*Proceedings of the Nineteenth (2009) International Offshore and Polar Engineering Conference*
*Osaka, Japan, June 21-26, 2009*

*ISBN 978-1-880653-53-1 (Set); ISSN 1098-618*

# Experimental Investigation and Estimation on Wind Forces for a Container Ship

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## ABSTRACT

Container ships operate with large number of unit containers on the deck, and then they have many kinds of external ship forms due to the position of them depending on need for delivery demands. In the operation of the ships, wind load mostly works as resistance. The estimation of wind effect has important role for calculation of economical cost for operation. There is, however, no simple method to calculate the wind load for those container ships with crested or lacked containers without carrying out wind tunnel experiments. In this paper, ease estimation method for wind load on such kinds of container ships is proposed using experimental investigations.

KEY WORDS: Ship; Container; Wind load; Estimation; Experiment; Operation.

## INTRODUCTION

Large-scale container ships, which have 6000TEU more over containers onboard and 300m length over, are built one after another recently. A large container structure above sea level is largely affected from wind at sea. Assessing navigational performance of the ships, it is important to estimate wind effect exactly.

Ordinary, specification of a ship external form in case of a tanker, a bulker, a PCC etc. doesn't change excluding the main hull's thickness that means the height from sea level to main hull deck top. The estimation methods of wind load often used basically target fully loaded or ballast ships' condition (Yamano, T and Saito, Y, 1970; Isherwood, 1972; Fujiwara et al., 2005a, 2005b, 2006 etc.).

On the other hand, container ships have many kinds of ondeck forms depended on the number of containers. Under these situations, it is difficult to reflect individual shape influence on the deck of the ships in the estimation methods, since the methods on the basis of regression analysis are basically proposed using fully loaded or ballast ships' experimental results and only use some simple ship external form parameters, that is, lateral projected area, center potion of the projected area above sea etc. for calculation. There is no estimation method to calculate the wind effect easily by only the external ship specifications including the crest or lack influence of the containers at some areas on deck.

Then, the authors carried out the wind tunnel experiments of a container ship for many kinds of stowage of containers on deck in order to grasp aerodynamic specification. Using the experimental results, the estimation method for wind load on no fully loaded container ships is considered.

At first, the problem of the original estimation method of wind load by one of the authors (Fujiwara et al., 2005a) is shown in this paper. The experimental model and setup at wind tunnel are explained in the next chapter. After them, the basic characteristics of wind forces acting on the containers are understood from experimental results, and the way of assessment of wind forces needed at the stages of departure and delivery planning etc. is shown. Finally, the calculated results of comparing with experimental ones and the steady ship speed reduction under strong wind are presented using the original and new-presented estimation method of wind forces under one container arrangement as a example.

## ORIGINAL WIND FORCES ESTIMATION METHOD

### Coordinate system of wind forces

Fig. 1 defines the Cartesian x-y coordinate reference system. The origin is located the amidship at the intersection of the still water place and on the longitudinal line of ship symmetry. Fig. 1 also provides definitions and associated sign conventions for the longitudinal force $X_A$, the lateral force $Y_A$ and the yaw moment $N_A$. The apparent angle of attack of the wind relative to the positive x-axis of the ship is defined as $\psi_A$. The non-dimensional form of the longitudinal & lateral forces and yaw moment are defined as follows:

$$C_X(\psi_A) = X_A(\psi_A)/(q_A A_F)$$
$$C_Y(\psi_A) = Y_A(\psi_A)/(q_A A_L) \qquad (1)$$
$$C_N(\psi_A) = N_A(\psi_A)/(q_A A_L L_{OA})$$

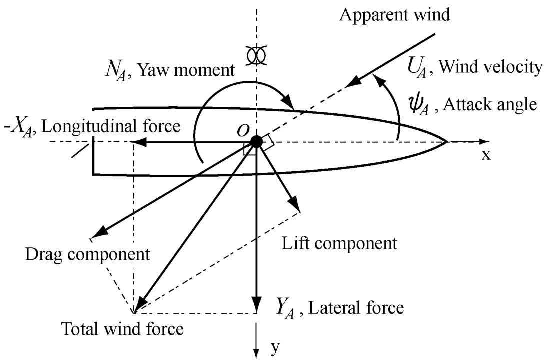


Fig. 1 Coordinate system of wind force coefficients

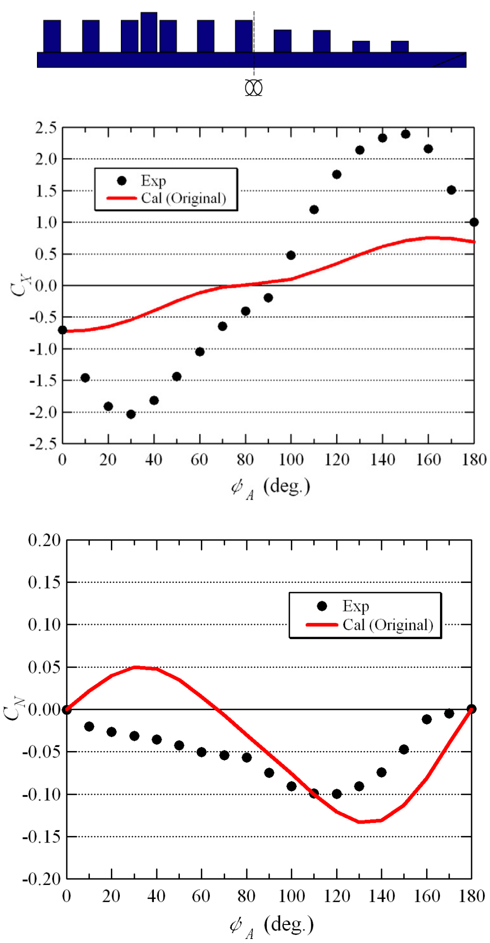


Fig. 2 Comparison between the experimental results and calculated ones of the original estimation method for the container ship model with Comb type of containers on deck

where,

$$q_A = \frac{1}{2}\rho_A U_A{}^2 \tag{2}$$

with $\rho_A$ the indicating air density, $U_A$ the apparent wind velocity, $A_F$ the frontal projected area, $A_L$ the lateral projected area and $L_{OA}$ the all of length of the ship.

### Example of experimental results comparing with calculated ones

For instance, Fig. 2 shows the experimental results of comparing with the calculated ones for a container ship model with Comb type of containers on deck. Calculated results are obtained from the latest method of one of the authors (Fujiwara et al., 2005a). The example container ship in the figure may be unreasonable and extreme ondeck containers' condition, but it seems the limitation of the estimation method using only some external form parameters, that is, the lateral projected area $A_L$ and center position of the lateral projected area, $C$ etc. The trend of this figure is as same as it of the other methods (Yamano, T and Saito, Y, 1970; Isherwood, 1972 etc.). This paper tries to calculate the wind load for such kinds of container ships with no fully loaded containers, using only some additional external form parameter of containers.

## WIND TUNNEL EXPERIMENT OF MANY TYPE CONTAINER FORMS

### Experimental model

The experimental model consisting of 20(longitudinal) × 3(height) blocks shown in Fig. 3 was used to investigate basic aero-hydrodynamic characteristics working on the blocks. Here, the blocks that are one unit for breadth span can be easily removed and the external form of them can be also easily changed. The hydrodynamic loads are measured using the one loadcell at the center base of the model.

Two types of container trends as shown in Fig. 4 were investigated in the experiment, which one is the Comb container form and the other is large amount of lack container style, that is called as OLG (One Large Gap) in this paper. The 5 Comb forms were prepared in the experiments. All Comb form models are symmetry for longitudinal direction. One case, for example, 3 blocks height is at an odd number, and 1 block height is at an even number positions. The OLG forms were set 12 kinds of models including the 2 or 4 lines center part lack subjected for the numbered containers from 9th to 12th in the figure, or from 10th to 11th and the 2 or 4 lines fore part lack container types subjected for them from 4th to 7th, or from 5th to 6th from fore.

Secondly, the container ship type model shown in Fig. 5 was ready using the previous block model in Fig. 3. A fore bow unit at front position of the base hull and a bridge unit were added to the Fig. 3's base of the block model.

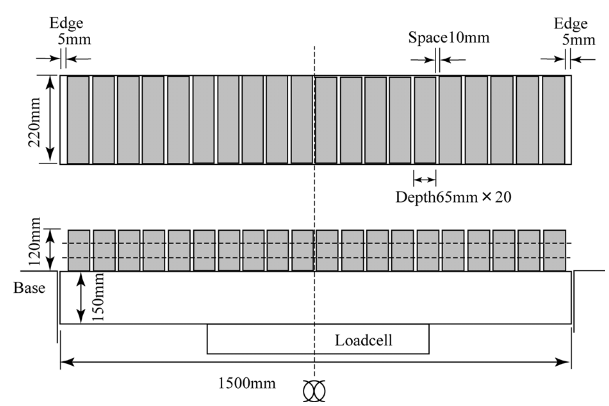


Fig. 3 Block model similar to containers on ship's deck

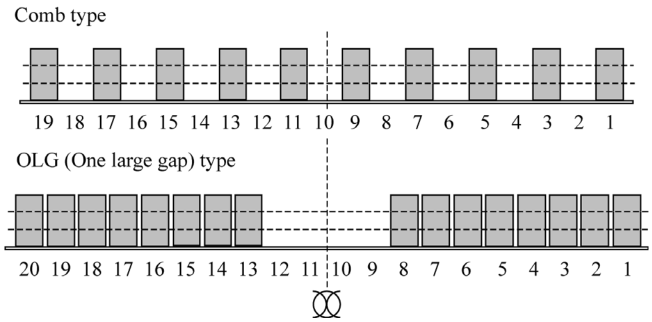


Fig. 4 Two types of container characteristics (Examples of Comb and OLG type)

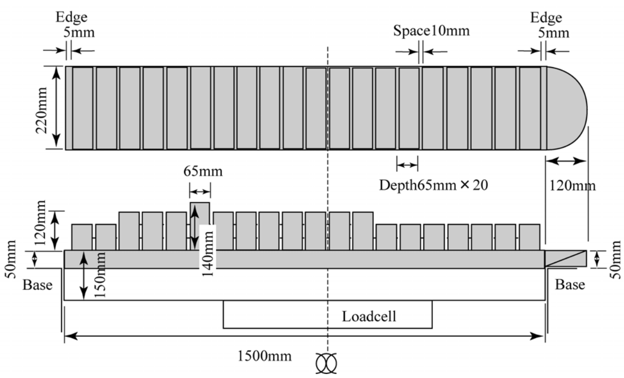


Fig. 5 Example of the ship type model with containers on deck

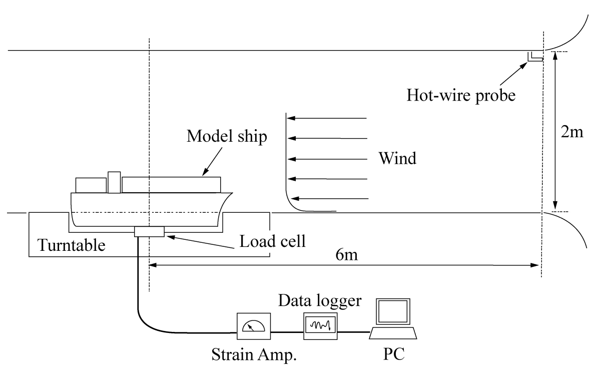


Fig. 6 Experimental setup in the wind tunnel

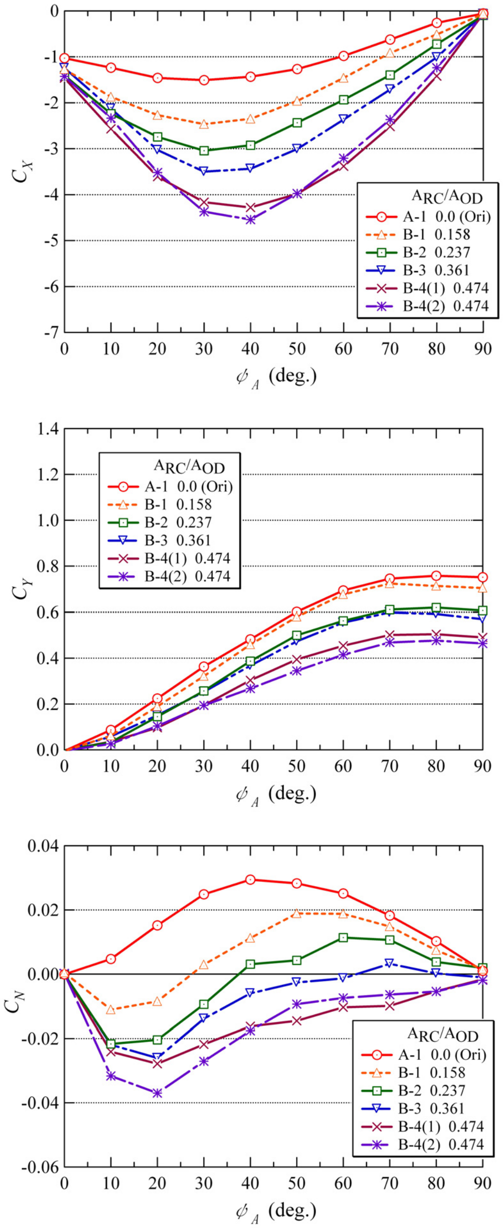


Fig. 7 Experimental results for the block models in case of Comb type

## Experimental setup

The wind tunnel experiments were carried out at NMRI. The tunnel is a Gottingen type, breadth 3m × height 2m test section and has ability to make 30m/s wind velocity.

The wind velocity was arranged to be uniform in the vertical direction apart from the thin boundary layer over the wind tunnel floor. The boundary layer has a maximum thickness of approximately 10cm. The wind velocity selected for the investigations corresponds to a mean value of approximately 25m/s and a Reynolds' number of about $2.4\times10^6$ for a length scale based on the base hull length, 1.5m, where the model is in turbulent flow condition, since the drag coefficients were independent of the Reynolds' number in this region.

## Experimental results for the block models

Fig. 7 & 8 present the some part of experimental results for the block models on Comb and center OLG forms. The figures of the lopsided one large gap's results are omitted in the paper. Each figure shows the coefficients of longitudinal, lateral forces, $C_X$ & $C_Y$, and yaw moment, $C_N$, respectively. Each coefficient is obtained by the same $A_F$, $A_L$ values worth for the fully loaded form. In the legend, each number stands for the ratio of $A_{RC} / A_{OD}$, which $A_{RC}$ is the lack part area in the lateral projected area on the deck's fully imaged containers $A_{OD}$. The definitions of them are shown in Fig. 9 as an example image. Here 'fully loaded' doesn't mean the maximum values on deck from view points of specification, but the form of the no lack or gap. Averaged value of wind velocity from the wind tunnel floor to top height of a

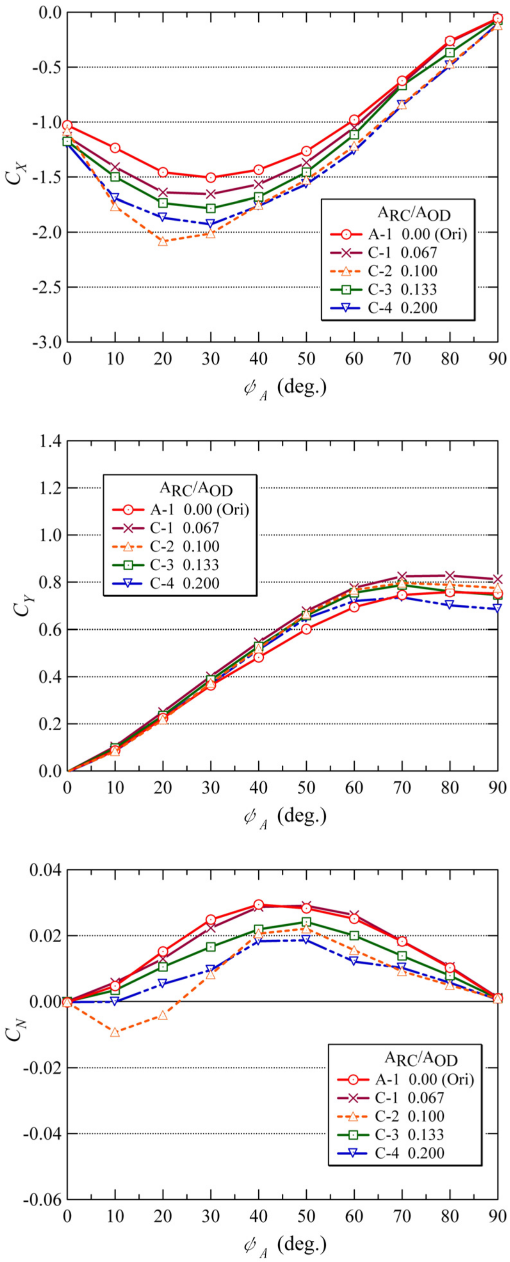


Fig. 8 Experimental results for the block models in case of OLG type

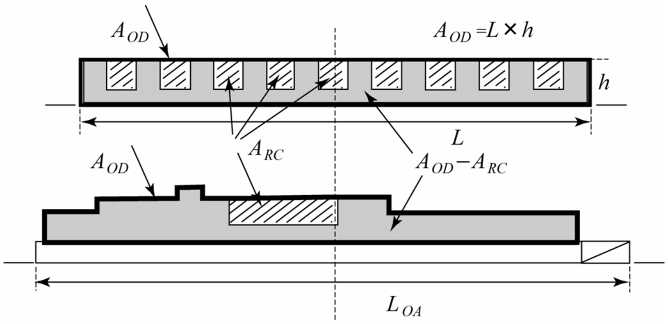


Fig. 9 $A_{RC}$ & $A_{OD}$ definitions in the lateral projected area of the models

block is used to obtain the non-dimensional wind force coefficients as the apparent wind velocity in Eq. 2.

Increase (or decrease) on $C_X$ & $C_Y$ is actually associated with an increase of $A_{RC}/A_{OD}$ value. In case of $C_N$, the trend of the results is changed depending on $A_{RC}/A_{OD}$. Although the both results of Comb and OLG type forms are similar tendency, the value level of increasing and decreasing is not same.

From the observation of two sets of the results, the method of estimation for the container ship with arbitrary form of ondeck containers is considered in the next chapter.

## ESTIMATION METHOD OF WIND LOAD FOR SHIPS WITH NO FULLY LOADED CONTAINERS

### Longitudinal force coefficient

The longitudinal force coefficient, $C_X$, of the original method (Fujiwara et al., 2005a) is consist of the longitudinal flow drag, $F'_{LF}$, which worth for the main stream line flow, lift & drag, $F'_{XLI}$, caused by the liner potential theory and additional force caused by the 3-dimentional flow effect, $F'_{ALF}$ as follows (Please refer to the original paper for each term of the coefficients and number):

$$\begin{aligned} C_X(\psi_A) &= F'_{LF} + F'_{XLI} + F'_{ALF} \\ &= C_{LF}\cos\psi_A \\ &\quad + C_{XLI}(\sin\psi_A - \tfrac{1}{2}\sin\psi_A\cos^2\psi_A)\cdot\sin\psi_A\cos\psi_A \\ &\quad + C_{ALF}\sin\psi_A\cos^3\psi_A \end{aligned} \tag{3}$$

Front side pressure drag brought by wind is assumed to be main factor of increase of wind load. In case that lack of containers situation between other containers is on deck like Fig. 10, the projected area, $l_{RC}\tan\psi_A \times h_{RC}$, in the wind direction $\psi_A$ increases rather then no lack situation, id est. fully loaded condition.

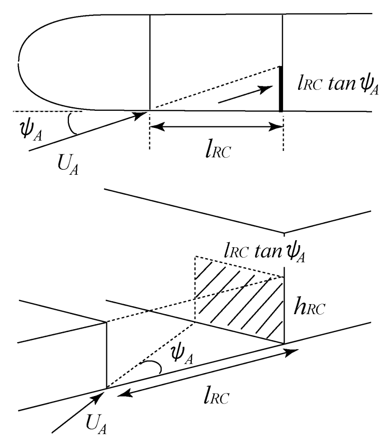


Fig. 10 Increased pressure drag area model

Then, on the basis of $x$ axis, increased longitudinal force transformed into non-dimensional form using the parameter $A_{OD}$ is defined as follows:

$$l_{RC}\tan\psi_A \times h_{RC} \times \cos^2\psi_A / A_{OD} \tag{4}$$

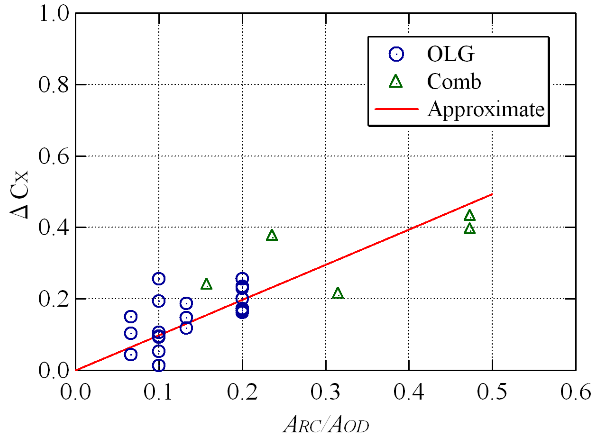


Fig. 11 Experimental results of $\Delta C_X$ in $\psi_A$=0deg.

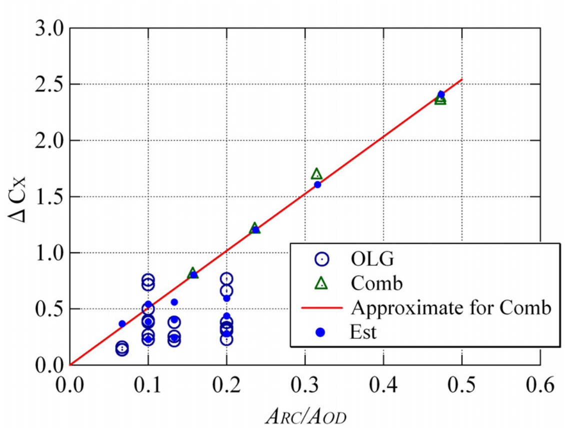


Fig. 12 Experimental results of $\Delta C_X$ in $\psi_A$ = abt. 30deg.

Using same manner, the drag in $\psi_A$=0 may be considered depending on $l_{RC}$ value relating to vortex shedding drag.

$$l_{RC} \times h_{RC} \times \cos^2 \psi_A / A_{OD} \tag{5}$$

As a result, the longitudinal force coefficient, $C_X$, is represented using the experimental coefficients, $C_{D1}$ & $C_{D2}$, like that,

$$\begin{aligned} C_X(\psi_A) &= F'_{LF} + F'_{XLI} + F'_{ALF} + F'_{RC} \\ &= C_{LF}\cos\psi_A \\ &+ C_{XLI}(\sin\psi_A - \tfrac{1}{2}\sin\psi_A\cos^2\psi_A)\cdot\sin\psi_A\cos\psi_A \\ &+ C_{ALF}\sin\psi_A\cos^3\psi_A \\ &+ \frac{A_{RC}}{A_{OD}}\left(C_{D1}\cos^2\psi_A + C_{D2}\sin\psi_A\cos\psi_A\right) \end{aligned} \tag{6}$$

Fig. 11 shows the experimental results of $\Delta C_X$ in $\psi_A$=0. $\Delta C_X$ means the drag difference between the Comb & OLG and fully loaded form's results. Generally speaking, $\Delta C_X$ has linear character for $A_{RC}/A_{OD}$. $\Delta C_X$, that is equal to $C_{D1}\cdot(A_{RC}/A_{OD})$, is decided from the results of Fig. 11 as follows:

$$\Delta C_X = C_{D1}\frac{A_{RC}}{A_{OD}} = \mp 0.986\frac{A_{RC}}{A_{OD}} \qquad \begin{cases} 0 \le \psi_A < \pi/2 \\ \pi/2 < \psi_A \le \pi \end{cases} \tag{7}$$

Next, inclined wind angle case is considered. $\Delta C_X$ is calculated using the each maximum $C_X$ in 20-40deg. as shown in Fig. 7&8 based on the $C_X$ value at $A_{RC}/A_{OD}$ =0.0. Experimental results of $\Delta C_X$ are shown in Fig. 12.

In case of Comb type, $\Delta C_X$ simply increases by the effect of $A_{RC}/A_{OD}$. The OLG type's $\Delta C_X$ is also increase by that, however, the inclination of $\Delta C_X$ is dull response rather than the Comb type. Then, the candidate equation of $\Delta C_X$ is separated by two parts as follows:

$$\Delta C_X = \Delta C_{XRC} + \Delta C_{XOLG} \tag{8}$$

Basically the effect of container lack is represented in the first term of Eq. 8, $\Delta C_{XRC}$. In case of OLG type, modification term, $\Delta C_{XOLG}$, is added in the equation. As shown in Fig. 12, large lack of containers of OLG causes reduction of increase of drag by the effect of minus pressure behind the containers (for example, Hoerner (1965)).

Finally, the longitudinal force coefficient, $C_{D2}$, is represented using the experimental coefficients like that:

$$\begin{aligned} C_{D2} &= -5.09\frac{A_{RC}}{A_{OD}} && \textit{for Comb type} \\ &= -5.09\frac{A_{RC}}{A_{OD}} \\ &+ \left\{4.57(\frac{A_{RC}}{A_{OD}} - 0.150) \pm (0.625\frac{C_{RC}}{L_{OA}} + 0.373)\right\} \quad \begin{cases} 0 \le \psi_A < \pi/2 \\ \pi/2 < \psi_A \le \pi \end{cases} \\ & && \textit{for OLG type} \end{aligned} \tag{9}$$

with $C_{RC}$ the center potion for lateral projected area above sea on the container ship form with OLG. These estimated results ('Est' in figure) are mostly coincided with the experimental ones as shown in Fig. 12.

## Lateral force coefficient

The lateral force coefficient, $C_Y$, have also simple relation with $A_{RC}/A_{OD}$. Fig. 13 shows experimental results of $\Delta C_Y$ in $\psi_A$ = 90deg.

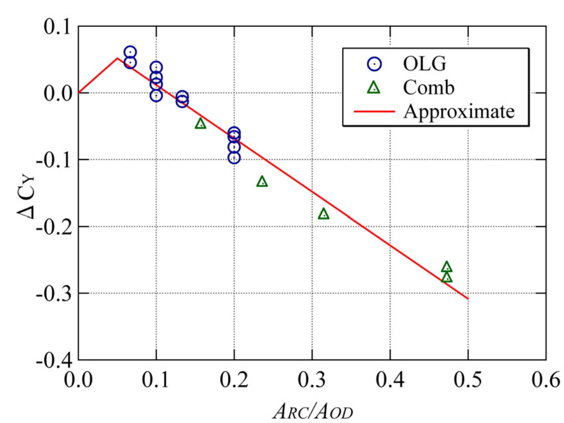


Fig. 13 Experimental results of $\Delta C_Y$ in $\psi_A$ = 90deg.

$\Delta C_Y$ is calculated on the basis of $C_Y$ value at $A_{RC}/A_{OD}$=0.0 as same treat as $\Delta C_X$. In the estimation of the experimental results $\Delta C_Y$, same $A_L$ value is used to calculate non-dimensional $C_Y$. According to increase $A_{RC}/A_{OD}$, $\Delta C_Y$ value is linearity decreasing, however, it is understood that $\Delta C_Y$ has some plus value at $A_{RC}/A_{OD}$=0.05, and $\Delta C_Y$ has also not –0.5, but –0.3 at $A_{RC}/A_{OD}$=0.5 by the interaction effect of aerodynamics.

From the results of Fig. 13, $C_Y$ for a container ship is calculated simply using next formulation by adding the cross flow drag $C_{CR1}$ term, considering the ratio of the $A_{OD}$ in $A_L$, in the original estimation equation.

$$C_Y(\psi_A) = (C_{CR0} + C_{CR1})\sin^2\psi_A + (C_{LF}\sin\psi_A\cos\psi_A)\cos\psi_A + (C_{YID}\sin^2\psi_A\cos^2\psi_A)\sin\psi_A \tag{10a}$$

$$\begin{aligned} C_{CR1} &= C_{CR11}\cdot C_{CR12} \\ C_{CR11} &= \frac{A_{OD}}{A_L} \\ C_{CR12} &= 1.04\frac{A_{RC}}{A_{OD}} \quad in \quad \frac{A_{RC}}{A_{OD}} < 0.05 \\ &= -0.801\frac{A_{RC}}{A_{OD}} + 0.0918 \quad in \quad 0.05 \le \frac{A_{RC}}{A_{OD}} < 0.5 \end{aligned} \tag{10b}$$

$C_{CR0}$ equal to $C_{CR}$, $C_{LF}$, $C_{YID}$ are the coefficients presented in the original proposed paper (Fujiwara et al., 2005a).

### Yaw moment coefficient

The original method of calculating $C_N$ is represented like this:

$$C_N(\psi_A) = C_{N0} = C_Y(\psi_A)\cdot L_N(\psi_A) = C_Y(\psi_A)\cdot\left[0.927\times\frac{C}{L_{OA}} - 0.149\times(\psi_A - \frac{\pi}{2})\right] \tag{11}$$

Wind moment works to the ondeck containers as shown in Fig. 14 in case of $l_{CRi} \le B$. It is appropriate in case of $l_{CRi} > B$ to calculate the $C_N$ by using the present method since the special and peculiarity tendency of the large lack containers is very small, as observational decision of the experimental results. That is, wind moment works in the following equation referring to Fig. 14:

$$N_A = N_H + \sum X_{Ci}\, l_{C2i} + \sum Y_{Ci}\, l_{C1i} \tag{12}$$

Here, $N_H$ means yaw moment acting on a ship's main hull. First and third terms are the ordinal $C_N$ components, then, modified $C_N$ including the effect of container lacks is presented as follows:

$$C_N = (1 - A_{RC}/A_L)\times C_{N0} + C_{N1} \tag{13}$$

The $C_{N1}$ is the additional effect of the container lacks, and longitudinal direction force included in the $C_{N1}$ is formed as $\sin\psi_A\cos\psi_A$ by the same logic of Eq. 4. Therefore, the $C_{N1}$ with two empirical parameters is represented as follows:

$$C_{N1} = C_{N11}\cdot C_{N12}\cdot\sin\psi_A\cos\psi_A \tag{14a}$$

$$\begin{aligned} C_{N11} &= 1 - \left(\frac{2\psi_A}{\pi}\right)^{1/5} \quad in \quad 0 < \psi_A < \frac{\pi}{2} \\ &= 1 - \left(\frac{2(\pi - \psi_A)}{\pi}\right)^{1/5} \quad in \quad \frac{\pi}{2} < \psi_A < \pi \\ C_{N12} &= -0.613\frac{A_{RC}}{A_{OD}} - 0.194 \end{aligned} \tag{14b}$$

The $C_{N11}$ stands for moment lever working at containers worth for $l_{C2i}$. The $C_{N12}$ is the parameter of ratio of the container lacks and stands for the effect of drag for vortex behind the blocks. The $C_{N12}$ is decided from the trend of the experimental results.

Fig. 15 shows the estimated results of $C_{N1}$, equal to $\Delta C_N$, for Comb type block comparing with the experimental results. Estimated results by the Eq. 14 are enough accuracy comparing with the experimental results.

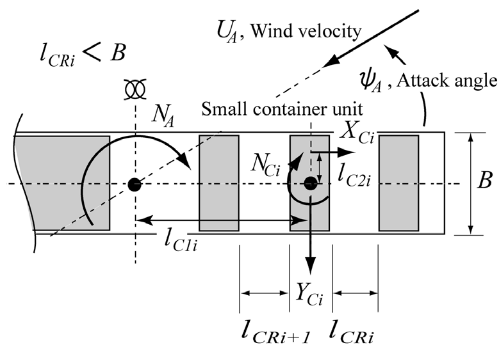


Fig. 14 Force and moment components relating with yaw moment $N_A$ in the coordinate system for Comb type of container arrangement

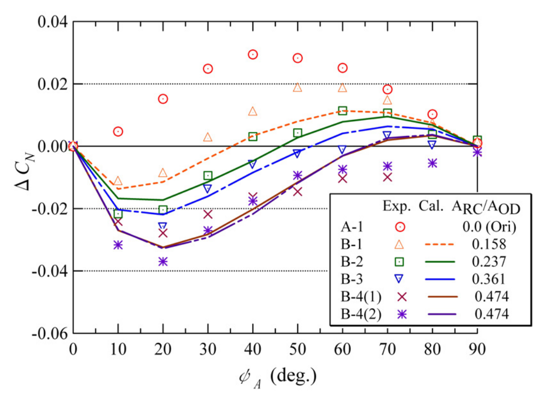


Fig. 15 Estimated results of $\Delta C_N$ for Comb type block comparing with the experimental ones

## ASSESSMENT OF PRESENT MODIFIED WIND FORCE ESTIMATION METHOD FOR A CONTAINER SHIP

At Fig. 2, the comparison between the experimental results and original calculated ones for the container ship with Comb type of containers on deck are presented, where large difference of the both is clearly understood. Now, the estimated results of present calculation method are added in Fig. 2 as Fig. 16 on wind force coefficients of $C_X, C_Y, C_N$. In the Fig. 16, the estimated results of the original method are initially modified for coinciding with the experimental results, which is shown as "Modified" since the experimental results used the block models have the peculiar values different from ordinal container ships. After that, calculated values by the ondeck container effect terms presented in the previous chapter are added to the modified estimated results. As a reminder, when calculating the wind force coefficients, in the Eq. 6, for example, no crest and lack specification ($A_{RC}$=0.) must be used in the 1st-3rd terms of Eq. 6, and remained term, $F_{RC}^{'}$, is only reflected the container form. This treatment has same manner for $C_Y$ and $C_N$.

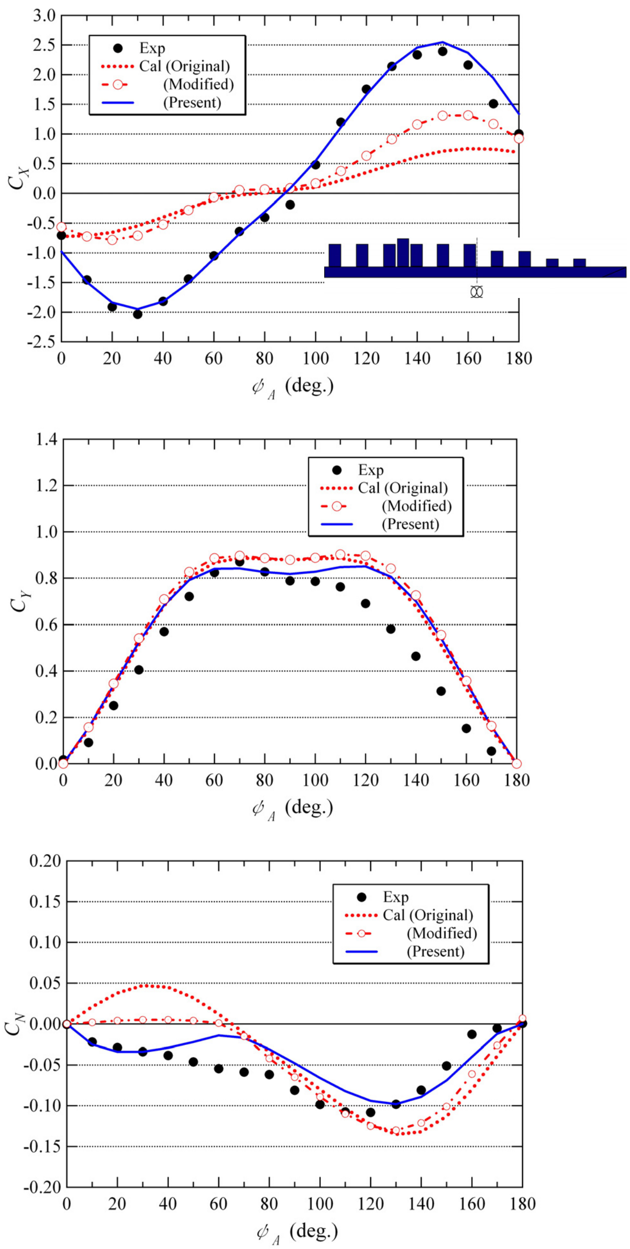


Fig. 16 Wind force coefficients comparing the calculated results with experimental ones for the block container ship model

Table 1. Principal particulars of the 300m container ship

| | | |
|---|---|---|
| $L_{OA}$ | m | 318 |
| $L_{PP}$ | m | 300 |
| B | m | 40 |
| d | m | 14 |
| $A_F$ | $m^2$ | 1469 |
| $A_L$ | $m^2$ | 7417 |
| $A_{OD}$ | $m^2$ | 4405 |
| $A_{RC}$ | $m^2$ | 1854 |
| $D_P$ | m | 9.6 |
| $H_R$ | m | 11.7 |
| $\Lambda$ | | 1.47 |

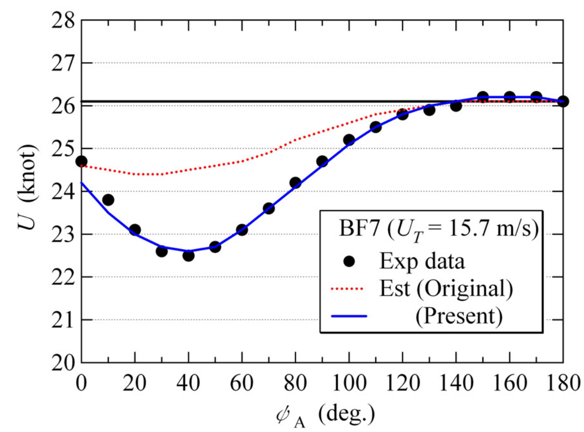


Fig. 17 Speed reduction by wind load for the 300m container ship

Comparing with the original method, the present method is able to get the better results for the experimental ones. For $C_Y$, as one selection, it had better not to calculate using the present calculated method, since the original method has enough accuracy for the experimental results.

reduction for a 300m container ship with external form in Fig. 2 & 16 and with ability to carry 6500TEU. Table 1 shows the principal particulars of the container ship. In the table, $D_P$ is propeller diameter, $H_R$ is rudder height, and $\Lambda$ is aspect ratio of the rudder.

Fujiwara et al. (2008) were referred to for the calculation method of steady cruising condition and hydrodynamic coefficients from. The steady-state equations are formulated based on the MMG model for ship manoeuvring simulation to obtain the steady ship conditions like the ship speed, drift, heel and rudder angles. In this case, wave effect is neglected to know the effect of wind force coefficients' estimation quality.

The result in Fig. 17 under the situation of BF7 on ship speed $U$ is reasonable since the present estimated results of the wind force coefficients are close value for the experimental ones rather than the original estimation results. And using the present method, the large estimation error, that is nearly 2 knot at about $\psi_A$ =30-50 deg., is canceled.

## CONCLUSIONS

At sea, a ship is suffered from wind and waves. Especially, a container ship, that has large volume structure above sea level comparing with other ships, for example, tanker, bulker etc, is strongly affected by wind. Then, in order to investigate the aerodynamic characteristics on many types of external forms of a container ship, wind tunnel experiments were carried out using 1.5m block models. Moreover, a new method of estimating wind force coefficients for container ships is presented in this paper. The results of this paper are summarized as follows:

1. Aerodynamic characteristics for the longitudinal and lateral wind forces and the yaw moment of the many type block models similar to containers on deck are presented in this paper.
2. $A_{RC} / A_{OD}$ is important factor for representing the effect of comb and lack container forms.
3. Using the experimental results of many type block models, the new method of estimating wind force coefficients for the container ships with various loading conditions is presented. This method is simple and easy way for use since the $A_{RC}$ & $C_{RC}$ are only treated as the additional parameter comparing with the original wind load estimation method.
4. The effect of the estimated result is shown with simulation on the mathematical modeling of a container ship. It is shown that the present method of wind force coefficients has important role to calculate the ship speed etc. in the operational stage of container ships.


## ACKNOWLEDGEMENTS

The authors wish to acknowledge valuable discussions with Dr. Sasaki, N, head of our project group for ship performance index ‘10 mode at sea’.


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