Wind Velocity Profile and Representative Wind Velocity for Wind Resistance Measurement of Ship Models

by Kenichi Kume^{*}, *Member* Hiroki Ohba^{*}, *Member*
 Hideo Orihara^{**}, *Member* Shuji Mizokami^{***}, *Member*

Summary

Wind resistances and moment acting on a ship model measured in a wind tunnel are non-dimensionalized using the air density, the projected area of the model and the representative wind velocity. However, there is no common definition of the representative wind velocity in wind tunnel tests for ships, thus wind velocities which are obtained by an anemometer fixed in a certain place in a wind tunnel or measured at a height equivalent to 10 m from the sea surface are often used. In principle, there is no problem as long as the wind velocity profile under the same condition is assumed and the wind velocity at the same position is employed when the wind resistance coefficients are converted into forces of different scales. Nevertheless, if the wind velocity distributions between in the wind tunnel test and the assumed distribution by the user are different, the wind resistance coefficients cannot be used in the first place. And the existence of various definitions of non-dimensionalization makes it difficult to simply compare wind resistance coefficients themselves.

Since it is meaningful to clarify the definition of the representative wind velocity which can provide wind resistances in a realistic and reasonable manner using the wind resistance coefficients without being influenced by the assumed wind velocity distribution, it was derived from the results of wind tunnel tests under the conditions of various wind velocity profiles and using various types of ship models. Furthermore, the influence of the wind velocity profile on the wind resistance measurement was evaluated with the results of the wind resistance measurement in different wind velocity profiles. Several findings on the wind velocity profile required for wind resistance measurements are reported in this paper.

1. Introduction

A wind tunnel test is one of the methods for accurately obtaining the wind resistance acting on a ship. In a wind tunnel test, a ship model is placed in a tunnel and the measurement is made for the hydrodynamic forces acting on it. Since the model test is generally performed to predict the hydrodynamic forces acting on the ship, the measured wind resistance is non-dimensionalized using the air density, the projected area of the model and the representative wind velocity. However there is no common definition of the representative wind velocity in the wind tunnel test. Thus, wind velocities which are obtained by an anemometer fixed in a certain place in a wind tunnel or measured at a height equivalent to 10 m from the sea surface are often used. Nevertheless, if the wind velocity distributions between in the wind tunnel test and the assumed distribution by the user are different, the wind resistance coefficients cannot be used in the first place. As long as the wind resistance coefficients are converted into the wind resistances with the wind velocity at the same position of the same profile, contradiction does not occur. But it may be difficult to implement in the aspect of time and cost.

There is also a demerit that it makes hard to simply compare wind resistance coefficients themselves non-dimensionalized by representative wind velocities of different definitions.

Since it is meaningful to clarify the definition of the representative wind velocity which can provide wind resistances in a realistic and reasonable manner using the wind resistance coefficients without being influenced by the assumed wind velocity distribution, it was derived from the results of wind tunnel test under the conditions of various wind velocity profiles and using multiple types of ship models.

In addition, from the results of wind resistance measurements in different wind velocity profiles, the influence of the difference of the profiles has been evaluated and the wind velocity profile to be used for wind resistance measurement has been investigated.

In this paper, the appropriate method for the representative wind velocity determination is derived from the results of wind resistance measurements. And it also concluded that there is a certain degree of freedom in the wind velocity profile to be used during wind tunnel tests.

2. Dimensions of Wind Tunnel and Ship Models

Wind resistance measurements were carried out in the wind tunnel of National Maritime Research Institute (NMRI). The plan view of the tunnel is illustrated in Fig. 1. In order to ensure the effectiveness of the study, as many different types of ships as possible were selected as test models, which are the models of Bulk Carrier, Chemical Tanker, Container Ship (Full Load and

* National Maritime Research Institute, MPAT

** Japan Marine United Corporation

*** Mitsubishi Shipbuilding Co., Ltd.

Ballast conditions) and Pure Car Carrier (PCC). The specifications of the wind tunnel and test models are shown in the following section.

2.1 Wind Tunnel

- Gettingen-type horizontal recirculation system
- Wind tunnel measuring part: Closed type, 3 m width, 2 m height and 15 m length
- Performance of fan: Steady wind velocity 1.0 ~ 30 m/s
- Turbulence intensity: less than 0.5 %

Fig. 1 Plan view of wind tunnel in NMRI.

2.2 Ship Models

Figs. 2 ~ 6 show the views of front and side projection of the 5 conditions for 4 models. The principal dimensions are shown in Table 1, where L_{OA} is length overall, L_{PP} is length between perpendiculars, B is Breadth and d_m is mean draft. The L_{PP} of the model ships was all set to 1.2 m.

Table 1 Dimensions of subject ships in ship scale.

Type of ships	Condition	L_{OA} [m]	L_{PP} [m]	B [m]	d_m [m]	Trim [m]
Bulk Carrier	Full Load	291.3	280.0	45.0	16.5	0.0
Chemical Tanker	Full Load	177.6	170.5	27.7	10.0	0.0
Container Ship	Full Load	311.7	300.0	40.0	14.0	0.0
	Ballast				11.2	0.0
PCC	Full Load	200.0	190.0	32.26	7.6	0.0

Fig. 2 Projected shape of Bulk Carrier.

Fig. 3 Projected shape of Chemical Tanker.

Fig. 4 Projected shape of Container Ship (Full Load Condition).

Fig. 5 Projected shape of Container Ship (Ballast Condition).

Fig. 6 Projected shape of PCC.

2.3 Blockage Ratio

The blockage ratio is one of the main parameters to be considered in order to accurately measure the wind resistance in the wind tunnel. The blockage ratio means the proportion of the area occupied by the model to the cross-sectional area of the wind tunnel. In the range of 5 % or less, the influence of the blockage ratio is small and it is reported to be acceptable¹⁾. Table 2 shows the blockage ratio when the ship models shown in the previous section are installed in the wind tunnel of NMRI (Cross-sectional dimensions of the measurement section: 3×2 m). In all the cases, the blockage ratios are less than 5 % at the wind direction angle ψ (cf. Fig. 14) of 90 deg. at which the pressure receiving area of the model becomes the maximum. From Table 2, it is apparent there is less influence in the wind resistance test.

Table 2 Blockage ratio (Beam wind, $\psi=90\text{deg.}$).

Type of ships	Condition	Blockage ratio %
Bulk Carrier	Full Load	1.0
Chemical Tanker	Full Load	1.2
Container Ship	Full Load	2.0
	Ballast	1.2
PCC	Full Load	3.6

3. Wind Velocity Profile and Turbulence Distribution in the Wind Tunnel

In the measurement of the wind resistance test, the model ship is placed on a turntable to change the wind direction. The midship position of the center line of the model ship is fixed to the center position of the turntable. In order to vary the boundary layer

thickness in the wind resistance tests, the installation position of the model ship in the wind tunnel is to be changed as well as the turntable is to be lifted from the floor of the wind tunnel to make the boundary layer thinner as shown in Fig. 7. The positions are named Case-A, -B and -C. Wind velocity profiles are measured by a 5-hole pitot tube shown in Fig. 8. The 5-hole pitot tube which has a diameter of 3 mm was chosen so as not to distort the measured flow. Figs. 9(a) ~ 9(c) and Figs. 10(a) ~ 10(c) show the wind velocity profiles and the intensity distributions of turbulence at the center of the turntable at each position without a model. The projected shapes of the front view in the figures are the shape of Bulk Carrier for reference. The pressure sampling frequency was set to 200 Hz in order to measure the intensity of the turbulence. The response characteristics of the flow velocity measurement system consisting of a 5-hole pitot tube and pressure gauges are 20 Hz or less.

In the wind velocity profiles of Case-A and Case-B shown in Fig. 9(a) and Fig. 9(b), a thick boundary layer developed on the wind tunnel floor surface is seen, and the each thickness δ is approximately 130 mm and 90 mm respectively. In addition, the figures show that the shapes of the boundary layer distribution have the equivalent properties with the 1/7 power distribution represented by the Eq. (1) as $\alpha=1/7$. On the other hand, the wind velocity profile of Case-C shown in Fig. 9(c) is the case where the boundary layer is thinner than the others. A separated floor to lift the model up from the boundary layer is installed in the wind tunnel. The thickness δ of the boundary layer of Case-C is approximately 30 mm. However, the vertical distribution of the wind velocity in Case-C was not uniform in the lateral direction of the wind tunnel, so the data of wind resistance in the Case-C is adopted only in the range of $\psi=0$ to 30 and 150 to 180 deg. which can be analyzed using only the wind velocity profile in the center of the turntable.

Figs. 10(a) ~ 10(c) show the intensity of the turbulence of the wind velocity calculated by Eq. (2) and those are considerably smaller than the figures observed in the ocean wind.

$$U(z) = (z/z_{10m})^\alpha \cdot U_{10m} \quad (1)$$

$$I_U(z) = \sigma_U(z)/U(z) \quad (2)$$

Where, $U(z)$ is the wind velocity at each height, $I_U(z)$ is the turbulence intensity and $\sigma_U(z)$ is the standard deviation of the velocity at each height, z is the vertical distance from the sea surface, z_{10m} is the reference height of 10 m in ship scale, U_{10m} is the average wind velocity at the reference height, and α is the power index of the power law (1/9 ~ 1/7 in the case of ocean wind).

Fig. 7 Measurement positions in the longitudinal direction of the wind tunnel.

Fig. 8 5-hole pitot tube.

Fig. 9(a) Wind velocity profile at the centerline of the midship (Case-A) (δ = abt. 130 mm).

Fig. 9(b) Wind velocity profile at the centerline of the midship (Case-B) (δ = abt. 90 mm).

Fig. 9(c) Wind velocity profile at the centerline of the midship (Case-C) (δ = abt. 30 mm).

Fig. 10(a) Distribution of the turbulence intensity at the centerline of the midship (Case-A) (δ = abt. 130 mm).

Fig. 10(b) Distribution of the turbulence intensity at the centerline of the midship (Case-B) (δ = abt. 90 mm).

Fig. 10(c) Distribution of the turbulence intensity at the centerline of the midship (Case-C) (δ = abt. 30 mm).

4. Representative Height and Wind Velocity

4.1 Representative Height

Here, calculation method of representative wind velocity used for non-dimensionalization which includes the integration of wind velocity is investigated with reference to the concept of dynamic pressure which the effectiveness has been shown in the references 3) and 4). The method is adopted so that it can be applicable to a flow having a thick boundary layer developed on the wind tunnel floor or an arbitrary flow distribution such as a power law distribution, with reference to the documents²⁾⁻⁵⁾. The averaged wind velocities U_{A1} and U_{A2} shown in Fig. 11, which are used for non-dimensionalizing the longitudinal force F_X , the lateral force F_Y and yaw moment C_N shown in Fig. 13 are obtained by dividing the rectangle area drawn with a dashed line in Fig. 11 by representative heights H_{BR} or H_L . The equations are as follows.

$$U_{A1}^2 = A_1 / H_{BR} \quad (3)$$

$$U_{A2}^2 = A_2 / H_L \quad (4)$$

Where, A_1 and A_2 is the rectangular area equivalent to the area calculated from an integral of the wind velocity profile in the range from the bottom of the model to the height of H_{BR} or H_L respectively. H_{BR} is the height of the top of the navigation bridge from the sea surface and H_L is the average height which is derived from dividing the side projected area A_L of a ship by the ship length (L_{OA}) as shown in the Fig. 12(a) and Fig. 12(b).

Table 3 Representative heights of the ships in model scale.

Type of ships	Condition	z_{10m} [mm]	H_{BR} [mm]	H_L [mm]
Bulk Carrier	Full Load	42.9	121.8	49.6
Chemical Tanker	Full Load	70.4	152.0	56.6
Container Ship	Full Load	40.0	141.3	96.1
	Ballast		152.5	54.7
PCC	Full Load	63.2	189.5	169.2

In references 2) to 5), the dynamic pressure at H_L , the average dynamic pressure up to H_L and the experimental constant are combined and used for non-dimensionalization of wind resistances, whereas this paper suggests a simpler method and confirms the effectiveness. Table 3 summarizes the H_{BR} and H_L for each ship type.

4.2 Wind Velocity

The wind resistance measurement was performed at four wind velocities in order to investigate the Reynolds number effect. The wind velocities during the test were set to be 10, 15, 20, and 25 m/s so that the reference wind velocity U_{ref} measured by a pitot tube. As shown in Fig. 7 and Fig. 13, the pitot tube was installed at the top of the measurement chamber, approximately 3,400 mm upstream from the center of the turntable in Case-B and 360 mm down from the ceiling surface. Tables 4 ~ 6 summarize the averaged wind velocities, U_{A1} and U_{A2} , and the wind velocity at the height equivalent to 10 m in a ship scale, U_{10m} , for each set. When calculating U_{A1} , U_{A2} and U_{10m} , trapezoidal integration and interpolation were performed on the data measured in the wind tunnel.

Fig. 11 Conceptual figure of averaged wind velocities U_{A1} and U_{A2} analyzed with integration.

Fig. 12(a) Conceptual figure of H_{BR} .

Fig. 12(b) Conceptual figure of H_L .

Fig. 13 Pitot tube in the wind tunnel.

Table 4 Averaged wind velocity U_{A1} for F_X .

for F_X		U_{ref} [m/s]			
		10.00	15.00	20.00	25.00
	Case	U_{A1} [m/s]			
Bulk Carrier	A	9.187	13.86	18.40	22.98
	B	9.371	13.97	18.60	23.19
	C	10.13	15.25	20.15	25.10
Chemical Tanker	A	9.440	14.18	18.91	23.79
	C	10.18	15.30	20.21	25.20
Container Ship (Full Load)	A	9.367	14.10	18.81	23.66
	C	10.16	15.29	20.19	25.17
Container Ship (Ballast)	A	9.438	14.20	18.93	23.82
	C	10.18	15.30	20.21	25.20
PCC	A	9.619	14.43	19.23	24.19
	C	10.22	15.33	20.26	25.27

Table 5 Averaged wind velocity U_{A2} for F_Y and M_Z .

for F_Y, M_Z		U_{ref} [m/s]			
		10.00	15.00	20.00	25.00
	Case	U_{A2} [m/s]			
Bulk Carrier	A	8.256	12.47	16.54	20.64
	B	8.261	12.30	16.52	20.59
	C	9.782	14.85	19.61	24.20
Chemical Tanker	A	8.329	12.55	16.88	21.23
	C	9.846	14.94	19.72	24.39
Container Ship (Full Load)	A	8.928	13.47	18.02	22.67
	C	10.06	15.19	20.06	24.94
Container Ship (Ballast)	A	8.307	12.54	16.87	21.21
	C	9.830	14.92	19.69	24.34
PCC	A	9.535	14.32	19.08	24.00
	C	10.20	15.32	20.24	25.23

Table 6 Wind velocity U_{10m} at the height of 10 m in ship scale.

		U_{ref} [m/s]			
		10.00	15.00	20.00	25.00
	Case	U_{10m} [m/s]			
Bulk Carrier	A	8.925	13.53	17.96	22.29
	B	9.234	13.74	18.39	22.78
	C	10.29	15.57	20.53	25.71
Chemical Tanker	A	9.563	14.39	19.17	24.13
	C	10.36	15.54	20.55	25.73
Container Ship (Full Load, Ballast)	A	8.805	13.29	17.81	22.39
	C	10.27	15.56	20.53	25.70
PCC	A	9.417	14.18	18.91	23.80
	C	10.35	15.56	20.54	25.73

5. Measurement Results of Wind Resistance

5.1 Coordinate System and Non-dimensionalization of Wind Resistances

Wind resistances act on the model ships were measured with a load cell fixed to the midship which is the rotation center of the hull. Since the hull and the load cell are fixed to each other, the direction of the hydrodynamic forces F_X and F_Y always coincide with the axes of the hull as shown in Fig. 14. The sampling frequency of wind resistance is 100 Hz, low-pass filter is not used. The wind resistances and moment are non-dimensionalized by the Eqs. (5) ~ (7).

Fig. 14 Coordinate system.

$$C_X = F_X / \left(\frac{1}{2} \rho U^2 A_T \right) \quad (5)$$

$$C_Y = F_Y / \left(\frac{1}{2} \rho U^2 A_L \right) \quad (6)$$

$$C_N = M_Z / \left(\frac{1}{2} \rho U^2 A_L \cdot L_{OA} \right) \quad (7)$$

Where, ρ is the air density, U is the representative wind velocity, A_T and A_L are the projected areas of transverse and longitudinal sections and L_{OA} is length over all, respectively.

5.2 Effect of Reynolds Number

The Reynolds number Re at the wind tunnel test is shown in Table 7. U_{ref} is used for the Reynolds number calculation. According to the references⁴⁾⁶⁾⁷⁾, if Re becomes 1.0×10^6 or more, the influence of the Reynolds number on the wind resistance is negligible. Fig. 15 shows the changes in C_X , C_Y and C_N according to the Reynolds number in this study. As for the wind tunnel tests using the models with the length of 1.2 m, the negligible condition can be applied when Re is 1.2×10^6 (U_{ref} is 15 m/s) or more.

Table 7 Reference velocity U_{ref} at the upstream end of wind tunnel and Reynolds numbers.

U_{ref} [m/s]	Re [$\times 10^6$]
10.00	0.81
15.00	1.21
20.00	1.62
25.00	2.02

Fig. 15 Changes in C_X , C_Y and C_N to Reynolds number (Chemical Tanker).

5.3 Representative Wind Velocity and Wind Velocity Profile in Wind Tunnel Test

The coefficients of C_X , C_Y and C_N measured in three different wind velocity profiles (Case-A ~ Case-C) are shown in Figs. 16 ~ 30 for each representative wind velocity and ship type. Only the results of $U_{ref} = 25$ m/s are shown in those diagrams because there are no Reynolds number effect in the velocity as indicated in Fig. 15. In the case of U_{ref} is used for non-dimensionalization of wind resistance and moment in any type of ships, the data of C_X , C_Y and C_N are varied due to the difference in wind velocity profiles, while it is found that the agreements of C_X , C_Y and C_N are improved when the averaged wind velocities U_{A1} , U_{A2} or the wind velocity U_{10m} are used. Fig. 31 shows the coefficient of variation of C_X of Bulk Carrier as an example. At wind direction angles ($\psi = 0$ to 30 , 150 to 180 deg) where C_X has a large effect, the maximum variation is about 0.17 in absolute value when U_{ref} is used, while the coefficient of variation becomes small to 0.07 or less in absolute value when U_{A1} or U_{10m} is used.

This is probably due to the fact that U_{ref} does not properly represent the inflow velocity, because it is measured at a distant position from the model ship. On the other hand, the reason why the C_X , C_Y and C_N in different wind conditions are agreed with each other when using the averaged wind velocities U_{A1} and U_{A2} is that those were derived based on the concept of kinematic energy by integrating the square of the wind velocity and helps to perform an adequate calculation of wind resistance coefficients. In addition, when U_{10m} is used, C_X , C_Y and C_N also show good agreement. It is thought that most part of the wind velocity profile in the region of the model ships is similar to the profile of 1/7 power law distribution for Case-A and Case-B, and uniform flow for Case-C. It inevitably gives a high correlation between U_{10m} and U_{A1} , U_{A2} as shown in Fig. 32(a) and Fig. 32(b), and results in good agreement. However, it is still recommended to use the averaged wind velocities U_{A1} and U_{A2} , because when the wind velocity profile becomes more arbitrary, such as not following a power law, the correlation may be lowered even if it is non-dimensionalized by U_{10m} . U_{10m} is just one value measured at a fixed height where wind velocity profile cannot be taken into account. Furthermore, a significant difference appears in the absolute values of C_X , C_Y and C_N depending on whether U_{A1} , U_{A2} or U_{10m} applies for non-dimensionalization, which is seen in Fig. 22(b) and Fig. 22(c) for example. From the investigation, it is considered preferable to use the averaged wind velocities U_{A1} and U_{A2} including the kinematic energy concept, in order to reduce the influence of the difference of wind velocity profiles, which differ depending on the test facilities and model ship size.

Further, from another viewpoint of setting wind conditions in a wind tunnel, as long as the non-dimensionalization using the averaged wind velocities U_{A1} and U_{A2} is performed, the data of wind resistance coefficient show good agreement within the range of the above-mentioned variation regardless of wind velocity profile and thus the wind velocity profile during the wind resistance test is not necessary to be simulated the power law distribution or the advance speed of a ship which a ship will encounter at sea.

It can be found that a wind velocity profile having a characteristic of a uniform flow or a naturally developed boundary layer on the wind tunnel floor is appropriate to be used

for the wind resistance measurement.

5. 4 Round Robin Tests with Bulk Carrier Model in Three Wind Tunnels

In order to confirm the validity of the test results at NMRI, wind resistance measurements were carried out as round robin tests with the same ship model (Bulk Carrier model) in the other two wind tunnels in Japan. The photographs under the round robin tests are shown in Figs. 33 ~ 35. The dimensions of each wind tunnels for round robin tests are shown in Table 8. Boundary layer thickness of the wind velocity profiles is about 130 mm in NMRI and about 30 ~ 50 mm in the other wind tunnels. The comparisons of the wind resistance coefficients measured in the three wind tunnels are shown in Figs. 36(a) ~ 36(c). The measured data in the three wind tunnels are all non-dimensionalized with averaged wind velocities U_{A1} and U_{A2} . The three data sets of the round robin tests have differences from the mean line of about $\pm 6\%$, $\pm 3\%$ and $\pm 3\%$ in C_X , C_Y and C_N respectively.

5. 5 Influence of Differences in the Coefficients of Wind Resistances and Moment on Speed Reduction and Required Engine Output of a Ship

The differences of C_X , C_Y and C_N in the round robin tests were reported above as $\pm 6\%$, $\pm 3\%$ and $\pm 3\%$ when U_{A1} and U_{A2} are used for non-dimensionalization. As a next step, the influence of the differences, which affects to the accuracy of estimation of the speed reduction was examined by a program VESTA (Vessel Performance Evaluation Tool in Actual Seas)⁸⁾ under the condition of constant engine output. A result of examination using PCC, which is known as strongly affected by winds, is shown in Fig. 37. The influence of the differences in coefficients was estimated to be about ± 0.02 knots of the speed reduction in the averaged sea condition (Wave and wind directions are averaged in all direction) of Beaufort Scale 6 (BF 6) and it corresponds to the error of estimation about $\pm 0.4\%$ of required engine output.

It is found that the calculation method for the representative wind velocity using U_{A1} and U_{A2} has practically sufficient accuracy to evaluate the ship performance in actual seas, and the applicability of the arbitrary wind velocity profile at wind tunnel tests are also confirmed by the round robin tests.

6. Conclusions

We measured the wind resistance of several types of ship models with different boundary layer thickness distributions, and showed the effectiveness of the usage of the averaged wind velocity derived from integration of the squared values of wind velocity as a representative wind velocity. This calculation process can convert and align the wind resistance coefficients measured under different wind velocity profiles to the values as though those were measured under the same condition. As a result of the verification in this study, it is found that the wind resistance coefficients could be obtained with practically sufficient accuracy even with a simpler method of integration of the squared values of the wind velocity, even if there was a difference in the wind

velocity profiles within the range of 30 to 130 mm in the boundary layer thickness.

In fact, the coefficient of variation of C_X of Bulk Carrier decreases to 0.07 when using U_{10m} or U_{A1} compared to 0.17 when using U_{ref} . The same applies to wind tunnels in which the boundary layer distribution developed naturally on the wind tunnel floor without any turbulence stimulators, as in this study.

When we view the wind velocity profiles in wind tunnels, the flow distributions near model ships are close to 1/9 power to 1/7 power distribution in the cases of Case-A and Case-B which have the boundary layer thicknesses of about 130 mm and about 90 mm, and Case-C has an almost uniform distribution with a boundary layer thickness of about 30 mm.

All these things make it clear that the wind velocity profile during the wind resistance test in a wind tunnel does not necessarily to faithfully reproduce the power law distribution or including the advance speed of a ship which a ship will encounter at sea. It is considered that the wind velocity profile having a characteristic of a naturally developed boundary layer on a wind tunnel floor without any turbulence stimulators or a uniform flow can be employed for the wind resistance measurement.

Acknowledgments

This research was performed by the Project for Evaluation of Ship Performance in Actual Seas - Japan Maritime Cluster Collaborative Research - (OCTARVIA Project). The authors would like to express their gratitude for the support and suggestions.

The authors are also grateful to Dr. Toshifumi Fujiwara for providing valuable advices to determine the direction of this research and Mr. Tadashi Nimura for giving us appropriate instructions to perform measurements successfully in the wind tunnel.

References

- 1) Whitbread, R. E.: Model Simulation of Wind Effects on Structures, Proceedings of International Conference on Wind Effects on Buildings and Structures, pp. 284-302, 1963.
- 2) Blendermann, W.: Estimation of Wind Loads on Ships in Wind with a Strong Gradient, Proceedings of OMAE, Vol. 1-A, pp. 271-277, 1995.
- 3) Fujiwara, T., Ueno, M. and Nimura, T.: Estimation of Wind Forces and Moments acting on Ships [in Japanese], Journal of SNAJ, Vol. 183, pp. 77-90, 1998.
- 4) Nonaka, K., Nimura, T., Ueno, M., Fujiwara, T., Miyazaki, H. and Haraguchi, T.: Basic Study on External Forces and a Drifting Motion of a Ship [in Japanese], Report of Ship Research Institute, No. 5, Vol. 36, pp. 1-41, 1999.
- 5) Fujiwara, T., Ueno, M. and Ikeda, Y.: Cruising Performance of Ships with Large Superstructures in Heavy Sea -1st Report: Added Resistance Induced by Wind- [in Japanese], Journal of JASNAOE, Vol. 2, pp. 257-269, 2005.
- 6) Wagner, B.: Windkrafte an Uberwasserschiffen [in German], Schiff und Hafen, pp. 894-900, 1967.
- 7) Tsuji, T., Takaishi, Y., Kan, M. and Sato, T.: Model Test

about Wind Forces Acting on the Ships [in Japanese], Report of Ship Research Institute, No. 5, Vol. 7, pp. 13–37, 1970.

- 8) Tsujimoto, M., Sogihara, N., Kuroda, M. and Sakurada, A.: Development of a Ship Performance Simulator in Actual Seas, Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, Vol.11, 2015.

 Fig. 16 C_x of Bulk Carrier.

 Fig. 17 C_x of Chemical Tanker.

 Fig. 18 C_x of Container Ship (Full Load Condition).

 Fig. 19 C_x of Container Ship (Ballast Condition).

 Fig. 20 C_x of PCC.

Fig. 21 C_Y of Bulk Carrier. Fig. 22 C_Y of Chemical Tanker. Fig. 23 C_Y of Container Ship (Full Load Condition). Fig. 24 C_Y of Container Ship (Ballast Condition). Fig. 25 C_Y of PCC.

Fig. 26 C_N of Bulk Carrier.

Fig. 27 C_N of Chemical Tanker.

Fig. 28 C_N of Container Ship (Full Load Condition).

Fig. 29 C_N of Container Ship (Ballast Condition).

Fig. 30 C_N of PCC.

Fig. 31 Coefficient of variation of C_X (Bulk Carrier). Fig. 32(a) Correlation diagram between U_{A1} and U_{10m} . Fig. 32(b) Correlation diagram between U_{A2} and U_{10m} .

Table 8 Dimensions of wind tunnels for round robin tests.

	Test section	Max. wind velocity	Thickness of boundary layer
Tunnel-A (NMRI)	15×3×2 m	30 m/s	abt. 130 mm
The other tunnels	24×6×3 m	15 m/s	abt. 30 mm
	30×6×5 m	20 m/s	abt. 50 mm

Fig. 33 Bulk Carrier model under the wind tunnel test (NMRI).

Fig. 34 Bulk Carrier model under the wind tunnel test (other than NMRI, 1 of 2).

Fig. 35 Bulk Carrier model under the wind tunnel test (other than NMRI, 2 of 2).

Fig. 36(a) Comparison of C_X measured in three different wind tunnels with Bulk Carrier model (using U_{A1}).

Fig. 36(b) Comparison of C_Y measured in three different wind tunnels with Bulk Carrier model (using U_{A2}).

Fig. 36(c) Comparison of C_N measured in three different wind tunnels with Bulk Carrier model (using U_{A2}).

Fig. 37 Influence of the difference in wind resistance coefficients on power curves of PCC.