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A Study on a Vessel with Multiple Flat and Hard Sails to Keep Service Speed in High Winds

Seiki Onishi, Tsutomu Momoki* and Yoshiho Ikeda

Graduate School of Engineering, Osaka Prefecture University
1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan

Abstract: Ships which have large structures above water surface, such as pure car carriers (PCCs) and container vessels, have large speed reduction by wind pressure. In the present study, the running speed of a large PCC with two or more sails for using wind power is simulated. The simulated results demonstrate that the ship can keep a constant service speed even in winds of 20m/s except head and bow winds. This sail system can shorten annual average navigation time by about 4 hours per voyage.
Keywords: pure car carrier (PCC); flat-plate sail; oblique sailing; vessel speed
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1 Introduction

Although economic activities are rapidly contracting in the wake of the subprime problem, marine transportation volume has been significantly increasing over the past several years because of rapid economic growth of emerging countries. Ships are being upsized to handle massive quantity of shipments. Ships such as pure car carriers (PCCs) and container vessels have large structures above water surface. Such ships have been often strongly influenced by wind during a rough weather, and this influence is expected to become more remarkable as the structures are larger. Tanaka(2003) has pointed out on the basis of operation of real ships that especially the wind pressure acting on the structures leads to large speed reduction due to an oblique sailing and counter-helm. Therefore, the wind pressures acting on such ships are desired to be minimized in terms of economic operation and safety, and countermeasures against the speed reduction should be developed.

In the present study, the running speed of a large PCC with two or more sails for using wind power is simulated. The sail is a flat-plate one used to reduce initial cost and maintenance cost. The navigation time of the ship during sailing from Tokyo to Los Angeles is also estimated.

2 An overview of control system of sails

2.1 Coordinate system

In this study, a 6500-unit PCC is considered. The principal particulars of the PCC are as follows. The length between perpendiculars is 192.0 m, the breadth is 32.26 m, the draft is 9.0 m, the height from water level is 25.53 m and the displacement is about 30 000 ton, respectively.

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***Corresponding author Email:** momoki@marine.osakafu-u.ac.jp

Fig.1 shows the coordinate system used in this study.

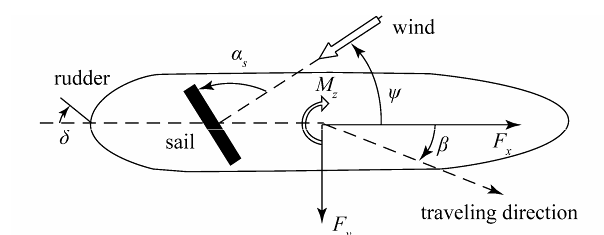


Fig.1 Coordinate system

2.2 Wind forces for sails

Fujii et al. deduced the following empirical equation (Fujii and Tuda, 1961). The force on a flat plate sail is shown in the following Eq.(1).

$$F_{NS} = \frac{1}{2}\rho_{\text{air}} A_S U_W^2 \sin\alpha_S \cdot f(\Lambda_S)$$
$$f(\Lambda_S) = \frac{6.13\Lambda_S}{\Lambda_S + 2.25}, \quad \Lambda_S = \frac{h_S^2}{A_S} \tag{1}$$

Longitudinal and lateral forces on the sails are shown in the following Eqs.(2) and (3).

$$X_S = F_{NS} \times \cos(\pi/2 - \psi - \alpha_S) \tag{2}$$

$$Y_S = F_{NS} \times \sin(\pi/2 - \psi - \alpha_S) \tag{3}$$

Where, the term with subscript S is the wind force on the sail. ρ_{air} is the density of the air, A_s is the area of a sail, ${}_sU_{WS}$ is the relative wind speed, α_s is the attack angle of a sail, h_s is height of a sail, Λ_S is aspect ratio of a sail and ψ is relative wind angle.

When the angle of attack increases up to 35 degrees, the flat plate is in a stalled condition. Then, the drag coefficient will be set to C_D=sin(α_S)$f(\Lambda_S)$ = 1.9.

The yaw moment "*Ns*" created by a sail is shown in the following equations.

$$N_S = F_{NS} \times l_S$$
$$l_S = x_S \times \sin(\pi/2 - \psi - \alpha_S) \quad (4)$$

where, x_s is the distance between midship of the hull and each sail.

2.3 Forces acting on the hull and sails

Drift angle "β", rudder angle "δ" and vessel speed "V" can be calculated by the equation of motion as follows. The components of longitudinal force, lateral force and yaw moment are expressed as follows:

$$X = X_{H0} + X_H + X_P + X_R + X_A + X_S$$
$$Y = Y_H + Y_R + Y_A + Y_S \quad (5)$$
$$N = N_H + N_R + N_A + N_S$$

The suffixes H, P, R, A and S denote hull, propeller, rudder, upper structure and sail, respectively. Resistance to the vessel with system of sails can be expressed by the Eq.(6).

$$R_W(\alpha) = X_H + X_R + X_A + X_S \quad (6)$$

The hydrodynamic force and moment on the hull are determined by the result of oblique towing test of the ship model (Momoki *et al*.,2009). The force and moment of rudder are predicted by Kijima's method (Kijima *et al*.,1990). The wind force and moment on the structure above water surface are determined by the result of wind tunnel test (Momoki *et al*.,2008,2009) (See Appendix). The force and moment on sails are predicted by the theory for a flat-plate wing (Motora *et al*.,1992).

2.4 Method of deciding the attack angle of the sails and prediction process of the vessel speed

Fig.2 shows the flow chart for computing the attack angles of sails "α_s". A drag of the vessel in a high wind consists of the following three components: (1) the longitudinal wind force which acts on a structure and a sail, (2) the hydrodynamic force acting on underwater hull accompanying oblique sailing, (3) the rudder resistance accompanying counter-helm. The attack angle of each sail is determined as the total of these forces will create the maximum thrust force on the ship. With this computational result, the presumption of the running speed in any wind becomes possible.

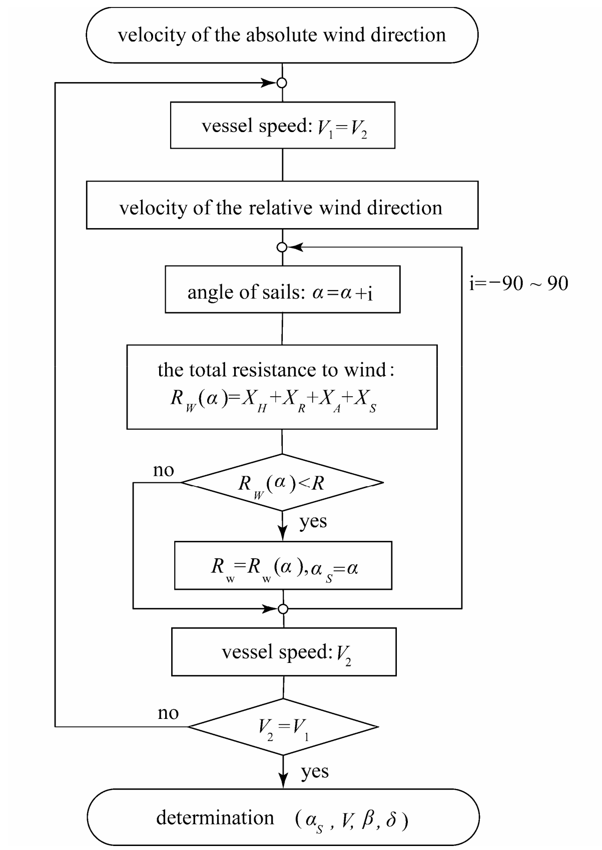


Fig.2 Procedure for determination of vessel speed

Table1 Dimensions of the sails

		A	B
h_s	[m]	12	13.9
b_s	[m]	20	6.9
$A_s = h_s \times b_s$	[m]	240	96
A_s	[m]	0.6	2
n	[m]	2	5
$A_{s\_all} = h_s \times b_s \times n$	[m]	480	480

3 Principal particulars of the sails and estimated result of ship speed

3.1 Principal particulars of sail systems

As mentioned above, the sail is a flat-plate one to reduce initial cost and maintenance cost. The height of the sail is smaller than 14.0m, since the height of the vessel must be lower than max-height of the bridge of Nagoya port (38m).Two types of systems of a sail are investigated in this study. Type A consists of two sails. The breadth of a sail is 20m in order that a sail may not collide with a tunnel.

It is necessary to enlarge area or aspect ratio of a sail to gain bigger lift forces because forces of a sail depend on area and aspect ratio of a sail. Therefore the aspect ratio of the sail of Type B is modified to 2.0. In order to make the total area of sails the same as Type A, the number of the sails has been increased to five. The principal particulars of the sails are shown in Table 1.

3.2 Estimated results of vessel speed

To verify the effectiveness of the system of the sails, the vessel speed in high wind is computed under the following two assumptions. The vessel sails in winds of 20 m/s, and the horsepower of a main engine has a fixed value to keep the service speed in calm water. The conditions of the calculation are shown in Table 2, and the arrangement of the sails is shown in Fig.3.

Table 2 Conditions of the calculation

Main Engine(const.) / kW	13260
Service speed / knot	20
Absolute wind direction / deg.	00,15,30,…,180
Absolute wind velocity / $(m \cdot s^{-1})$	20

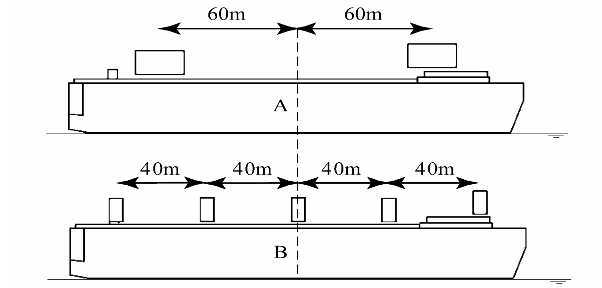


Fig. 3 Side view of ship with two kinds of sails

There is little change in the vessel speed between 0 and 30 degree of wind direction even when the sails are operated. However, ship speed loss is decreased by the system of sails at about 45 degrees. Especially, the ship of Type B is hardly slowed down in the 60 to 90 degrees of wind direction. Vessel speed of Type B is faster than that of Type A under this condition. Furthermore, the angle of attack of each controlled sail is 35 degrees. These results suggest that by controlling the attack angle of the sails, the sails can generate large propulsion power. And, these experimental results demonstrate the aspect ratio of the sails is important. But, from 120° to 180°, Type A and Type B generate the same power. Therefore, in the following wind, strength of the propulsion power by sails depends on the area of the sails. Moreover, an increase in speed is small. It may be that the relative wind velocity becomes small.

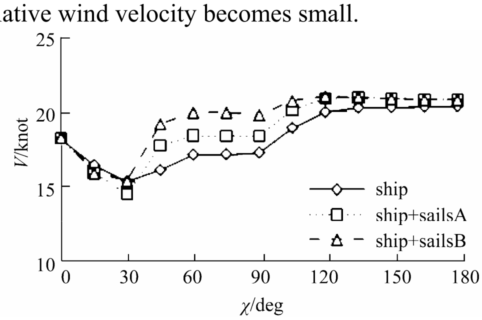


Fig.4 Calculated results on the speed of vessel with sail

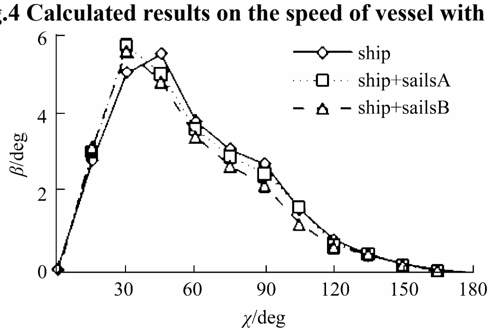


Fig.5 Calculated results of oblique angles (Absolute wind velocity is 20 m/s)

Table 3 Attack angle of each sail / deg.

ψ			0	30	60	90	120	150	180
α_S	A	a	5	-11	-35	-35	90	90	90
		b	5	-17	-35	-35	90	90	90
	B	a	5	-14	-35	-35	-35	90	90
		b	5	-8	-35	-35	-35	90	90
		c	5	-14	-35	-35	-35	90	90
		d	5	-14	-35	-35	-35	90	90
		e	5	-14	-35	-35	-35	90	90

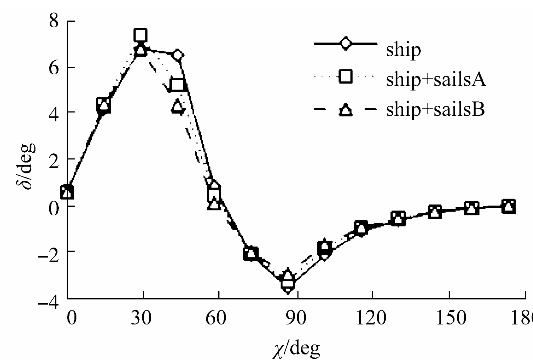


Fig.6 Calculated results of counter-rudder angle (Absolute wind velocity is 20 m/s)

The simulated results show that the vessel of Type B can keep the service speed of 20 knots in the wind of 20 m/s except for head and quarter winds.

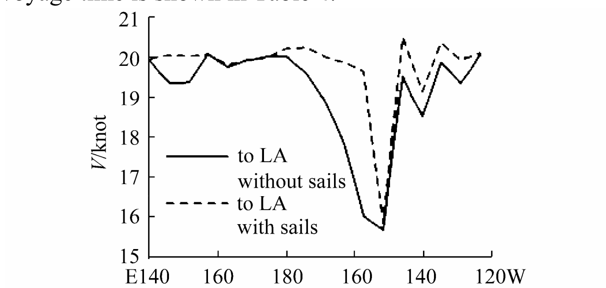
The relation between a wind direction and a drift angle is shown in Fig.5, and the relation between a wind direction and a rudder angle is shown in Fig.6.

When the system minimizes total resistance of the vessel, the amount of change of drift angle and counter rudder angle is small compared with that of vessel speed. This result shows that the sail systems can hardly generate lateral force and yaw moments, when the optimal control of a sail system is carried out.

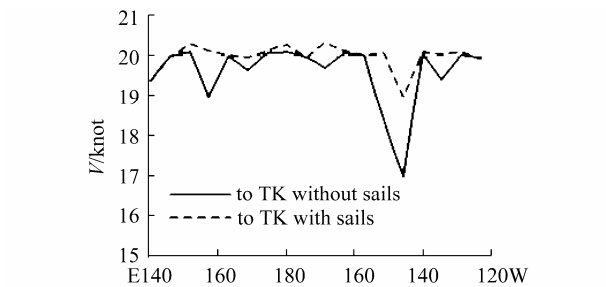
4 The calculated vessel speed using the sail system at the real sea

Vessel speed is simulated at the real sea for the ships of Type B and without sails. The assumed course is a great-circle course between Tokyo (TK) and Los Angeles (LA). Weather data was donated by JAMSTEC (Japan Agency for Marine-Earth Science and Technology). These data were simulated ones in every 6 hours in January, April, July and October, respectively. The grid interval of meridian direction of the date is about 2.8 degrees (128 cells), and latitude direction is irregular pitch from 87.864°N to 87.864°S (64 cells). It is assumed that the velocity and direction of winds are constant in each cell.

Calculated vessel speeds are shown in Figs.7~10 and voyage time is shown in Table 4.

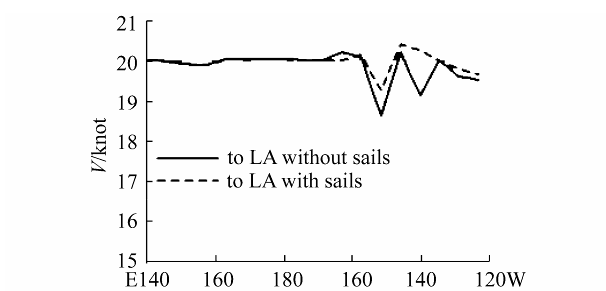


(a) Calculated vessel speed to LA -Winter (Jan.)

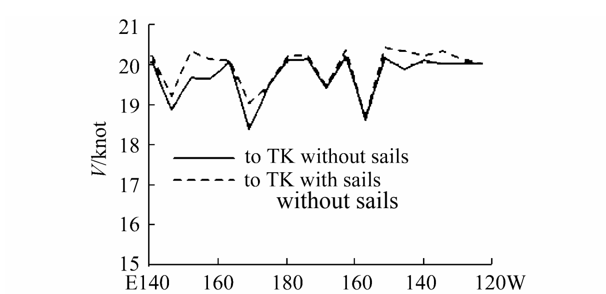


(b) Calculated vessel speed to TK -Winter(Jan.)

Fig.7 Calculated vessel speed

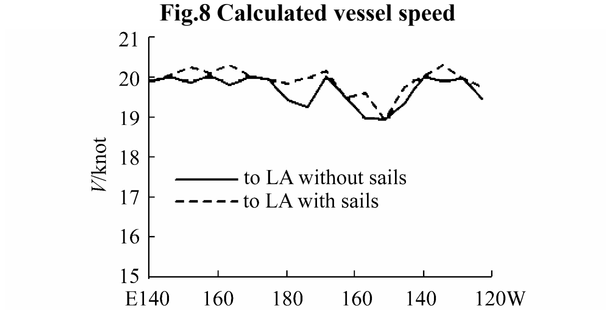


(a) Calculated vessel speed to LA -Spring(Apr.)

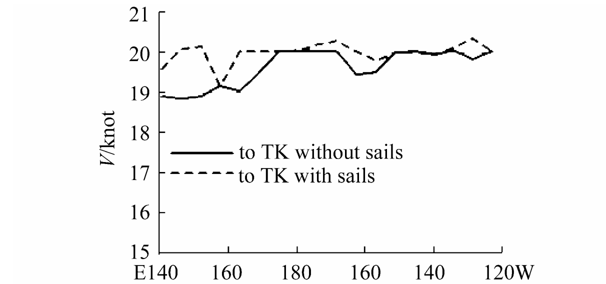


(b) Calculated vessel speed to TK -Spring(Apr.)

Fig.8 Calculated vessel speed

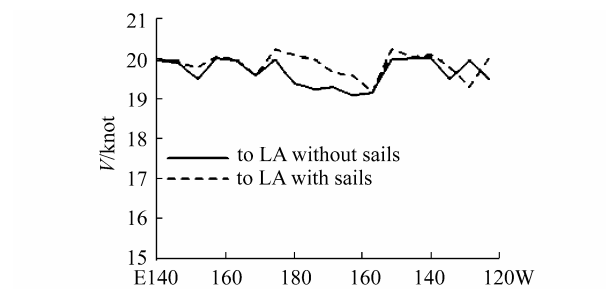


(a) Calculated vessel speed to LA -Summer(Jul.)

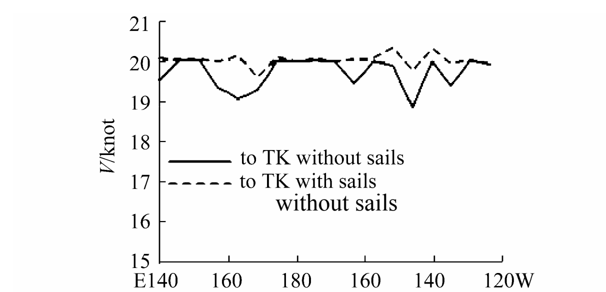


(b) Calculated vessel speed to TK -Summer(Jul.)

Fig.9 Calculated vessel speed



(a) Calculated vessel speed to LA -Autumn(Oct.)



(b) Calculated vessel speed to TK -Autumn(Oct.)

Fig.10 Calculated vessel speed

Table 4 Difference of calculated Navigation Time / hour

bound	winter	spring	summer	autumn	Avg.
East	8.87	1.89	2.76	2.22	3.94
West	5.59	3.08	4.82	4.09	4.40

The results shown in Fig.7 demonstrate that large speed reduction occurs at the region between 150°W to 160°W in winter (January). This reduction occurs because the ship runs in strong atmospheric depression. The results show that the sail system works well to considerably reduce the speed loss when the ship without sails is experienced. We can see, however, the sail system always does not work because of head or bow winds.

In the calculated results shown in Figs.8 and 10, large speed reduction does not occur, because the ship seldom encounters the strong atmospheric depression in spring, summer and autumn.

In terms of annual average, the period to maintain the service speed of the ship increases. The results of reduction of estimated navigation time by using the sail system are shown in Table 4. The results demonstrate that the sail system can save the navigation time by four hours per voyage as annual average.

5 Conclusions

In the present study, flat-plate sail systems for a large PCC are proposed and a control system of the sails to keep a constant service speed in high winds is developed. The following conclusions are drawn through this study.

The simulated results demonstrate that the ship with five small flat sails can keep a constant service speed of 20 knots even in strong winds of 20m/s except head and bow winds.

The proposed system can reduce an annual average navigation time by about 4 hours per voyage in the route between Tokyo and Los Angeles.

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Appendix

A.1 Wind tunnel experiments

The open-type wind tunnel installed in the towing tank of Osaka Prefecture University is used for the experiment. Fig.a shows the schematic view of the experiment. In this experiment, the model is placed at the position 4.0 m away from the open-type wind tunnel, and the wind force acting on the model is measured by a watertight six-component load cell. This model is a 1/96 scale model of a 6500-unit car carrier. The principal particulars of the ship in real scale are as follows. The length between perpendiculars is 192.0m, the breadth is 32.26 m, the draft is 9.0 m, the height from water level is 25.53 m, and the displacement is about 30 000 ton, respectively. Moreover, in order to measure wind forces acting on a superstructure, the model has actual designed form of superstructure with ramp, funnel and so on. Fig.b shows a coordinate system of the experiments.

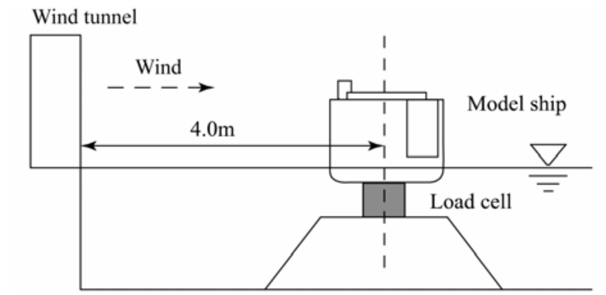

Fig. a Schematic view of the experiment

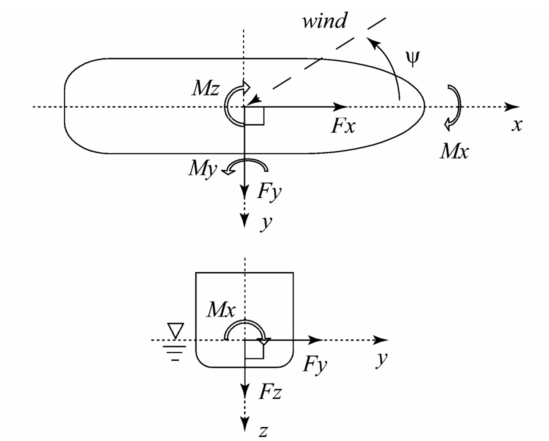

Fig.b Coordinate system of the experiment

The six-component of wind forces: longitudinal force, lateral force, heave force, roll moment, pitch moment and yaw moment are measured. The wind velocity is set to 3.0 m/s and 6.0 m/s respectively. The direction of the wind is also set from 0 to 330 degrees for every 30 degrees.

The longitudinal force, lateral force, heave force, roll moment, pitch moment and yaw moment coefficients are defined in non-dimensional forms as follows:

$$\begin{cases} C_{Fx} = Fx \Big/ \left(\frac{1}{2}\rho U^2 A_F\right) \\ C_{Fy} = Fy \Big/ \left(\frac{1}{2}\rho U^2 A_L\right) \\ C_{Fz} = Fz \Big/ \left(\frac{1}{2}\rho U^2 A_U\right) \\ C_{Mx} = Mx \Big/ \left(\frac{1}{2}\rho U^2 A_L L_{OA}\right) \\ C_{My} = My \Big/ \left(\frac{1}{2}\rho U^2 A_F B\right) \\ C_{Mx} = Mz \Big/ \left(\frac{1}{2}\rho U^2 A_L^2 / L_{OA}\right) \end{cases} \quad \text{(a)}$$

Here, ρ: density of air, U: velocity of wind. L_{OA}: length overall, A_F: frontal projected area of a superstructure, A_L:

lateral projection area of a superstructure, A_U: upper surface projection area of a superstructure.
The measured wind forces are shown in Figs. c,d,e.

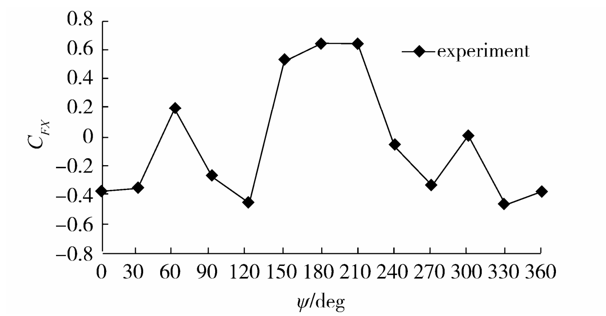

Fig. c Measured longitudinal wind force coefficients of the model of PCC

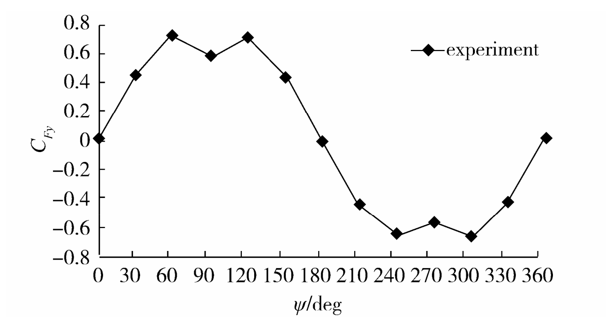

Fig. d Measured lateral wind force coefficients of the model of PCC

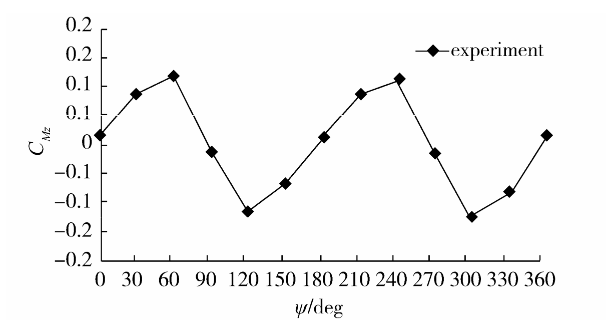

Fig. e Measured yaw wind moment coefficients of the model of PCC

Seiki Onishi was born in 1986. He is a student of Osaka Prefecture University. His current research interests include vessel speed reduction by winds and sail-equipped vessel.

Tsutomu Momoki was born in 1974. He is an assistant professor of Osaka Prefecture University. His current research interests include sail-equipped vessel, ship maneuverability and Computational Fluid Dynamics.

Yoshiho Ikeda was born in 1950. He is a professor of Osaka Prefecture University. His current research interests include next generation ship, high speed craft, economics and passenger ship.