)$ ……………. Eq. 3

Therefore, when the following are given:

- Translational force command H
- Translational force azimuth η
- Yaw force command M

we can calculate the relationships between the following parameters needed to generate the desired force on the hull:

- Port thruster azimuth α
- Port thruster thrust T_L
- Starboard thruster azimuth β

- Starboard thruster thrust T_R

2.2.4.1 Definition of Thrust Value

The thrust when the hull is at a standstill and the propeller rotation speed has reached the rated rotation is defined as 1.0 (100%), and the thrust at this situation is represented as T_{max}. (Fig.8)

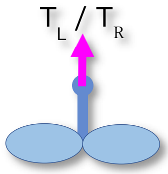


Fig. 8: Thrust at T_{max} (=1.0)

Therefore, when both port and starboard proceed at rated output, the resultant thrust H acting on the hull is 2.0 (= H_{max}). (Fig. 9)

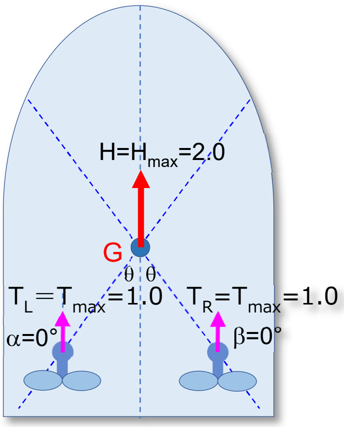


Fig. 9: Thrust at H_{max} (=2.0)

2.2.4.2 Definition of the Yaw Component Value

The yaw component M is defined as 1.0 (100%) when the state of the thruster is as follows;

- Starboard thruster thrust T_R = 0
- The direction of the starboard thruster β is irrelevant.
- Port thruster thrust $T_L = T_{max}$ = 1.0
- Starboard thruster direction $\alpha = 90° + \theta$

(Fig. 10)

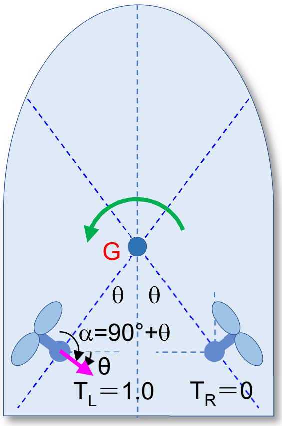


Fig. 10: Yaw component at M max (=1.0)

2.2.4.3 Example

In the previous Equations 4 to 8, when θ = 10°, H = 0.2, M = 0, and η = 45°, the relationship between α, β, T_L and T_R is as shown in Fig. 11 when plotted on a graph.

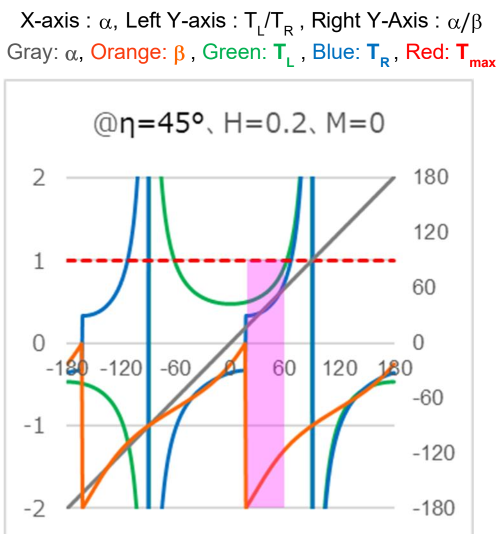


Fig.11: Relation between α, β, T_L and T_R

Please note that the scalar quantities T_L and T_R can not be negative, and they cannot exceed the rated thrust T_{max} = 1.0. So that their range is limited to $0 \leq T_L \leq T_{max}$, $0 \leq T_R \leq T_{max}$. Furthermore, in order to prevent the water flow from hitting the other thruster or the hull, the thruster azimuth is made inward, so it becomes $0° \leq \alpha \leq 180°$, $-180° \leq \beta \leq 0°$ Therefore, the range that satisfies both conditions is the pink area in the graph (Fig. 11).

2.2.4.4 Thrust Vector Allocation Summary

When the following commands are given:

- Translational force command H

- Translational force direction η

- Yaw force command M,

we can calculate the relationships between the following parameters needed to generate the desired force on the ship's body:

- Port thruster direction α

- Port thruster thrust T_L

- Starboard thruster direction β

- Starboard thruster thrust T_R

In other words, they indicate the combinations of thrust vectors that should be used to achieve a desired state of the thrusters when a command is given for how the ship should be moved. However, there are an infinite number of these combinations. For example, all of the patterns shown in Fig.12 represent the vector allocation when moving laterally to the starboard (right) side.

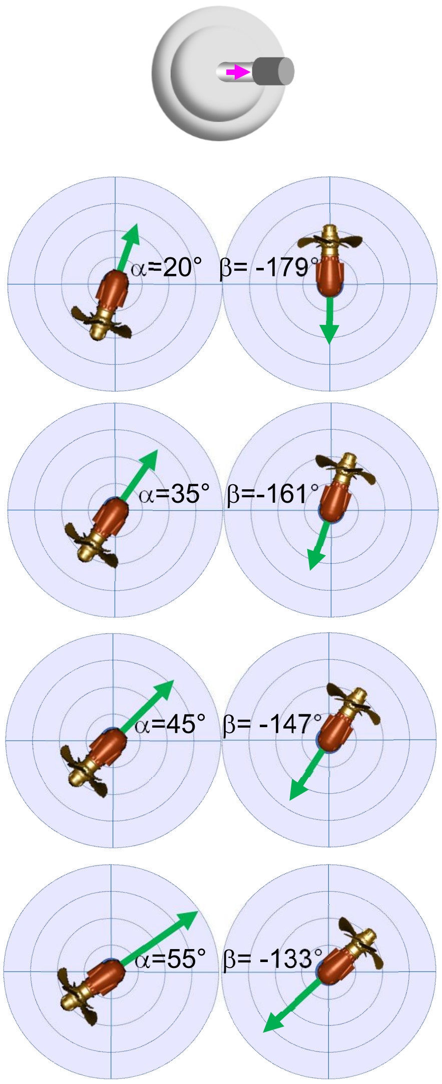


Fig. 12: Vector allocation pattern at sideway movement

The process of "selecting the best one" from these countless allocation patterns (combinations of α, β, T_L, T_R) will be necessary in the subsequent stages.

2.3.5 Selection of Optimal Vector Allocation Patterns

In selecting the optimal allocation pattern (a combination of α, β, T_L, T_R), there are several methods, which will be explained next.

2.2.5.1 Fuel Economy Priority Mode

Among the countless combinations of vectors, the lower the thruster force, the lower the fuel consumption. Therefore, from the perspective of fuel economy, it can be said that it is optimal to choose the combination of α, β, T_L, T_R where the larger of T_L and T_R is the smallest value.

Fig.13 to 17 shows the vector allocation pattern in pink color according to the above-mentioned manner when θ = 10°, H = 0.2, M = 0 and η = 0°, 45°, 90°, 135°, 180°.

X-axis : α, Left Y-axis : T_L/T_R , Right Y-Axis : α/β

Gray: α, Orange: β , Green: T_L , Blue: T_R , Red: T_{max}

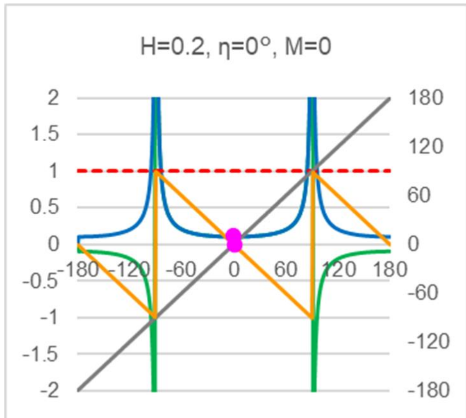


Fig.13: η =0°

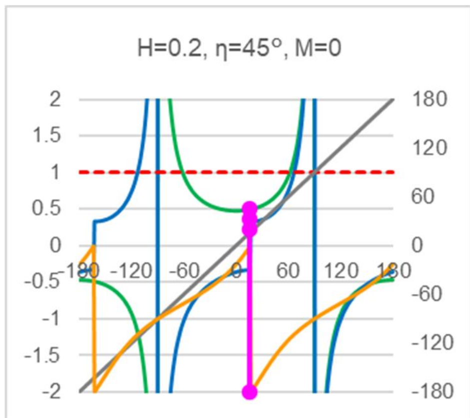


Fig.14: η =45°

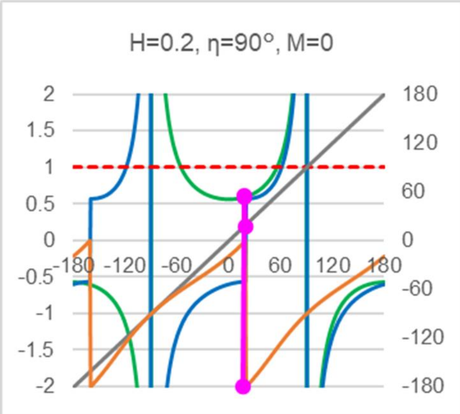


Fig. 15: η =90

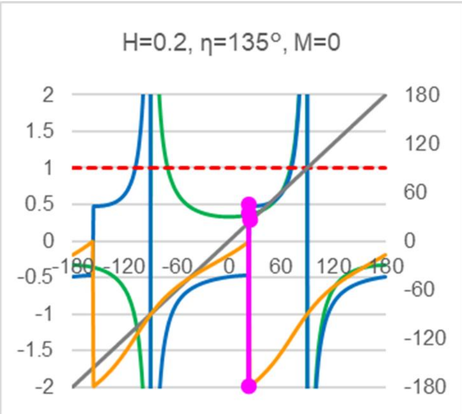


Fig. 16: η =135°

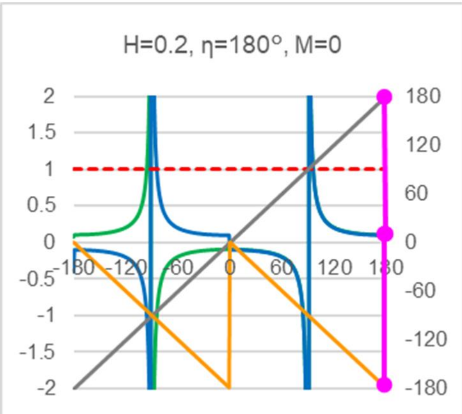


Fig. 17: η =180°

From the perspective of fuel efficiency, this method always seems to be the best. However, consider a situation such as docking maneuvers where the ship approaches the pier from a starboard course (η = 90°) and then takes a counter steering (η = -90°). When η = 90°, if we choose the point where the propeller rotation is at its lowest, it will be like the purple line in Fig. 18.

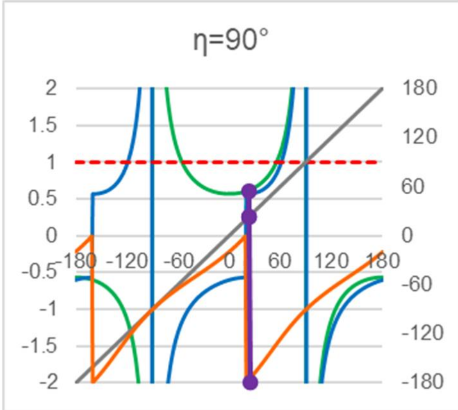


Fig. 18: η =90°

From this state, if the Joystick is turned in the opposite direction (-90°), the thruster azimuth moves significantly (about 170°) as shown in Fig. 19. The dark purple in the graph of Fig.19 represents the state of η = 90°, and the peach color represents the state after changing to η = -90°. Considering that the ship's position is adjusted by moving the Joystick side to side, it is not suitable for departure and berthing operations.

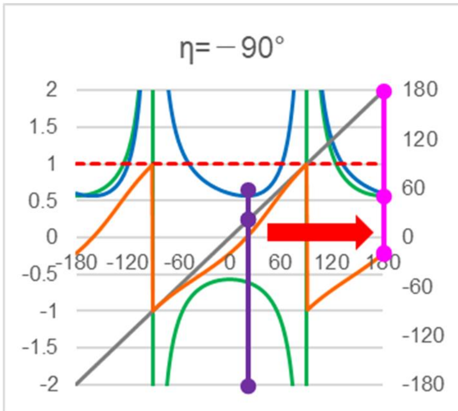


Fig.19: η = - 90°

2.2.5.2 Displacement Priority Method

When the hull is moving according to a vector allocation pattern ($\alpha 1$, $\beta 1$, T_L1, T_R1), if the Joystick is moved to a different point, the smaller the distance from the current state ($\alpha 1$, $\beta 1$, T_L1, T_R1) to the next state ($\alpha 2$, $\beta 2$, T_L2, T_R2), the more efficient and smooth the ship maneuvering is. That is, we choose the combination of $\alpha 2$, $\beta 2$, T_L2, T_R2 where the largest value among $|\alpha 2-\alpha 1|$, $|\beta 2-\beta 1|$, $|T_L2-T_L1|$, $|T_R2-T_R1|$ is the smallest. Since the angle and the thrust have different dimensions and cannot be compared directly, in order to align the dimensions, α: 0°~180°, β: 0°~-180° are set to 0%~100%, and T_L, T_R are set to the minimum-maximum propeller rotation speed of 0%~100% for comparison. Normally, in case of a two-axis azimuth ship, in the hull stop state (where the Joystick is not tilted), the state is given as the initial value ($\alpha 1$ = 90°, $\beta 1$ = -

90°, $T_L1 = T_R1$). Efficient, smooth ship maneuvering is possible by repeating the above-mentioned manner each time the Joystick is moved. Fig. 20 and 21 show examples of selecting the combination of $\alpha 2$, $\beta 2$, T_L2, T_R2 when the Joystick is moved from η = 90° to -90°, moving from combination 1 (purple) to combination 2 (pink), with relatively small displacement.

X-axis : α, Left Y-axis : T_L/T_R , Right Y-Axis : α/β
Gray: α, Orange: β , Green: T_L , Blue: T_R , Red: T_{max}

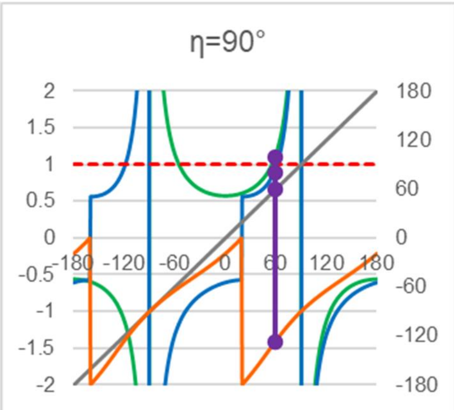


Fig. 20: η =90°

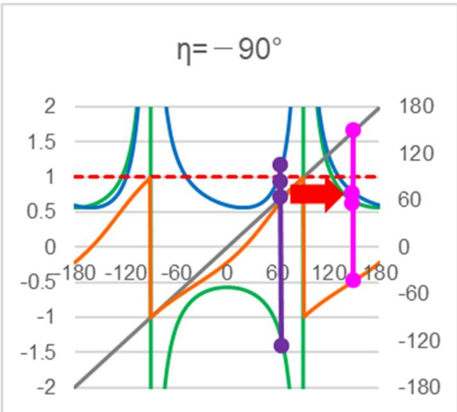


Fig. 21: η = - 90°

In this method, the optimal choice is not always selected from the perspective of fuel consumption. Therefore, when sailing for a long time without moving the Joystick, that is, if there is no change in the Joystick position for a certain period of time, it can be effective to gradually shift to the previously mentioned "Fuel Economy Priority Mode". (Fig. 22)

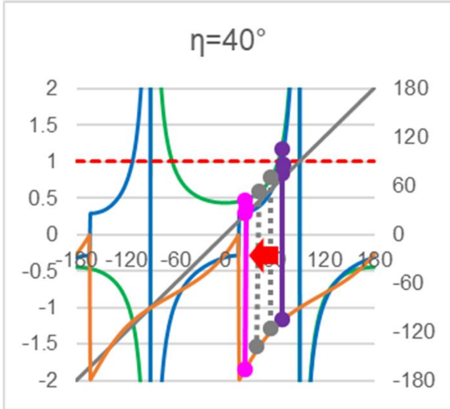


Fig. 22: Shifting to fuel minimum

2.4 Differences in the Application of Logic depending on Navigation Mode

The application of the afore-mentioned logic varies depending on the method of the navigation, as will be explained below.

2.4.1 On-the-spot Turn

In the case of on-the-spot turning, there is no translational motion, so H in the previous equations 7 and 8,

$Fx = H\boldsymbol{sin}\eta$,

$Fy = H\boldsymbol{cos}\eta$,

becomes 0, resulting in

$Fx = 0, Fy = 0$.

When this is substituted into the previous equations 4, 5 and 6, we get

$\beta = \alpha + 180°$

$T_L = T_R (= T)$

resulting in point symmetry around the midpoint of the thruster position, as shown in Figure. 23.

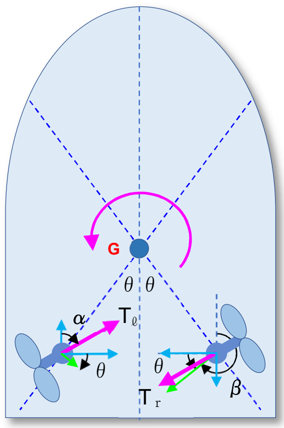


Fig. 23: Point-symmetry vector allocation

When we substitute this into the previous Eq. 3:

$M = T_L\, \boldsymbol{sin}(\alpha-\theta) + T_R\, \boldsymbol{sin}(\beta+\theta)$,

the equation simplifies to

$M = -2T\,\boldsymbol{sin}\theta\,\boldsymbol{cos}\alpha$.

In the case where the rotational component is maximized, α = 0° or 180° β = 180° or 0°. (Fig. 24)

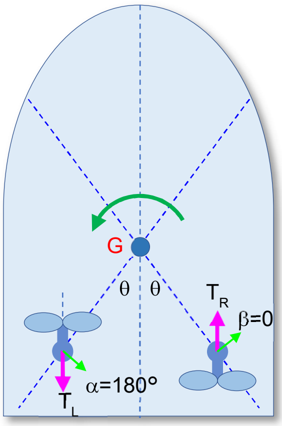


Fig. 24: Yaw maximum pattern

The maximum yawing component M_{max} at this time is given as $M_{max} = 2T_{max}\boldsymbol{sin}\theta = 2\boldsymbol{sin}\theta$, since the maximum thrust on one side of the ship is T_{max} = 1.0. For θ = 10°, it becomes $M_{max} \approx 0.347$. Even if the ship turns in this state, the turning force obtained is small, which can also cause vibrations in the ship's hull.

Therefore, by setting:

$Fx = H\boldsymbol{sin}\,\eta + k * M$ .... Eq. 9

the pivot center shifts towards the bow instead of the center of gravity, but the yawing component capacity increases. When H=0 and the value of k is changed, the maximum value of M (M_{max}) is calculated as shown in Fig.25. When k=0.9, M_{max}>1.0, which is about three times the pivot component when the pivot center is set to the center of gravity (k = 0).

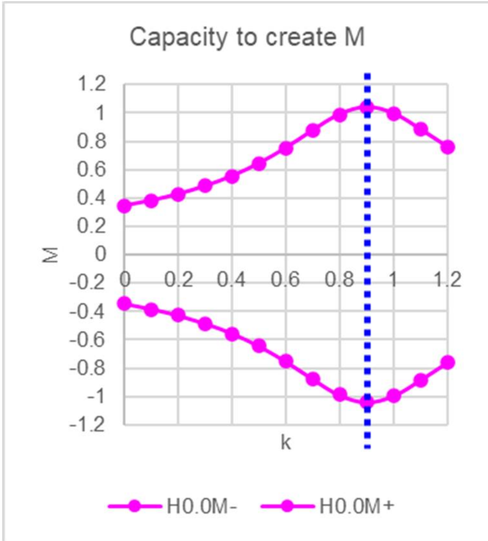


Fig.25: Capacity to create M

What "k" means ?

In Fig. 26, let LG be the distance between the thruster position and the center of gravity, and let LP be the distance between the pivot point P, which is on the bow side from the center of gravity G.

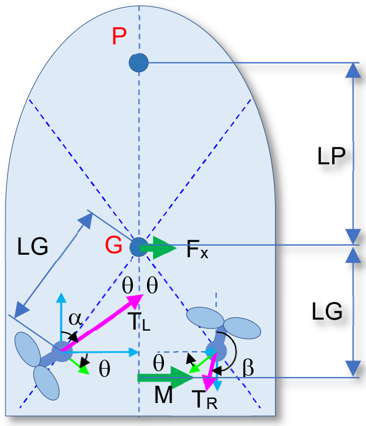


Fig. 26: Pivot point

The yawing force acting around the center of gravity by the yawing component M is represented by the yawing angle ϕ and the moment of inertia around the center of gravity I, as:

$$M \cdot LG = I\frac{d^2\varphi}{dt^2}$$

The angular displacement generated by this force is:

$$\Delta\varphi = \int \frac{LG}{I} M dt^2 \quad \text{......... (1)}$$

On the other hand, the motion caused by the lateral force F_x, with mass m and displacement x, is:

$$F_X = m\frac{d^2x}{dt^2}$$

The displacement of point P caused by this force is:

$$\Delta x = \int \frac{1}{m} F_X dt^2 \quad \text{......... (2)}$$

Also, the displacement caused by $\Delta\phi$ is equal to this, so:

$$\Delta x = \Delta\varphi \cdot LP$$

From this, we get:

$$\Delta x = \int \frac{LG}{I} M dt^2 \cdot LP \quad \text{......... (3)}$$

From (2) and (3),

$$\frac{1}{m} F_X = \frac{LG \cdot LP}{I} M$$

Therefore,

$$F_X = LG \cdot LP \frac{m}{I} \cdot M$$

If we replace it with

$$\boldsymbol{F_X = k * M}$$

we get:

$$\boldsymbol{k = LG \cdot LP \frac{m}{I}}$$

2.4.2 Parallel Translation

The aforementioned vector allocation Eq. 4-8 are also applicable to parallel movement. Although it is considered appropriate to calculate with M=0 for parallel movement, as it does not generate a yaw component, once the ship starts moving, hydrodynamic forces (resistance from water) occur, and with the addition of wind and wave influences, the ship's orientation changes. In order to maintain parallel movement, it is necessary to generate a yaw component M in the opposite direction to suppress the change in orientation due to these external forces.

However, concerning the orientation correction force, as explained in the previous section 2.2.1 for spot-turning, if the center of rotation is fixed at the center of gravity, the yaw component that can be generated is small, so we have

Fx = H***sin*** η + k * M …………… Eq. 9

H = 0.0, 0.1, 0.2, and the M_{max} graph for the k value when η is changed is shown in Fig. 28-31.

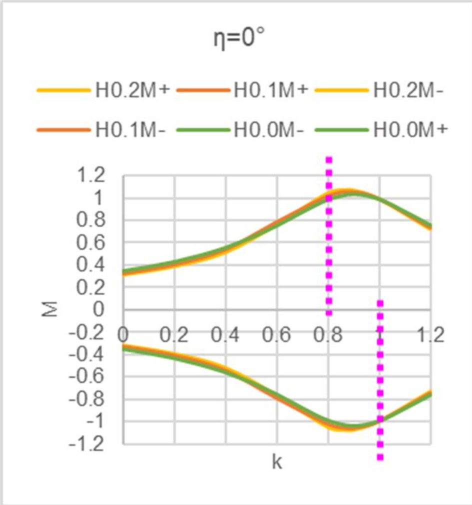


Fig. 27: Capacity to create M at η =0°

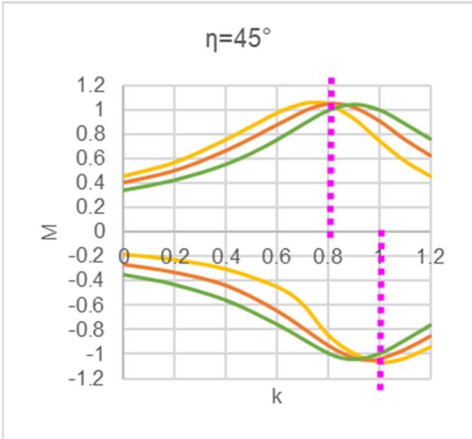


Fig. 28: Capacity to create M at η =45°

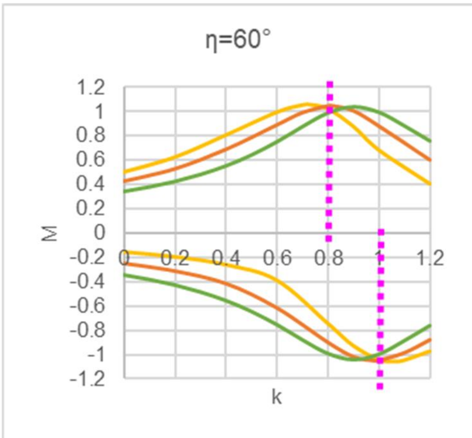


Fig. 29: Capacity to create M at η =60°

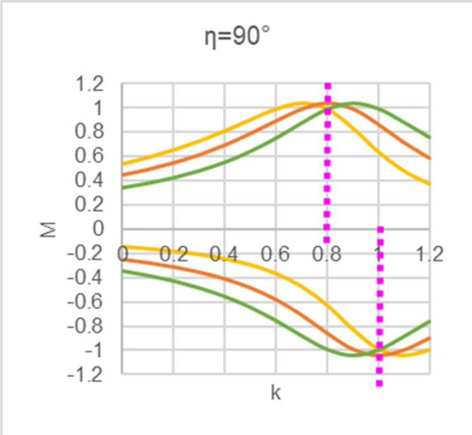


Fig. 30: Capacity to create M at η =90°

As mentioned earlier, the turning component M at k = 0 is small, but by setting k = 0.8 for M ≥ 0 and k = 1.0 for M < 0, M can be secured close to ± 1.0. Therefore, the k value should be selected according to the η range and the turning direction, as shown in the Table.1 below.

	0° < η < 180°	0° > η > -180°
M ≥ 0	k = 0.8	k = 1.0
M < 0	k = 1.0	k = 0.8

Table.1: Optimal k

Here, the validity of the aforementioned conditions was examined in the entire range of 0 ≦ H ≦ 2.0, 0 ≦ η ≦ 180°. The graph (Fig. 31) is for k=0, and the minimum coverage range is the light peach area for left turn (M ≧ 0) and the light blue area for right turn (M < 0), both of which can be seen to be significantly below 1.0 in the magnitude of M.

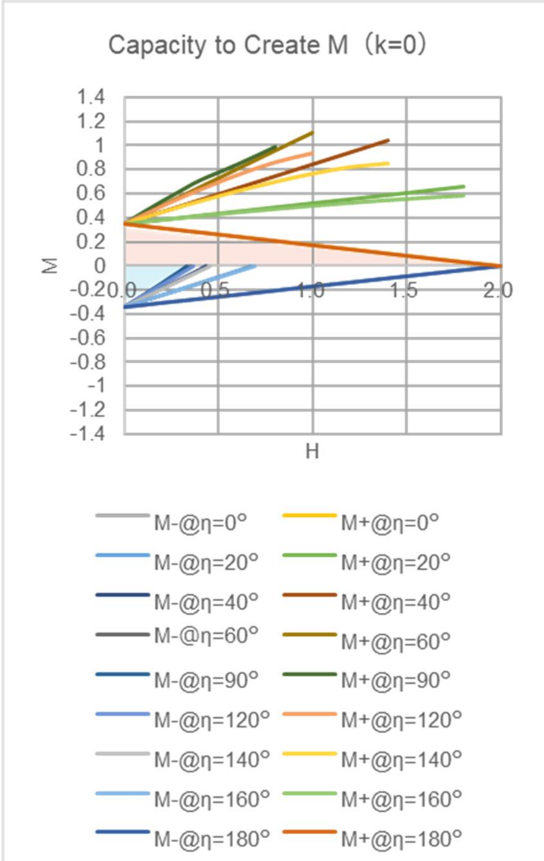


Fig. 31: Capacity to create M at k=0

Next, changing the k value according to the aforementioned conditions results in Fig. 32.

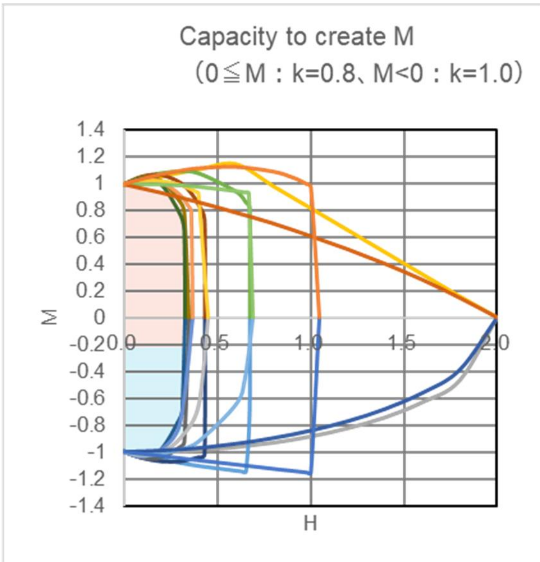


Fig. 32: Capacity to create M optimized

The light peach and light blue areas have both expanded, and in the region where H ≤ 0.3, M_{max} is expected to be ± 0.8, and in the region where H ≤ 0.2, M_{max} is expected to be more than ±0.9. In cases where high speed or large thrust is not required, such as when maneuvering away from or towards the shore, H_{max} can be set to 0.1 to 0.2 to achieve as large a turning force as possible.

2.4.3 Straight Navigation

Even in straight ahead navigation, the previous formulas 4-7, and 9 are applied. As forward and backward navigation, especially forward navigation, often continues for a long time, it is necessary to keep fuel consumption low. Also, since there is no need for "lateral movement and counter-helm" operation like in berthing and unberthing operations, the method of selecting vector allocation patterns adopts the Fuel-efficient Method. However, in order to smoothly switch between forward-neutral-backward, a switch point Hc is set before and after H=0 (neutral position), and the range from forward Hc to backward Hc is calculated as

$$\alpha = 90° - (90° / Hc) * H$$

The thrust vector on each side in response to the Joystick operation is as shown in Fig. 33. For explanatory purposes, Hc = 50% is set in the figure, but the suitable value is determined by the ship.

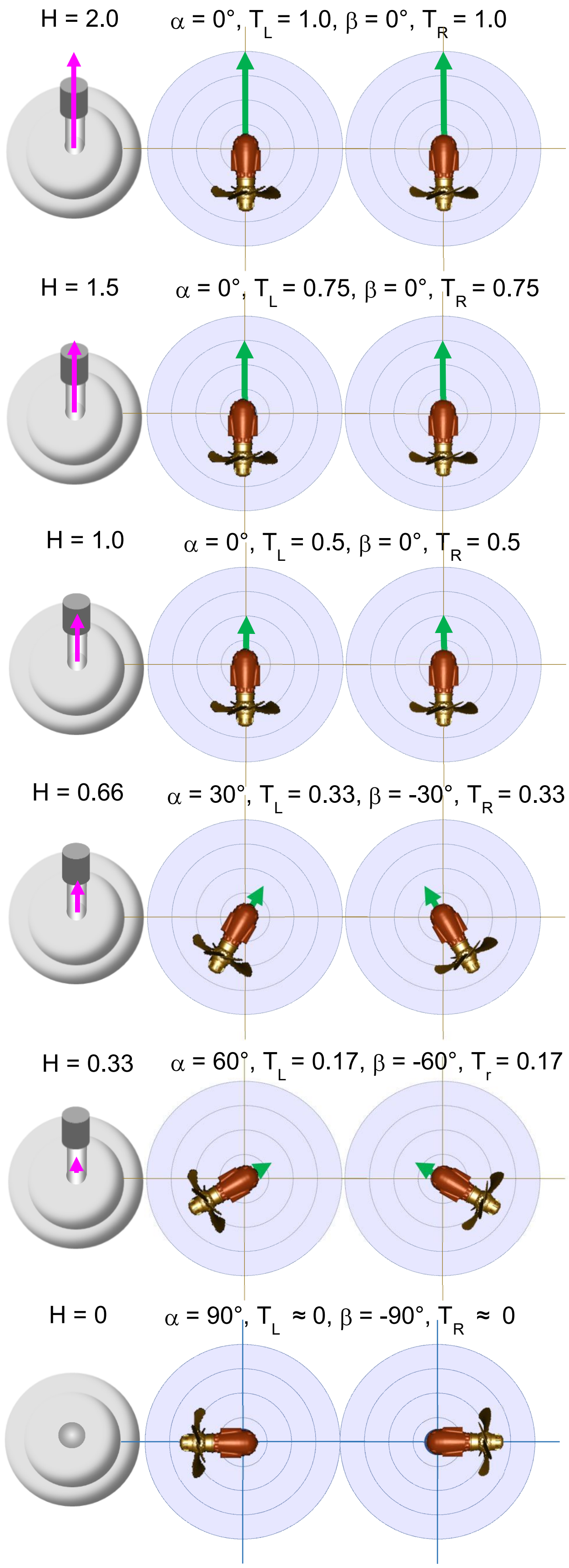


Fig. 33: Vector allocation patterns in straight navigation

2.4.4 Turning Navigation

For turning navigation, apply Eq. 4 to 7, 9, in the same way as for straight navigation.

2.3.4.1 Forward H_{max} to Forward Hc, Reverse Forward H_{max} to Reverse Hc

In this case as well, the method of selecting vector allocation patterns will adopt the "Fuel Efficiency Priority Method".

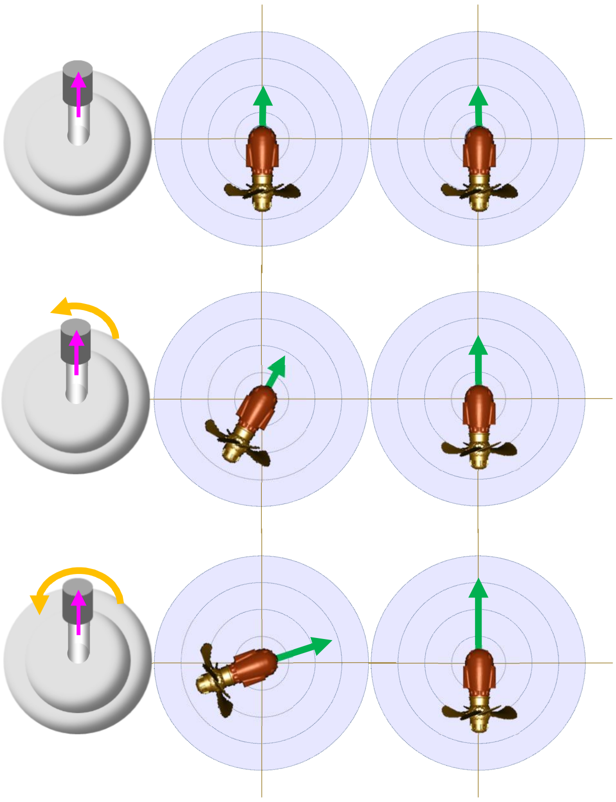


Fig. 34: Vector allocation patterns in turning navigation (H > Hc)

As a result, in the case of a left turn, the starboard thruster azimuth is maintained at 0°, and only the port thruster azimuth changes. (Fig. 34) In the case of a right turn, the movements are symmetric, and reversing is front-to-back symmetric.

2.3.4.2 Forward Hc to Reverse Hc

In this area, the formula is changed depending on the turning direction. In the case of a left turn, insert

$\alpha = 90° *(1 - H / Hc)$

into Eq.4-7, 9. As a result, in the case of a left turn, the starboard thruster azimuth is maintained at

$\alpha = 90° *(1 - H / Hc)$,

and only the port thruster azimuth changes. (Fig. 35)

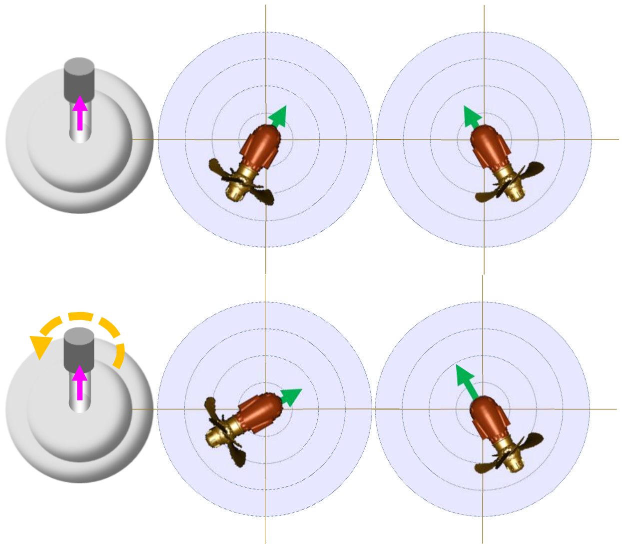


Fig. 35: Vector allocation patterns in turning navigation (H < Hc)

For a right turn,

$\beta = -90° *(1 - H / Hc)$

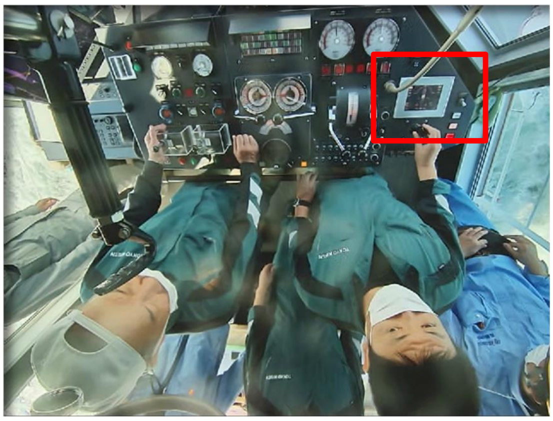
However, while Eq. 4 to 6 are derived from Eq. 1 to 3 to obtain "***tan***β", for a right turn, we use the ones derived to obtain "***tan***α".

The movement of a right turn becomes symmetrical from left to right, and the movement during reverse navigation becomes symmetrical from front to back.

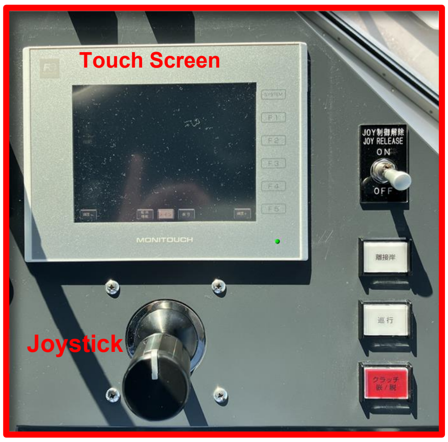
2.5 Loading onto the Actual Ship and Operation Test

We installed the integrated controller implementing the ship maneuvering control logic on the escort tugboat, Tokyo Kisen "Azuma Maru" (Pic. 1-Pic. 3), operating in the Yokosuka-Yokohama area (Fig. 36) and conducted a navigation test. As a result, we confirmed that all functions were working well. In addition, not only the captain, but even crew members who do not usually navigate the ship, were successful in docking and undocking maneuvers on their first trial.

Pic. 1: AZUMA-MARU
Overall length: 38.4 m
Overall width: 9 m
Tonnage: 192 ton
Main engine: 6L26HLX (Niigata)
Propeller: ZP21 (Niigata)



Pic. 2: Bridge



Pic. 3: Joystick Console

Fig. 36: Sailing route

3 CONCLUSIONS

We were able to devise a control logic from scratch and, through trial and error in a ship maneuvering simulator, confirm the validity of the logic on an actual ship. One challenge was the difficulty of balance control when making a sideways movement in a two-axis workboat without a bow thruster. However, we were able to achieve sideways navigation (including automatic heading control) without any problem by using the vector allocation formula that takes into account turning components and a method that ensures turning force by appropriately changing the turning center. Another challenge was the large thruster displacement when taking a "counter helm" during sideways navigation, but we were able to minimize displacement by using the Displacement-Priority logic for selecting vector allocation patterns.

So far, in trials with a real ship, we have obtained good results in terms of the navigation of the ship itself, such as medium/long distance movement and berthing/unberthing. Currently, we are proceeding with plans to verify the applicability of tugboat operations such as pushing / pulling a large ship.

We believe that this technology will bring significant merits as below,

- Reduction of operator's practical burden

- Reduction of operator training time and cost

- Reduction of employee turnover

- Improvement of safety (operation complexity with multiple operating levers leads to mis operations)

Furthermore, this technology can be applied to autonomous navigation/automatic ship control, as it can receive command signals from a higher-level system of autonomous navigation that makes situation awareness, routing decisions, and navigation action through sensor fusion, and can control the movement of the ship according to the commands. In addition, it is promising for remote ship operation from a Joystick installed at an operation center on land or on a large ship that a tugboat push/pull. (Fig. 37)

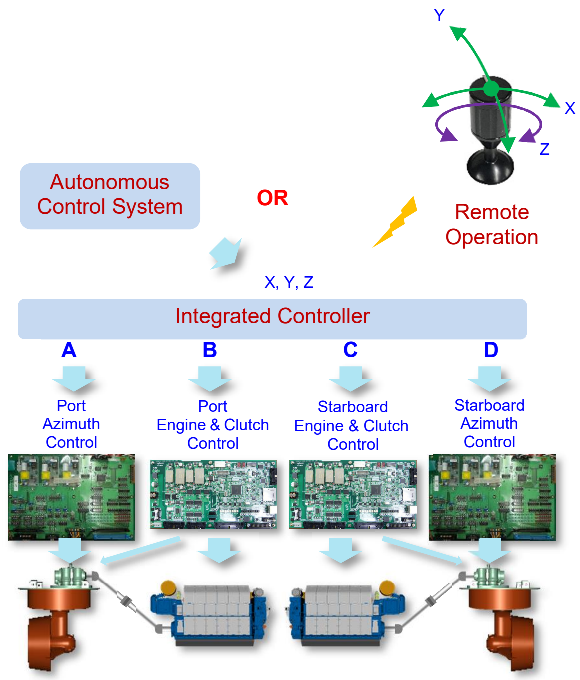


Fig. 37: Autonomous navigation / Remote operation

4 ACKNOWLEDGEMENTS

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