Ship Automatic Track keeping At Low Speed

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Abstract: There are lots of ship's situations when operating from port to port such as with full speed sailing, reducing speed inside traffic scheme, stopping at a certain area and berthing operation with designed heading angle. However, the previous studies on ship automatic track -keeping controllers have not been designed properly as they considered that the ship speed is stable and in constant value. It seems improperly situation in practical maneuverings, especially when the ship entering to ports.

In this paper, the authors focus on studying on the activities of the ship inside traffic scheme until ship is stopped at certain area before berthing. We considered ship operation at low speed and reducing speed situation under disturbance effect. However, in low speed and disturbance's influence, ship's Track-keeping is not easy. Extra auxiliary devices such as tug-boats, ship's bow and side thrusters, etc. are also needed. Without these assistances, other methods should be needed in order to help the ship that called "Boosting effect". "Boosting effect" study will be introduced in this paper and numerical simulations for this effect were carried out to perform the ship auto track-keeping inside traffic scheme at low speed under disturbance influence. The results of simulations showed good performance and this designed control can be adapted in near future.

Keywords: Simulation; Track-keeping; Nonlinear expression; Wind effect; Boosting Effect.

1. Introduction

In the field of maritime safety system, various reports have been given on the research of ship automatic Track-keeping control and ship automatic berthing control over a long time but they are distinct from each other. Until the late 1970s, marine control studies were focused on the design of different autopilots. While the classical proportional-integral-derivative (PID) autopilots perform reasonably well in a specified performance envelope, their overall operational effectiveness is limited; this is due to the fact that classical PID autopilots require manual adjustments to compensate for changes in environment (wind and sea state) and in the dynamics of the ship. With the advent of accurate marine positioning system installed on board, Track-keeping control for ships has been studied extensively during the 1980s.

Hasegawa, K. (1987) introduced an adaptive track keeping subsystem for automatic collision avoidance system using fuzzy control which is described quite similar to human behaviors and easily linkable to an expert system. Kallstrom (1999) suggested PID automatic track keeping algorithm for high speed craft. Hwang, C. (2002) suggested a H -autopilots using PID-type controllers for collision avoidance. His autopilots subsystem considered the worst case disturbances. Velagic, J. (2005) developed a standard fuzzy ship autopilot to an adaptive fuzzy autopilot for track keeping. Furthermore, Xue, Y.(2011) also introduced simulation result of PID heading control for automatic collision avoidance for ships navigating in waterway. However, they have considered in common just nearly constant speed, which could not be assured of in berthing circumstance. To be confirmed berthing in advance, a ship is required to reduce its own speed and to stop at a certain area with designed heading angle.

The automatic berthing control of ships has been a relatively new development beginning in earnest in the 1990s. In a marine context, the berthing maneuver is a complicated procedure in which both human experience and intensive control operations are involved. Ship berthing needs for handling multiple input and output parameters with the inclusion of data from environmental disturbances. Due to the slow speed of the berthing ship the controllability of the ship is significantly reduced, whereas the

disturbances from wind and current can become relatively large; intensive rudder/propeller adjustments and large lateral movement of the ship can intensify the non-linear aspects of the ship dynamics, making the behavior of the ship rather unpredictable; ship motion at low advance speed is difficult to represent using differential equations, there by negating most control methods which are dependent upon the mathematical model of the dynamics of the ship; the shallow water and bank effects will add further adverse influence upon the ship handling.

Hasegawa, K. and Im, N (2002) introduced comparison method in which wind forces and moment were compared with rudder and thrusters forces and moment respectively when ship maneuvers in port. More recently, Tran, V (2012) used nonlinear mathematical expression and equilibrium equation to calculated critical wind velocity in automatic berthing. These researches was successful as the effects of the wind to ship maneuvering were clearly verified. Although considering low speed situation and disturbances, those previous researches on automatic berthing control have been carried out in very short circumstances with few steps to finish the operation. And even they suggested auxiliary devices, it still did not make a perfectly benefit for whole auto-berthing system for ship from port to port.

Usually, the ship that manned carries out three stages to be berthed at a quay;
- Stage 1, the ship departs from previous port, takes manoeuvring through open sea, then approaches the entrance of port of arrival. She often operates at normal speed or full speed. Previous researches on auto-Track-keeping are in this stage;
- Stage 2, she navigates inside traffic scheme route leading to a certain area with reducing speed. She stops at that area with desired heading angle;
- Stage 3, with the assistant of other devices, the ship takes berthing to the wharf with no difficulties. Previous researches on auto-berthing are only in this stage.

In order to connect the automatic track keeping in with berthing procedure, this research recommended automatic Track-keeping for ship at low speed. That means only 2nd stage which stated above is the environment to carried out this research. It can be understood that Track-keeping operation of ship starts from the first approach of ship in port domain until the ship stops at anchorage area, just before berthing procedure is operated.

Ship's Track-keeping at low speed and reducing speed under disturbance's affection faces difficulties to keep heading angle. This difficulty comes when rudder is not enough effective. We suggest the engine operation "Boosting effect" to be a solution for ship under this situation, without extra auxiliary devices. The clarified definition of "Boosting effect" is showed further in this paper.

## 2. Ship mathematical model

Ship Motion Equation

There are lots of mathematical models such as MMG, HSVA four quadrant, DEN-Mark 1 and others for ship's maneuvering motion. In case of MMG mathematical model among the above methods it was originally proposed by MMG (Mathematical Models of Maneuvering Motion Group) which was established by the second section of the Japan Towing Tank Committee in March 1976. MMG models divided the hydrodynamic forces and moments acting on a ship in maneuvering motion into the modules such as hull, propeller, rudder and other considerable external hydrodynamic forces and moments.

$$
\begin{aligned}
(m + m_v)u - (m + m_v)vr &= X_H + X_P + X_R + X_W \\
(m + m_y)v + (m + m_x)ur &= Y_H + Y_P + Y_R + Y_W \\
(I_{zz} + J_{zz})r &= N_H + N_R + N_W
\end{aligned}
\qquad (1)
$$

The ship's motion equations (1) are applying MMG model for 3-DOF ship dynamic (surge, sway and yaw motion) in coordinate system (Fig. 1). Where, $O\text{-}x_0 y_0 z_0$ is the earth- fixed coordinate and $G\text{-}xyz$ is the body-fixed coordinate which is origin at the center of gravity,

In addition, because MMG mathematical model is presented as modular type, a recent researched model for module can be simply considered by changing older model used in the mathematical model, such as additions of the extra disturbance's forces and moments

m : mass of ship
m_x, m_y : added mass in surge and sway direction
u, v, r : surge and sway velocity and yaw rate
J_{zz}, I_{zz} : added mass moment, mass moment of inertia
X_H, Y_H, N_H : hydrodynamic forces acting on ship's hull
X_P, Y_P : hydrodynamic forces acting on ship's propeller
X_R, Y_R, N_R : forces and moment due to rudder
X_W, Y_W, N_W : forces and moment due to wind
u, v : acceleration in surge and sway direction
r : acceleration of yaw motion.
         : rudder angle
ψ : ship's heading
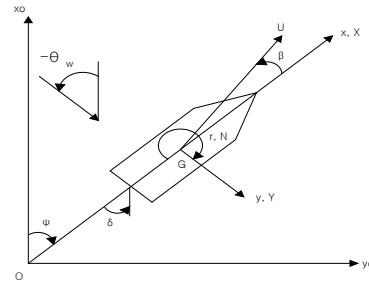
Model ship

Figure 1 Coordinate system for ship dynamic

The Mokpo National Maritime University's training ship SAE NURI was adopted as the model ship. The ship's principle particular is shown in Table 1 as follow;

Table 1 Principle particular of the ship

Type	Training ship
LoA	103[m]
Lpp	94[m]
Breadth	15.6[m]
Draft	5.4[m]
Thruster (Bow)	49000N
Transverse projected area	183.3[m2]
Lateral projected area	1053.7[m2]

Disturbance Model

Isherwood, R.M (1972) has analyzed the results of wind resistance experiments carried out at different laboratories with models covering a wide range of merchant ships. He gives empirical formulas for determining the two horizontal components of wind force and the wind-induced yawing moment on any merchant ship form for a wind from any direction. According to his model, the coefficient of wind effects can be defined as follows;

$$C_X = A_0 + A_1 \frac{2A_L}{L_{OA}^2} + A_2 \frac{2A_T}{B^2} + A_3 \frac{L_{OA}}{B} + A_4 \frac{S}{L_{OA}} + A_5 \frac{C}{L_{OA}} + A_6 M$$

$$C_Y = B_0 + B_1 \frac{2A_L}{L_{OA}^2} + B_2 \frac{2A_T}{B^2} + B_3 \frac{L_{OA}}{B} + B_4 \frac{S}{L_{OA}} + B_5 \frac{C}{L_{OA}} + B_6 \frac{A_{SS}}{A_L} \qquad (2)$$

$$C_N = C_0 + C_1 \frac{2A_L}{L_{OA}^2} + C_2 \frac{2A_T}{B^2} + C_3 \frac{L_{OA}}{B} + C_4 \frac{S}{L_{OA}} + C_5 \frac{C}{L_{OA}}$$

where, C_X : coefficient of fore and aft component of wind force
         C_Y : coefficient of lateral component of wind force
         C_N : coefficient of wind-induced yawing moment
         $A_0 \sim A_6, B_0 \sim B_6, C_0 \sim C_5$: Isherwood's coefficient for model

Then, wind force and moment would be calculated by following algorithm with the relative wind speed to ship (V_R);

$$X_W = C_X \frac{1}{2} \rho V_R^2 A_T$$

$$Y_W = C_Y \frac{1}{2} \rho V_R^2 A_L \qquad (3)$$

$$N_W = C_N \frac{1}{2} \rho V_R^2 A_L L_{OA}$$

when, X_W : Fore and aft component of wind force
           Y_W : Lateral component of wind force
           N_W : Yawing moment
           V_R : relative wind speed to ship

There are lots of disturbance models such as current, wave,.. to take into account, but this wind model was applied as the main disturbance model because in the area which simulation has been taken, wind is the most adverse effect to every ship (described in Chapter 3). More works needed to be done in future that considering extra disturbance models.

3. Automatic track-keeping concept

PID control

Nowadays, due to the development of high technology, various navigation aids installed on board such as a gyrocompass, AIS, GPS, Doppler log…can provide an accurate measurement of the ship state (heading, position, speed and yaw rate). As in the case of Sperry's work (1922), PID controller designs were predicated on visual observation of the way experienced helmsman would steer the ship. He acknowledged that helmsman would anticipate ship motions before applying rudder corrections but more importantly he postulated that they possessed the ability to judge angular velocity, yaw rate, there by effecting derivative control.

In this simulation-based research, a PID controller is designed under assumption that the ship state can be taken on board that ship. When K_p, K_d and K_i are proportional gain, derivative gain and integral gain, respectively. Eq. 4 shows the input and output data are designed rudder angle for each loop, and e is error between target heading ψ_T and current heading angle ψ_P.

$$\delta = K_p . e(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(\tau) d\tau \qquad (4)$$
$$e = \left(\psi_T - \psi_P \right)$$

Ship's Track Design

Previous researches related to ship's automatic Track-keeping control system have been considered at ship's high-speed (above 10 knots) and their scopes of application are not inside the port's domain. In spites of the fact that previous researches related to ship's automatic berthing control have been considered at ship's low speed, their scope of application are too small inside port domain, also in very short time. These above disadvantages are not solved, then they cannot cooperate which each other to adapt with whole ship's automatic berthing system.

This simulation based research using a traffic scheme in South Korea as the environent to operate Track-keeping. Ship's track was joined by 10 waypoints and the ship must keep-track on and stop by anchorage point as waypoint No. 10 (Fig. 2);

Figure 2 Designed Track for Simulation

Fig. 2 shows the traffic scheme in Mokpo-si, Jeollanam-do, South Korea, in front of Mokpo National Maritime University's quay. This area is the place that was taken as the environment in simulation. The breadth of traffic scheme at the most narrow segment is about 7 times of ship's length.

By using PID control for track keeping, the designed rudder angle is calculated by $\delta = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$ (with $K_p = -1$, $K_i = -0.015$ and $K_d = -0.8$ are gains for P, I, and D control respectively). Wind with direction from North to South and its varied strength from 0 knots, was chosen to apply to the disturbance model.

Track-keeping Algorithm

The ship moves on a segment between way-point P_i and P_{i+1}. The Fig. 3 shows current ship's position described by (x_t, y_t) and is calculated from inside ship's motion equations at time t of the loop system. The current way-point's position is (x_d, y_d). After that, the ship's bearing to current way-point (B_d) can be obtained as in Eq. 5. Then the ship's target heading (ψ_d) will be decided for proper quadrant of (B_d). At the end of simulation, if the ship reaches the anchorage place, she should head toward the berthing quay.

$$B_d = \text{arctg} \; \frac{y_d - y(t)}{x_d - x(t)} \tag{5}$$
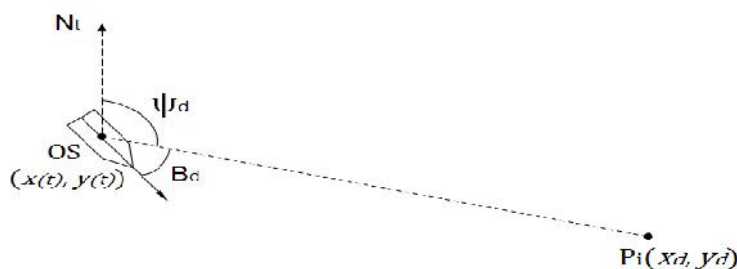

Figure 3 Ship's target heading to way-point

When the ship reached a certain remain distance (d_0) to current waypoint (P_i), she will change her heading toward the next waypoint (P_{i+1}). That means, when $d \leq d_0$ ship's direction changes from $\overrightarrow{P_{i-1}P_i}$ to $\overrightarrow{P_iP_{i+1}}$.

As to confirm that this research suggested Track-keeping control for ship's berthing, ship's speed at the starting point of simulation is equal to 10 knots, propeller index is 2.75 round per second. After the ship

reaches way-points one by one, the propeller's revolution will be reduced for safe approaching to berthing place (eg. If current waypoint is waypoint P_i then rpm $n_k = n_{k-1} - 0.25$).

From waypoint No.1 to waypoint No. 4, the ship's speed will be about 10 knots as same as the beginning of simulation. From way-point No.5 to waypoint No. 8 the ship's speed will be reduced to about 2 knots as real Track-keeping of T/S SAE NURI conducted by human. Then ship's speed will be continuously reduced its own speed until approximately 0 knots for safe approaching to anchorage place at waypoint No. 10. In case of the speed is too high even the engine stopped (i.e. n=0) and the ship has a risk of passing out the anchorage point, the astern thruster force should be made to reduce that inertial motion.

Hence, if ship's berthing procedure is to conduct, it will be carried out by automatic berthing controller or by assistant of tug boats, etc. as usual.

Boosting Effect method

The environment to carry out this reseach can be explained by following figure;
- At stage 1, ships in open sea usually use full speed or normal speed to manoeuvre.
- At stage 2, ships in port domain usually reduce their speed for safely manoeuvring. They have to stop at a certain area with desired heading angle.
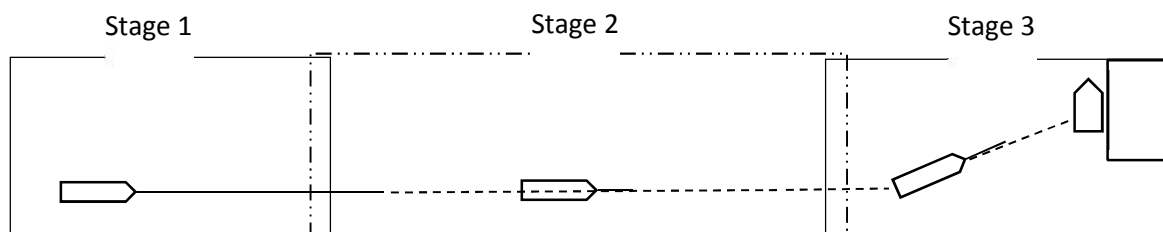- At stage 3, ships take berthing to wharf with the assistants of tug-boats, side-thrusters, port mooring equipments…

Figure 4 Operation of ship until berthing

Previous researches have been carried out in stage 1 or stage 3. That is the reason we suggested the stage 2 to be our environment of research to adapt with auto-berthing system for ship from port to port. Usually, keeping heading angle at low speed is difficult. Previous researches related to ship's auto-berthing suggested tugboats, side-thrusters, … in this situation for short moment. Meanwhile, previous researches that related to ship's auto-track keeping have not been mentioned this situation. Ship movement in low speed also occurred difficult to keep her own heading angle. In that case, rudder is not as effective as in high speed situation. It can be explained that at low speed situation, ship's turn rate is not change even its rudder reached the limit effective angle (i.e. 35°-40° both sides).
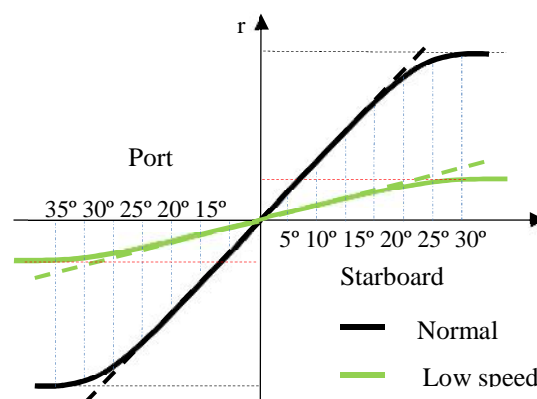

Figure 5 Diagram of turning characteristic is used to correct rudder's effect

The diagram in Fig. 5 shows how ship's turning characteristic depends on ship's speed. As normal as ship's high speed, ship's turn rate increases as fast as rudder angle increases for each side of turn. But at low speed, ship's turn rate is not effective as slow changing of turn rate or even unchanging. Due to the effect of disturbances, this problem will lead the ship off the designed track as soon as possible. According to Fig. 5, ship's turn-rate at normal speed (above 10 knots) changes to high value as fast as rudder angle is increased. While at low speed, it changes slowly and only can reach low value. That shows rudder effect is small at low speed.

To solve these problems, "boosting effect" was suggested as the advance solutions. "Boosting effect" has been used often in ship's berthing procedure. The ship's engine was ordered to "boost" for short time by the Pilot or ship's Captain to aid the turning when ship's speed is too low. "Boosting effect" has a character as a pulse signal, when applied, it won't increase ship's speed as much as normal speed but also increase ship's turn rate. Therefore, "boosting effect" is applied when ship's turn rate (yaw rate - r) has not changed big enough to aid the ship's turning while maximum effective rudder angle was also used for such moment. When this happened, ship's thruster is being boosted until yaw rate reaches a value for good enough ship's turning.

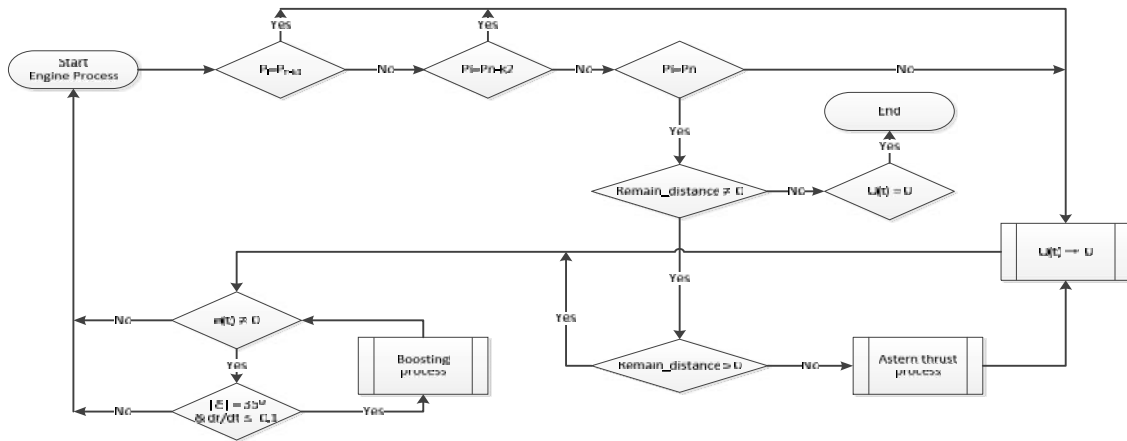The diagram below describes how the system responses for each time of facing this problem;

Figure 6 Block diagram of heading angle control

The diagram in Fig. 8 shows exact process of using engine for heading control. Speed of ship is reduced base on current waypoint P_i, some waypoints P_{n-k1}, $P_{n-k2,..}$ are marks for ship to keep her rpm at certain values. Engine is boosted only when the ship has problem on keeping heading angle, even the rudder reaches maximum effective angle 35°. Otherwise, astern force is used only to remove forward inertial force in order to stop the ship at certain area safely.
The engine control is stopped when ship stay near stopping point with no speed. The desired heading angle will continuously be kept until the stop of ship.

4. Simulation results

For a start of simulation, when no wind model was applied, the ship's trajectory under no wind's influence left small off-track errors. The ship kept close to the track inside traffic scheme and stayed firm in way-point No. 10 anchorage point. This would prove that without disturbance, this control is reliable for Track-keeping inside port domain with reduced speed. With the increased wind speed's affection from 0 to 5 knots, more errors have been seen in Fig. 7 below.
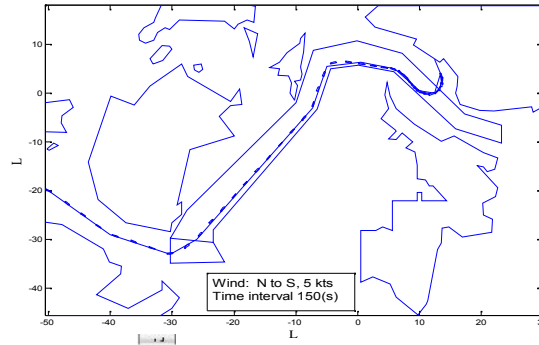
Figure 7 Ship's trajectory with the assistant of "Boosting effect"
under the affection of wind (from N to S, 5 kts)

More errors have been found when the ship at the very end of keeping track from way-point No. 9 to No. 10 when ship's speed was very low under 1.2 knots. However, the ship could keep stable as former situation. The ship reached the final point, kept staying at last waypoint. For outcome history data, the control seems to be reliable when keeping ship's track under small disturbance's influence.

When wind's speed was 10 knots high, it seems that the control finally completed the Track-keeping procedure with great effort. Fig. 8 shows the ship's Track-keeping trajectory with the assistant of "Boosting effect". In this circumstance, the last schedule of Track-keeping this trajectory is the most error trajectory among the last shown 3 results, under the wind's conditions of 0 kts upped to 10 kts. The ship drifted out of track from way-point No.6 to No.10.

In fact that this problem lead us to reconsider to improve the effort of the control. However, we should pay attention to the disturbance's affection to review this controller's effort. Wind speed in this circumstance was about 10 knots high meanwhile the ship's speed was very low at the end of the operation as about 1.0 knots when she had just passed waypoint No.9 and even equal to 0 knots when she reached way-point No. 10.
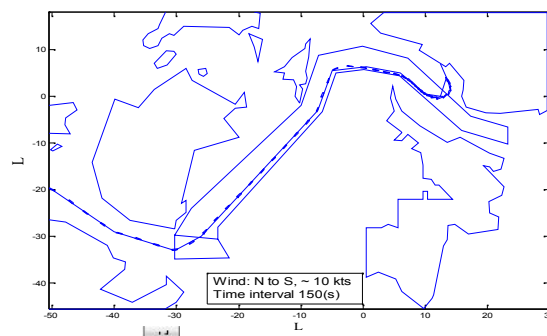

Figure 8 Ship's trajectory with the assistant of "Boosting effect"
under the affection of wind (from N to S, 10 knots)

Fig. 9 shows how the ship's Track-keeping without the assistant of "Boosting effect" under the same characteristic with the last condition shown above;
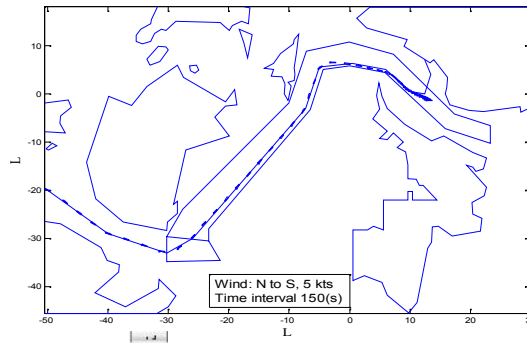
**Figure 9 Ship's trajectory without the assistant of "Boosting effect"
under the affection of wind (from N to S, 10 knots)**

According to Fig. 9, ship's Track-keeping under wind effect without using "Boosting effect" left so many errors. The ship did not only drift out of designed track from waypoint No. 6 to waypoint No. 8 but also could not reach the anchorage point.

To find out more details of the assistant of "Boosting effect", the comparison between the controllers of each situation with or without "Boosting effect" under wind's influence has been made by following figures;
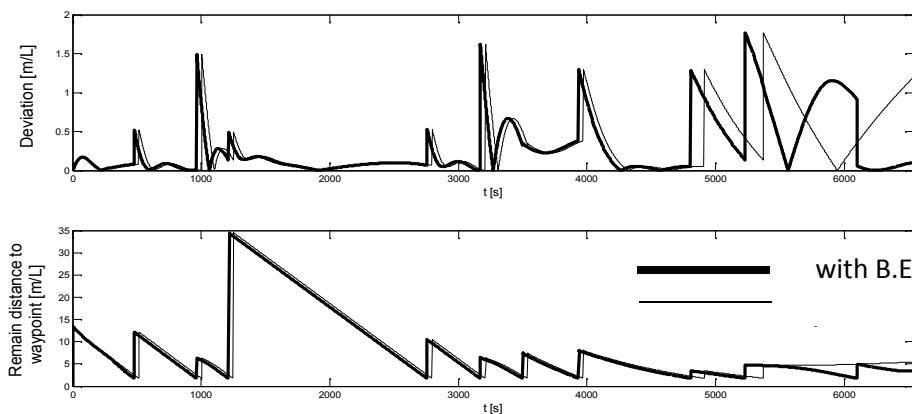

**Figure 10 Comparison between controllers with "B.E" and without B.E" by
time history of parameters: Deviation, Remain distance to waypoint**

Time history parameter "Remain distance to waypoint" in Fig. 10 shows how the ship passed each way-point. It was shown as the distance to previous way-point had been reduced to minimum value and distance to current way-point has been raised up to maximum value. The last distance should be the distance from the ship to the wharf. In this case, the controller without "Boosting effect" did not move the ship to way-point No.9, even drifted far off the track. Whilst the controller with "Boosting effect" has done it also brought the ship to way-point No.10.

While time history of parameter "Deviation" shows how the ship kept close to the designed track. The maximum deviation off-track of the ship using controller with "Boosting effect" is *160* meters, about 1.7 ship's length, according to the segment between waypoint No. 9 and waypoint No. 10. This deviation value was accepted because of this segment was inside anchorage place, and there are no obstacles of water level or passing ships. The others deviation value was also accepted because the traffic scheme's breadth was 6 to 7 times of ship's length and the ship's motion was inside the half safe of traffic scheme's route. The thicker line stands for engine process with "Boosting effect", the rest stands for engine process without "Boosting effect".
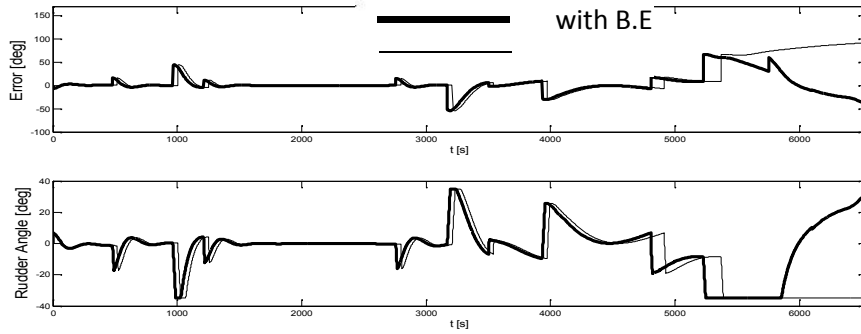
Figure 11 Comparison between controllers with "B.E" and without B.E" by time history of parameters: Error, Used Rudder Angle

According to Fig. 11, the controllers with "Boosting effect" totally helped the ship to reduce the heading error. At the end of simulation, controllers with "Boosting effect" was turned to port because of strong wind effect. This could be acceptable because the ship would conduct berthing procedure after finish Track-keeping. The controllers' simulation result was accepted in using rudder angle. Rudder angle was used without breaking the limitation (| | 35º).
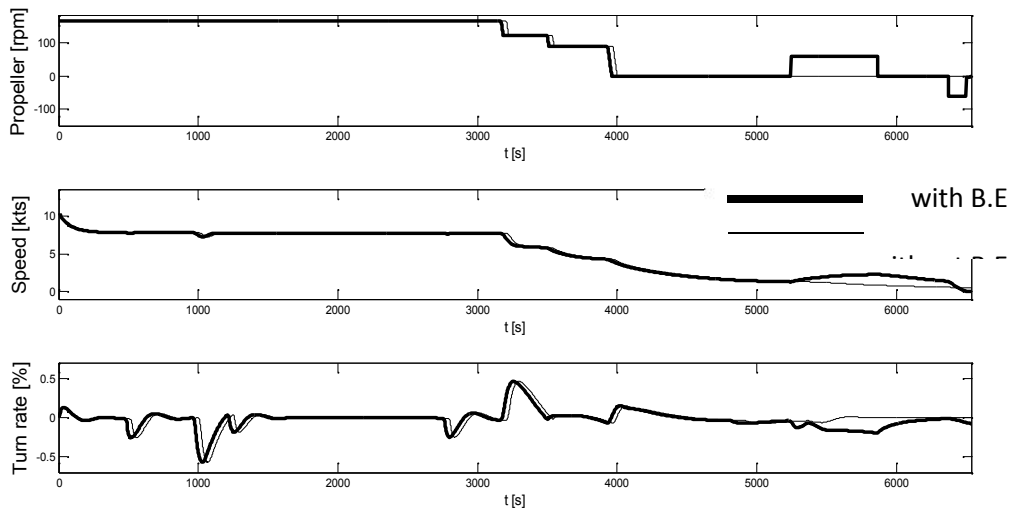

Figure 12 Comparison between controllers with "B.E" and without B.E" by time history of parameters: Change of turn rate, Propeller index and ship's speed

Fig. 12 shows how ship's engine control the ship's speed. Because of no "Boosting effect" was used, propeller history (*rpm*) of the controller without "Boosting effect" was reduced step-by-step to reduce ship's speed. At the end of simulation, ship's speed is equal to 0.5 knots that could not help the ship to return its track.

Otherwise, controller with "Boosting effect" using propeller index for both increasing and decreasing ship's speed. The speed was increased a little bit by "Boosting" of ship's engine when ship's turn rate was not being changed big enough. At that time, propeller index was increased up. When the ship's speed was too high to slow down, propeller was also used to astern thrust the ship. At the end of simulation, ship's speed was equal to 0.005 knots. This is safe enough as the ship stopped near the last waypoint. The criteria was met.

5. Conclusion

After reviewing the simulation results, this study proved that:

- The ship can use this controller for specific purpose of automatic Track-keeping at the specified moment as when finished ocean navigating and before berthing to a quay; in the specified place as Track-keeping insides traffic scheme that is leading to the wharf; and with difficulties are low speed, reducing speed and disturbance effect.
- Heading angle at low speed was controlled with the assistant of "Boosting effect" which is unfamiliar with other previous researches. "Boosting effect" was proved as a vital characteristic of this controller to aid the ship at low speed, under the strong wind and without any help of extra auxiliary devices.

Acknowledgement

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