

# On the Control of CPP Ships by Steering During In-Harbour Ship-Handling

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**ABSTRACT:** This paper describes the results of experimental and simulation studies that aimed at developing effective control methods for single-CPP single-rudder ships during the coasting manoeuvre and the stopping manoeuvre. In order to improve the manoeuvrability of CPP ships under coasting, the authors performed full-scale experiments and confirmed that CPP ships under coasting using the Minimum Ahead Pitch (MHP) of CPP are controllable by steering. A simulation study was also conducted to evaluate the ship-handling method during the stopping manoeuvre that applies a turning moment to the ship by the maximum rudder angle steering prior to the reversing operation of the CPP and it is confirmed that CPP ships can be controlled sufficiently by the proposed method.

## 1 INTRODUCTION

It is well known that a controllable pitch propeller (CPP) can provide smooth speed control. On the other hand, in case of ships with single CPP and single rudder, the difficulties of coasting manoeuvre and stopping manoeuvre are reported (Takeda 1992, Yabuki 2006).

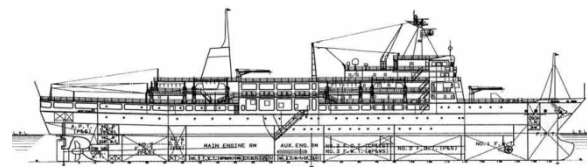
During coasting manoeuvre of CPP ships with propeller pitch feathered to zero, the rudder force reduces significantly and CPP ships are difficult to control their head turning motion by steering especially under windy condition. Furthermore, during the stopping manoeuvre of CPP ships, an additional unstable yaw moment is often exerted, which introduces a significant reduction in manoeuvrability, and, under this condition, it is difficult to control their head turning motion by steering.

In order to improve the manoeuvrability of CPP ships at coasting, the authors propose the use of the Minimum Ahead Pitch (MHP) of CPP. The MHP is the smallest blade angle of CPP for ahead propulsion which ensures adequate steerage. The authors conducted full-scale experiments using a 5,884 G.T. single-CPP, single-rudder training ship to confirm the effectiveness of the MHP operation in coasting.

Figure 1 shows the general arrangement and principal particulars of the test ship.

A simulation study using the MMG type mathematical model was performed in order to investigate the in-harbour ship-handling method to control the

unstable stopping motion of CPP ships. The test ship was the same CPP ship as stated above. Based on the results of the simulation study, the authors propose an effective ship-handling method that applies a turning moment to the ship by the maximum rudder angle steering prior to the reversing operation of the CPP.



Principal Particulars	
<b>Hull</b>	
Length: Lpp (m)	105.00
Breadth: B (MLD, m)	17.90
Depth: D (MLD, m)	10.80
Cb	0.5186
draft: d (m)	5.96
<b>Propeller (CPP)</b>	
Prop. Brade No.	4
Prop. Dia.: Dp (m)	4.70
P.R. (Brade Angle)	1.050 (25.5°)
<b>Rudder (Flap Rudder)</b>	
Ar (m <sup>2</sup> )	10.034
Ar/Ld	1/63.4
Aspect Ratio	1.865

Figure 1. Principal particulars of the test ship

## 2 CHARACTERISTICS OF TURNING MOTION OF CPP SHIPS DURING STOPPING MANOEUVRE AND COASTING

### 2.1 Turning motion during stopping manoeuvre

The test ship is equipped with a CPP and can also reverse the main engine directly. This system makes it possible to perform a comparative experiment using the same hull and engine under the same condition to investigate the difference of a turning motion during the stopping manoeuvre between CPP and FPP (Fixed Pitch Propeller) ships.

Full-scale stopping tests were performed under almost the same condition in deep water in both CPP and FPP operation modes. As light breeze was observed during the experiment, the initial course was set into the wind for all stopping tests. In Figure 2, the final head turning angle( $\Psi$ ) when the ship is stopped is plotted against the initial advancing constant  $J_{s0}(=U_0/(n \cdot P))$  both in the CPP mode and in the FPP mode. In the figure, the results of the stopping manoeuvre in which the propeller was reversed and the maximum rudder angle was applied simultaneously are plotted in addition to those with the rudder amidships.

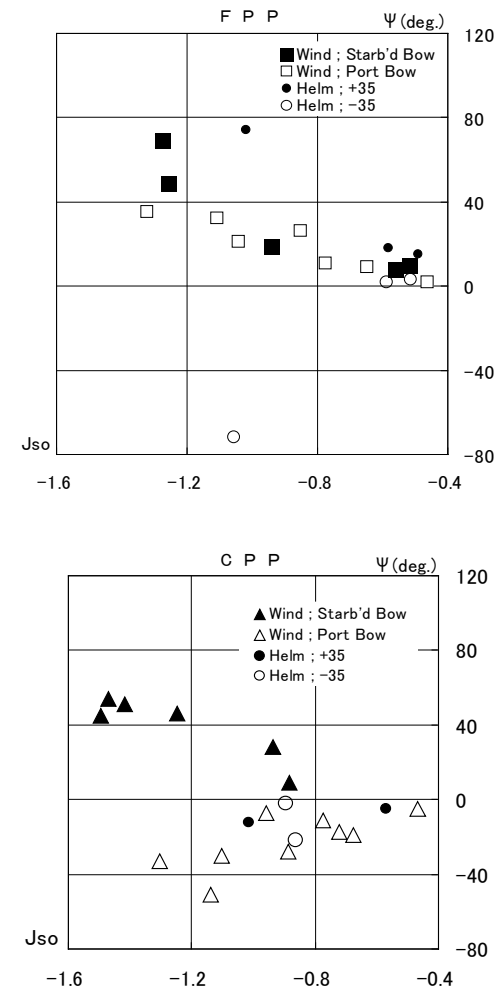


Figure 2. Comparison of the head turning angle between FPP and CPP

In the FPP mode, the test ship exhibits the typical stopping motion of a right turning single propeller ship, i.e. she turns her head to the starboard steadily and the direction of her turning motion can be sufficiently controlled by steering. On the other hand, the turning motion in the CPP mode proved to be less stable than that in the FPP mode and the effect of steering to control the direction of turning motion was not observed. The direction of turning motion in the CPP mode seems to be fixed mainly by the relative wind direction at the initial stage of propeller reversing.

From the above-mentioned results, it is assumed that the direction of turning motion of CPP ships is fixed by the head turning moment at the initial stage of propeller reversing.

### 2.2 Turning motion during the coasting manoeuvre

The authors performed course keeping tests using the same CPP ship as mentioned above in order to compare the effects of steering control under the coasting manoeuvre between the propeller pitch zero operation and the MHP operation. The time history of heading, rudder angle, CPP blade angle and ship speed are plotted in Figure 3.

In the coasting manoeuvre under the propeller pitch zero operation, the test ship turns her head into the wind even though the wind was very weak (1 m/s) and her head turning motion can not be controlled by steering with the maximum rudder angle. Since the obtained results agree with the results of other experiments (INOUE 1992) qualitatively, these characteristics seem to be common among ships with a single CPP and a single rudder.

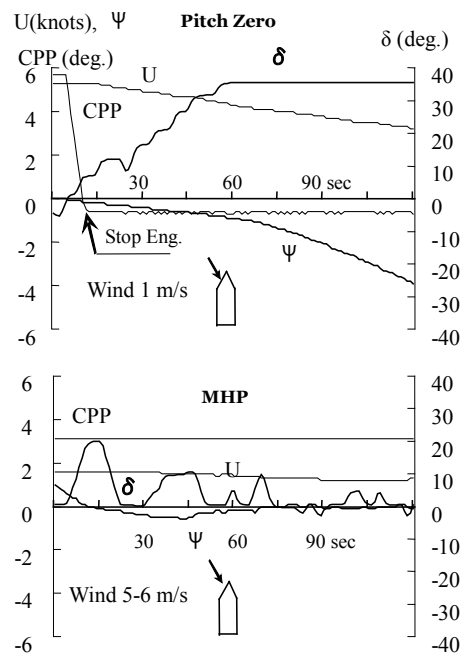


Figure 3. Comparison of the course keeping ability between pitch zero operation and MHP operation

This manoeuvring difficulty may be due to the pitch distribution of blades at propeller pitch zero operation. Though the pitch around the boss is maintained to the advance side, the pitch around the tip is changed to the reverse side at propeller pitch zero operation and the unstable flow which reduces the rudder force is generated around the stern.

On the other hand, in the case of the coasting manoeuvre with the MHP, the test ship can keep her original course under strong wind conditions (6 m/s) by applying the appropriate helm. This experimental result seems to prove the effectiveness of the MHP operation under the coasting manoeuvre and that CPP ships under coasting using the MHP can keep and control their heading by steering.

### 3 CONTROL OF TURNING MOTION OF CPP SHIPS DURING STOPPING MANOEUVRE

#### 3.1 Stopping motion prediction of CPP ships

The stopping motion of CPP ships is predicted using the MMG type mathematical model. The mathematical model can be described by the following equations of motion using the coordinate system in Figure 4.

$$\left. \begin{aligned} m\dot{u} - mvr &= X \\ m\dot{v} + mur &= Y \\ I_{zz}\dot{r} &= N \end{aligned} \right\} \quad (1)$$

The hydrodynamic forces can be expressed by the following equations.

$$\left. \begin{aligned} X &= X_H + X_P + X_R + X_W \\ Y &= Y_H + Y_P + Y_R + Y_W \\ N &= N_H + N_P + N_R + N_W \end{aligned} \right\} \quad (2)$$

where,  $m$  = mass of ship;  $I_{zz}$  = moment of inertia of ship in yaw motion;  $u, v, r$  = axial velocity, lateral velocity, rate of turn respectively.

The terms  $X, Y$  and  $N$  represent the hydrodynamic forces and moment. The subscripts  $H, P, R$  and  $W$  refer to the hull, propeller, rudder and wind force respectively.

The detailed expression of hydrodynamic forces and moment on the hull, propeller, rudder and wind are available in the references (Yabuki 2006, Yabuki 2007).

The hydrodynamic derivatives and coefficients for simulation were measured by the captive model

tests such as CMT, oblique towing tests, and rudder tests using 1/24.48 ( $L_{pp} = 4.29\text{m}$ ) model. The hull force and moment coefficients are measured by CMT and oblique towing tests. As for the forces and moment induced by propeller reversing, the thrust coefficients were estimated using the 4 quadrant POT result on the reversing blade angle and thrust data on MAU charts. The thrust deduction coefficient was obtained by the model test. The lateral force and moment were obtained from the captive model tests on the reversing blade angles. Rudder force and moment coefficients are measured by rudder tests and the interactive coefficients between hull and rudder are obtained from the gradients of these coefficients. The wind force and moment coefficients were derived from a wind tunnel test using the 1.5 m length model. The hydrodynamic derivatives and coefficients for simulation are available in the references (Yabuki 2006, Yabuki 2007).

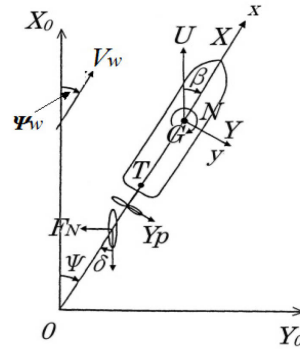


Figure 4. Coordinate system

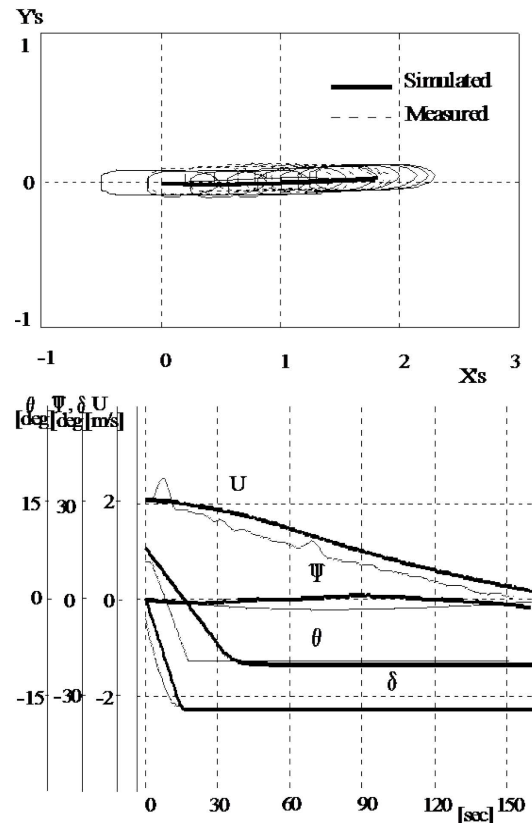


Figure 5. Comparison of the stopping motion between measured and simulated

The accuracy of the mathematical model of the test ship was confirmed by comparing the simulation results with those of full-scale experiments as shown in Figure 5. In the stopping test, turning moment is applied to the test ship by maximum rudder angle steering prior to making slow astern operation while proceeding at 4 knots. Although the time history of ship speed indicates some discrepancy between simulation and actual measurement, the predicted changes of heading and trajectory are in good agreement with the measured results. Thus, it seems reasonable to consider that the proposed simulation model represents the stopping motion accurately.

### 3.2 Steering control of CPP ships during stopping manoeuvre

As described in section 2.1, the direction of turning motion of CPP ships during the stopping manoeuvre seems to be determined by the yaw moment at the initial stage of propeller reversing. Therefore, the authors propose the stopping manoeuvre to control the head turning motion of CPP ships that applies turning moment by the maximum rudder angle steering prior to propeller reversing and performed the simulation test to confirm the effectiveness of proposed method.

Figure 6 shows the simulation results of the stopping manoeuvre where the propeller is put slow astern while proceeding at 3 knots under 10 m/s left wind. In the stopping manoeuvre with the rudder amidships, the test ship drifts leeward and turns her head into the wind. On the other hand, in the stopping manoeuvre that applies the maximum rudder angle steering to leeward prior to propeller reversing, although the test ship drifts leeward, the yaw moment can be reduced sufficiently and her original heading is well maintained.

## 4 APPLICATION OF PROPOSED METHODS TO IN-HARBOUR SHIP-HANDLIN

### 4.1 Anchoring under windy condition

The series of ship-handling for anchoring consists of four simple manoeuvring elements, i.e. approaching, stopping, laying out anchor and fetching up. When approaching, it is necessary to proceed on the planned track and reduce the speed by the coasting manoeuvre. The proposed MHP operation is applicable for the coasting manoeuvre while approaching the anchorage especially under windy condition. When stopping for laying out anchor, it is essential to control the ships heading into the resultant of all external forces such as wind and current. The proposed steering control method can be applied to the manoeuvre to stop the ship while keeping her heading into the wind.

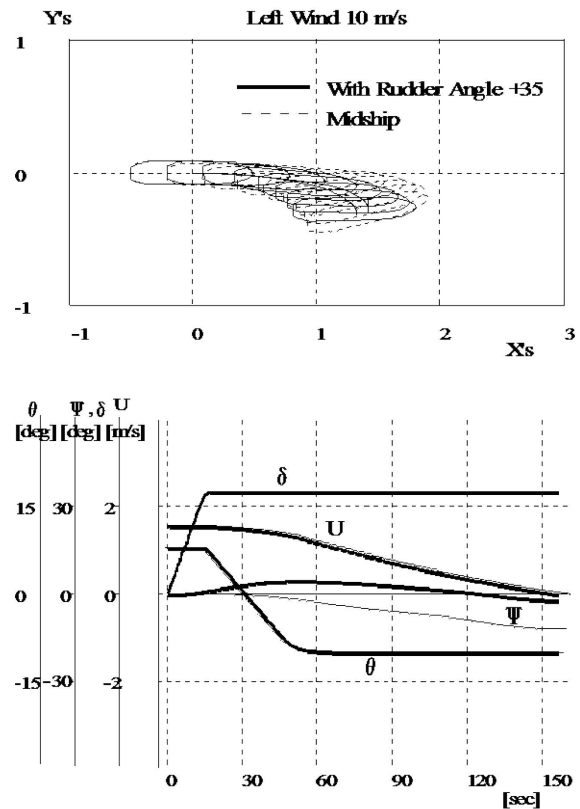


Figure 6. Example of controlling yaw moment by applying lee helm prior to reversing. (Left wind, 10 m/s)

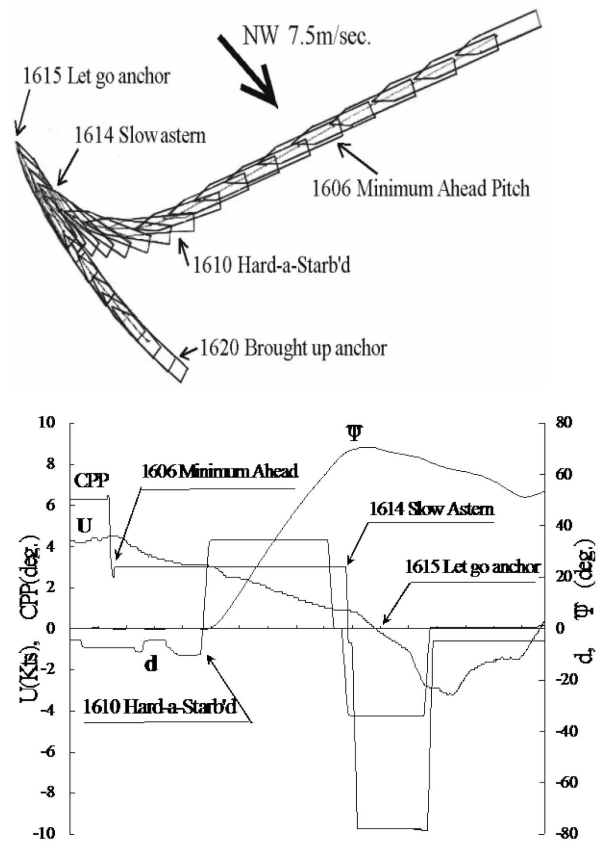


Figure 7. Effective CPP ship handling for anchoring in windy condition (Full scale trial)

The authors applied the above two control methods to the actual anchoring of the test ship under the 7.5 m/s beam wind condition and the results are

shown in Figure 7. During the approach ship-handling, the test ship first reduced her CPP blade angle from dead slow ahead to the MHP while proceeding at 4 knots for speed reduction and proceeded on the planned track by applying lee helm properly to control the head turning moment to windward. Next, when the headway was reduced to 3 knots, the test ship used hard-starboard steering to apply the maximum yaw moment to windward. After the yaw moment increased sufficiently, the test ship changed the blade angle to slow astern directly, skipping the propeller pitch zero operation. Finally, the test ship stopped with her heading into the wind and the chain was laid out adequately to leeward. The above results of the full-scale experiment indicate that the proposed methods can be effectively applied to anchoring under external forces.

#### 4.2 Crash stop astern manoeuvre in a harbour area

The proposed steering control method during the stopping manoeuvre is applicable to the crash astern manoeuvre to avoid collision with other ships. In this case, it is necessary to stop the ship with the shortest distance by the propeller reverse operation and turn her head to the starboard as great as possible by the steering. To achieve this collision avoidance manoeuvre, the authors recommend the ship-handling method that puts the propeller to full astern after applying the starboard head turning moment by the maximum rudder angle steering and confirm the effectiveness of this method by simulation.

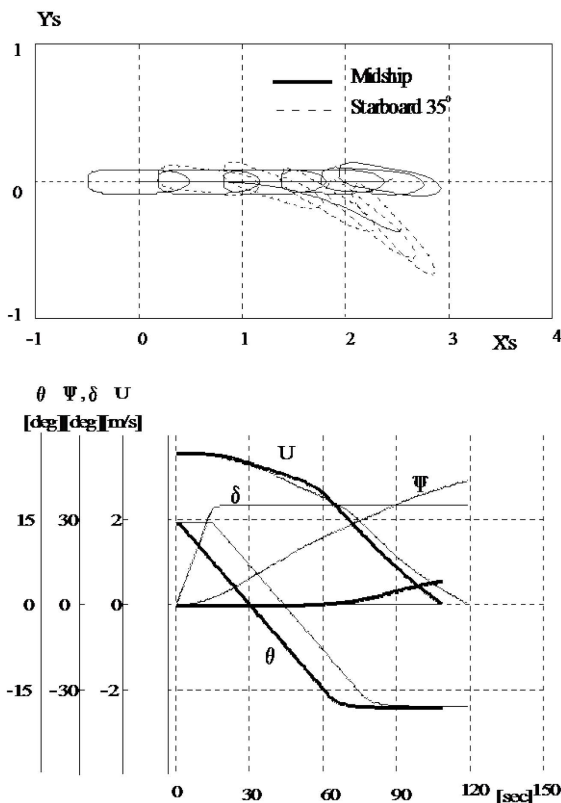


Figure 8. Example of the crash astern manoeuvre that applies maximum starboard rudder angle prior to the propeller reversing (Calm condition)

The results of the crash astern manoeuvre, while proceeding at 6 knots, that utilizes the maximum rudder angle steering to starboard prior to the full astern operation are shown in Figure 8. In the case of the crash astern manoeuvre with the rudder amidships, the test ship stopped turning her head slightly to the right of the original track, and both the head turning angle and the side reach are not enough to avoid collision. On the other hand, when the maximum starboard rudder angle was applied prior to the reverse operation, both sufficient starboard head turning angle and side reach to avoid collision were obtained. On this crash astern manoeuvre, although the 15 second delay in the reverse operation is observed compared to the manoeuvre with the rudder amidships, the head reach shows the same figure (2.5 L). This seems to be due to the additional resistance which is exerted by the steering and the oblique drift of the hull in the case of the manoeuvre with the maximum rudder angle steering. Therefore, it can be inferred that there is little effect of the reverse operation delay on the stopping distance in the proposed crash astern manoeuvre.

Next the authors performed a simulation study to confirm the effectiveness of the proposed crash astern manoeuvre under windy condition. The simulation was conducted with 10 m/s winds for various wind directions and the obtained results are shown in Figures 9-12.

In the case of the crash astern manoeuvre with the rudder amidships, the test ship stops almost on the original track with slight head turning, however the head turning angle is not sufficient for collision avoidance in the head-on situation. On the other hand, the crash astern manoeuvre with the maximum rudder angle steering, both sufficient side reach and head turning angle for collision avoidance are observed for each wind direction.

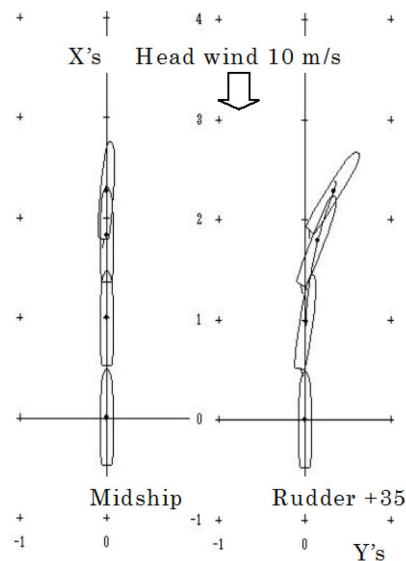


Figure 9. Crash astern manoeuvre with maximum starboard rudder angle (Head wind, 10 m/s)



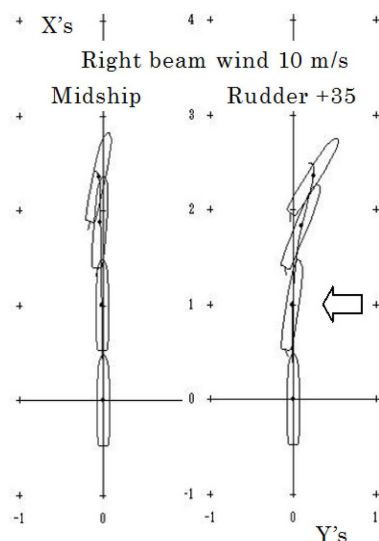


Figure 10. Crash astern manoeuvre with maximum starboard rudder angle (Right wind, 10 m/s)

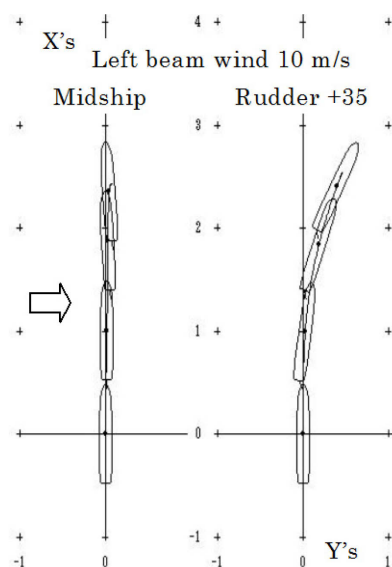


Figure 11. Crash astern manoeuvre with maximum starboard rudder angle (Left wind, 10 m/s)

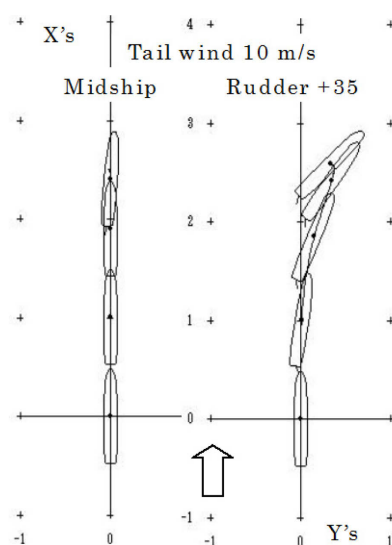


Figure 12. Crash astern manoeuvre with maximum starboard rudder angle (Tail wind, 10 m/s)

This simulation study demonstrates that the proposed crash astern manoeuvre is effective for collision avoidance under windy condition.

## 5 CONCLUSION

The authors performed full-scale experiments and a simulation study in order to develop an effective control method for CPP ships during the coasting manoeuvre and stopping manoeuvre. Results obtained in this study are summarized as follows.

- 1 CPP ships under coasting using the MHP are controllable by steering, making it possible to keep the planned course.
- 2 For ships with a single CPP and a single rudder, the MHP operation improves the manoeuvrability in coasting and in-harbour ship-handling.
- 3 The unstable head turning motion of CPP ships during the stopping manoeuvre can be controlled sufficiently by the ship-handling method that applies turning motion to the ship by the maximum rudder angle steering prior to the reversing operation of the CPP.
- 4 This ship-handling method is applicable to the ship-handling for anchoring under windy condition and the crash astern manoeuvre in a harbour area.
- 5 Proposed steering control techniques are applicable and effective for the in-harbour ship-handling of CPP ships with forward accommodations such as the test ship. It remains to be seen whether these techniques are applicable for the ships with different configurations

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