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AN ESTIMATION METHOD OF WIND FORCES AND MOMENTS ACTING ON SHIPS

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Summary

It is an important problem for a ship to evaluate accurately the influence of wind on manoeuvring performance to navigate safely. The authors proposed a new estimation method of wind forces and moments acting on ship represented the linear multiple regression model. This estimation method was obtained by using experimental results of various kinds of ships modified the effect of wind velocity profiles in the experimental condition. The estimation method has been confirmed to have high accuracy compared with past estimation methods. In this paper, formulation of the estimation method is introduced and application examples are shown to evaluate the method.

1 INTRODUCTION

A lot of researches have been investigated about the influence of wind on manoeuvring performance of a ship navigating under strong wind. Especially at harbor region it is very important to consider the effect of wind for a ship to avoid risks of collision and grounding.

Experimental results obtained from wind tunnel tests are normally used to evaluate the effect of wind forces and moments acting on a ship since shape of the ship on the surface of water is not simple. As practicable methods, the equations of linear multiple regression model based on the experimental results had already been proposed by Isherwood[1], Yamano[2] in 1970's to estimate the wind loads. Recently estimation method of mathematical modeling expanded the way to estimate fluid presser in the water was also presented by Yoneta[3] though the coefficients of the equation's terms were obtained from the regression analysis by using experimental results.

However, the new types of ships carrying products, natural resources and so on, such as large PCC, LNG, were built after 1970's and ships like tanker, container and passenger ship have enlarged in recent years from extension of their usage. The method to estimate the wind loads acting on ships exactly including such kinds of ship's forms would be expected.

From the purpose to obtain the wind effect accurately, new estimation method[4] on wind loads obtained from the linear multiple regression analysis was proposed, which has the features as follows;

(1) Many kinds and number of ships to make the equations of estimation on wind loads

Many kinds of experimental results on ships built in recent years were collected as much as possible. The samples of the results include VLCC, PCC, LNG, research vessel etc. Number of the samples is larger than that in the past estimation method used regression analysis.

(2) Modification on influence of velocity profiles of wind in the experimental conditions

In the experiments done in the past, measurements were carried out in the various velocity profiles of wind. Some experiments were carried out in boundary layer according to the power law and the other experiments in the condition where boundary layer hardly exists. In order to resume the effect of the boundary layer of wind in the experimental conditions, Blendermann's method[5] is used to modify them in this paper.

(3) Stepwise method in the linear multiple regression analysis

34 parameters, which consist of combination of 9 principal parameters, including the reciprocals were used in the linear multiple regression analysis.

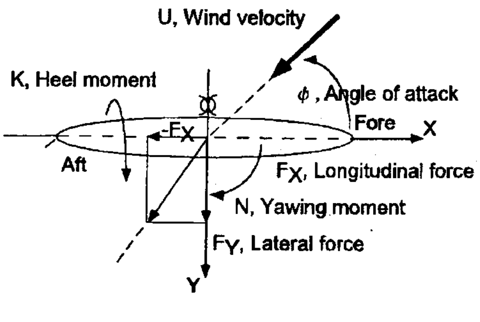


Figure 1 Coordinate system

The combination of most appropriate independent variables was selected by stepwise method that is one of the representative methods in the regression analysis.

(4) Estimation of heel moment generated by strong wind

Although there is no estimation method of heel moment by strong wind in the present, to estimate it of a ship with large lateral project area is important for considering heel effect in manoeuvring performance.
Therefore, the estimation method of heel moment was proposed.

In the present paper, the estimation method is introduced detail and accuracy of the method is confirmed by comparing with experimental results.

2 ESTIMATION METHOD OF WIND FORCES AND MOMENTS

The way of how to calculate the estimation equation of wind forces and moments acting on a ship is introduced in this section.

2.1 Samples and coordinate system of wind load coefficients

Experimental results used as samples in the analysis are shown in Table 1. Authors, published year (Pub.), sample number (N), experimental conditions on wind velocity profiles are shown in the table (The definitions of q, q_m are represented in equation (5) and section 2.2.). 68 results on longitudinal force, lateral force, yawing moment and 41 results on heel moment were collected. These samples contain in many kinds of ships.

Coordinate system is shown in Figure 1 and each wind force and moment coefficient is defined as follows;

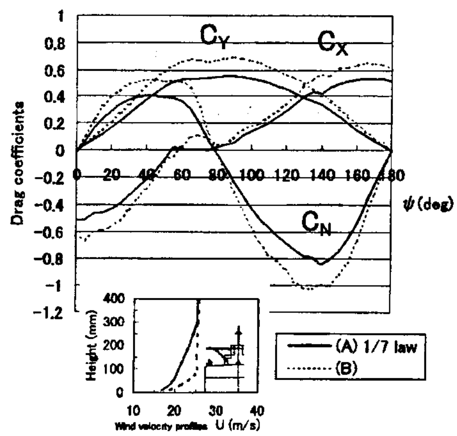


Figure 2 Influence on experimental results of VLCC in different wind profiles

$$C_X = F_X/(qA_T) \quad (1)$$

$$C_Y = F_Y/(qA_L) \quad (2)$$

$$C_N = N/(qLA_L) \quad (3)$$

$$C_K = K/(qA_LH_L) \quad (4)$$

$$q = (1/2)\rho U^2 \quad (5)$$

$$H_L = A_L/L \quad (6)$$

Here, U; velocity of wind, ρ; density of air, L; length over all, A_T; transverse projected area, A_L; lateral projected area.

The yaw moment is defined on the basis of amid ship. The origin of the heel moment is placed at water surface.

2.2 Modification of influence of wind velocity profiles

Experiments are carried out in various facilities and conditions. In case of using many kinds of experimental results, the effect coursed to the different conditions should be removed from the results to compare with each other.

Especially condition of wind profile in wind tunnel experiments affects the result directly. We investigated the effect of wind profiles by using two kinds of them. The experimental results on VLCC are shown in Figure 2 as one of examples. This figure shows that different of the wind profiles brings much different results of wind

Table 1 Experimental results used in the analysis with experimental conditions on wind velocity profiles

Author	Pub.	N	Exp. condition	[A]Boundary layer(m)	[B] Mean height H_L(m)	R [A]/[B]	q/q_m
B.Wagner[6]	1967	15	uniform	—	0.085	—	1.04
G.Aertssen[7]	1968	1	above sea	0.60	0.217	2.76	1.27
T.Tsuji[8]	1970	15	uniform	0.05	0.138	0.36	1.16
C.Aage[9]	1971	9	above sea	0.05	0.043	1.16	1.30
Y.Sezaki[10]	1980	1	—	—	—	—	—
W.Blendermann[11]	1996	25	uniform	0.02	0.125	0.16	—
T.Fujiwara[12]	1997	2	above sea	0.30	0.100	3.00	1.37

load coefficients in case of using the same wind velocity U. The trend of each coefficient, however, is almost same between condition (A) and (B).

Blendermann[5] pointed out that it could be argued that in gradient flow the force on the windward side essentially depended on average dynamic pressure q_m, whereas the force on the leeward side was governed by the dynamic pressure of object height, q_{H_L}. He proposed the method of modification of the effect on wind profiles by using the coefficients given from the experimental results as follows;

$$F_X: \quad q = q_{H_L} \qquad (7)$$

$$F_Y, N, K: \quad q = k_q \cdot q_m + (1 - k_q) \cdot q_{H_L} \qquad (8)$$

where

$$k_q \leq 1 \qquad (9)$$

The factor k_q obtained from the experiments seems to increase with q_m/q_{H_L} as shown in Figure 3. The experimental results with boundary layer assumed above sea are modified in accordance with equations (7)-(8) to coincide with the experimental conditions.

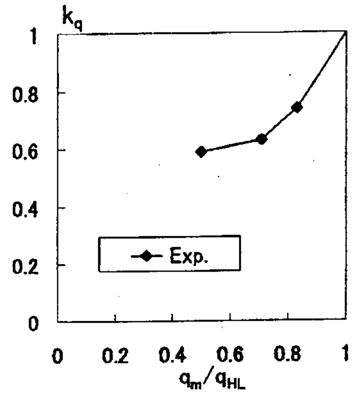


Figure 3 Factor k_q by Blendermann's experiments[5]

2.3 Formulation of estimation equations

2.3.1 Fundamental equations

Each experimental result is expressed simply by using trigonometrical series based on attack angle ψ as follows;

$$C_X = \sum_{i=0}^{5} X_i \cos i\psi \qquad (10)$$

$$C_Y = \sum_{i=1}^{5} Y_i \sin i\psi \qquad (11)$$

$$C_N = \sum_{i=1}^{5} N_i \sin i\psi \qquad (12)$$

$$C_K = \sum_{i=1}^{5} K_i \sin i\psi \qquad (13)$$

Each term of those equations is calculated by the method of least squares. To reflect distribution shape of experimental results approximately, the equations are decided to take up to fifth order terms. We confirmed in particular the series of fifth order were enough accuracy to express the experimental results practically.

However, there is possibility to add any meaningless terms when only all equations are mechanically taken up to the fifth order. It is also not easy to calculate the wind loads when the terms in the equations are enough more over the necessity.

To express the equations of series concisely without dropping accuracy in few terms, significant terms in equations (10)-(13) to represent the experimental results are selected according to the following procedures. The forecast value of the regression models would be expressed like next expressions.

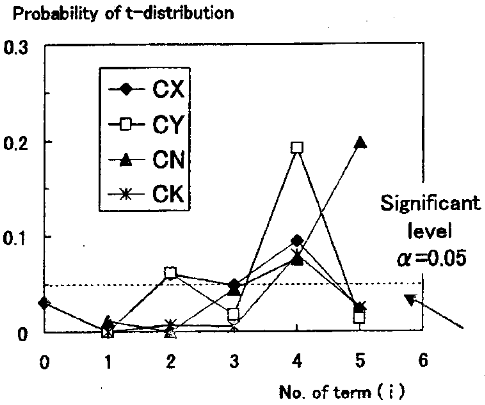


Figure 4 Effectiveness of each term

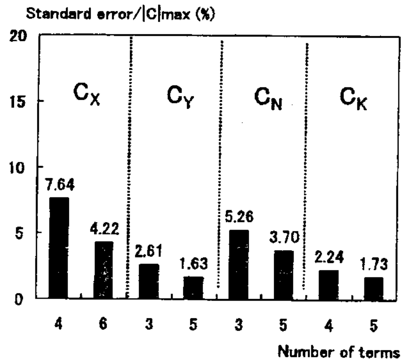


Figure 5 Applicability on trigonometrical series for wind force and moment coefficients

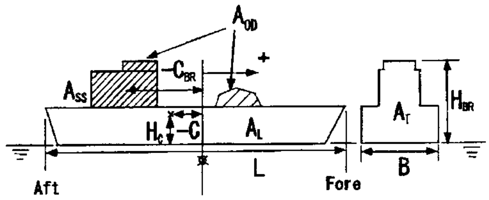
$$C_j = b_0 + \sum_{i=1}^{p} b_i x_{ij} (j = 1,2,\ldots,n) \quad (14)$$

$$x_{ij} = \begin{cases} \cos i\psi_j & (C_X) \\ \sin i\psi_j & (C_Y, C_N, C_K) \end{cases} \quad (15)$$

Here, b_i; regression coefficient.
The parameter p is equal to five here. The experimental results (n) of each wind load coefficient on a ship are given in 19 points of every 10 degree from 0 up to 180 degree. Effectiveness of the term is judged by using t-test. The limit value on $n-p-1$ degrees of freedom on t-distribution at confidence interval 100α% is defined as follow;

$$P_r(b_i/\sqrt{V_i} \geq t_\alpha(n-p-1)) = \alpha \quad (16)$$

$\sqrt{V_i}$ is a standard deviation of b_i which is obtained from samples automatically. Here, it is assumed $\alpha = 0.05$ which is 95% confidence interval. When the probability that $b_i/\sqrt{V_i}$ is larger than t_α is more



L : Length over all (m)
B : Breadth (m)
A_T : Transverse projected area (m²)
A_L : Lateral projected area (m²)
A_{OD} : Lateral projected area of superstructure (Ass) and LNG tanks, containers etc. on the deck (m²)
C : Distance from midship section to center of lateral projected area (m)
C_{BR} : Distance from midship section to center of the Ass (m)
H_{BR} : Height to top of superstructure (Bridge) (m)
H_C : Height to center of lateral projected area (m)

Figure 6 Definition of characteristic parameters that express form of a ship

than α, that is, the probability of t-distribution is smaller than 0.05, it is judged **i** term is significant. Figure 4 shows the mean values of probability on each term, which the horizontal axis shows number of the term. The terms judged significant in equations (10)-(13), which satisfy $\alpha \leq 0.05$, are shown as follows;

$$C_X = X_0 + X_1 \cos\psi + X_3 \cos 3\psi + X_5 \cos 5\psi \quad (17)$$

$$C_Y = Y_1 \sin\psi + Y_3 \sin 3\psi + Y_5 \sin 5\psi \quad (18)$$

$$C_N = N_1 \sin\psi + N_2 \sin 2\psi + N_3 \sin 3\psi \quad (19)$$

$$C_K = K_1 \sin\psi + K_2 \sin 2\psi + K_3 \sin 3\psi + K_5 \sin 5\psi \quad (20)$$

2.3.2 Influence of reduction of the terms

The effectiveness of the equations (17)-(20) is confirmed in this part. The ratio of standard errors to the maximum absolute experimental values of the wind load coefficients ($|C|max$) is calculated in case that the experimental results are expressed by equations (10)-(13) and equations (17)-(20). The result is shown in Figure 5, where the horizontal axis indicates number of the term in the series and the vertical axis indicates the ratio of average standard error of all sample ships. It is only slightly different of about 1% between equations (10)-(13) and (17)-(20) for C_Y, C_N and C_K and 3% is also only different between them on C_X.

The reason why the average standard error of C_X is larger than that of the other parameters is that value of C_X tends to change complexly near 90 degree. It is thought, however, that C_X at about 90 degree is comparatively small. Therefore, influence on ship manoeuvring due to the error on C_X at about 90 degree is considered small.

The equations (17)-(20) are decided to be used to make the estimation equation of wind loads.

2.3.3 Regression analysis

(1) Independent variables
It is necessary to use appropriate parameters that express feature of external shape on a ship as independent variables in the equations. Figure 6 shows characteristic parameters of a ship used in the equations.

19 kinds of non-dimensional combinations of the characteristic parameters and 15 kinds of reciprocals of them are used in the analysis (The combinations when C and C_{BR} are in denominators are excluded from the object.). The correlations of 19 kinds of independent variables are shown in Table 2.

(2) Stepwise method in regression analysis
Each coefficient of equations (17)-(20) is expressed by the following regression model using 34 kinds of independent variables.

$$X_i = x_{i0} + \sum_{m=1}^{m_x} x_{im} P_{x_{im}} \tag{21}$$

$$Y_i = y_{i0} + \sum_{m=1}^{m_y} y_{im} P_{y_{im}} \tag{22}$$

$$N_i = n_{i0} + \sum_{m=1}^{m_n} n_{im} P_{n_{im}} \tag{23}$$

$$K_i = k_{i0} + \sum_{m=1}^{m_k} k_{im} P_{k_{im}} \tag{24}$$

Here, x_{im} etc.; regression coefficient, $P_{x_{im}}$ etc.; independent variable.

The stepwise method[13] is used as the method how to choice the parameter of the term in the equation. The method can be excluded the effect of multi-collinearity. The judgment of significance on each independent variable is decided comparing with the F value defined in the next as one example.

$$F = x_{im}^2 / V_{x_{im}} \tag{25}$$

Here, $V_{x_{im}}$ represents a variance of x_{im}.
When the number of samples is n, this F value is known according to F distribution of $n - m_x - 1$ degrees of freedom. The critical value $F_r = 2.0$ is used to decide the efficiency of selection of the terms[13]. As the results, the following combinations of the terms are judged efficient from the statistical point of view.

Each term on C_X is expressed as follows;

$$X_0 = x_{00} + x_{01}\frac{BH_{BR}}{A_T} + x_{02}\frac{C}{H_C} + x_{03}\frac{A_{OD}}{L^2} \tag{26}$$

$$X_1 = x_{10} + x_{11}\frac{A_L}{LB} + x_{12}\frac{LH_C}{A_L} + x_{13}\frac{LH_{BR}}{A_L} + x_{14}\frac{A_{OD}}{A_L} + x_{15}\frac{A_T}{LB} + x_{16}\left(\frac{A_T}{L^2}\right)^{-1} + x_{17}\left(\frac{H_C}{L}\right)^{-1} \tag{27}$$

$$X_3 = x_{30} + x_{31}\left(\frac{LH_{BR}}{A_L}\right)^{-1} + x_{32}\frac{A_L}{A_T} + x_{33}\frac{LH_C}{A_L} + x_{34}\frac{A_{OD}}{A_L} + x_{35}\frac{A_{OD}}{L^2} + x_{36}\frac{C}{H_C} + x_{37}\frac{C_{BR}}{L} \tag{28}$$

$$X_5 = x_{50} + x_{51}\left(\frac{A_{OD}}{A_L}\right)^{-1} + x_{52}\frac{C_{BR}}{L} + x_{53}\frac{A_L}{LB} \tag{29}$$

Each term on C_Y is expressed as follows;

$$Y_1 = y_{10} + y_{11}\frac{C_{BR}}{L} + y_{12}\frac{C}{L} + y_{13}\left(\frac{A_{OD}}{A_L}\right)^{-1} + y_{14}\frac{C}{H_C} + y_{15}\left(\frac{BH_{BR}}{A_T}\right)^{-1} \tag{30}$$

$$Y_3 = y_{30} + y_{31}\frac{A_L}{LB} + y_{32}\frac{LH_C}{A_L} + y_{33}\frac{C_{BR}}{L} + y_{34}\left(\frac{H_{BR}}{B}\right)^{-1} + y_{35}\frac{A_{OD}}{A_L} + y_{36}\left(\frac{BH_{BR}}{A_T}\right)^{-1} \tag{31}$$

$$Y_5 = y_{50} + y_{51}\frac{A_L}{LB} + y_{52}\left(\frac{H_{BR}}{L}\right)^{-1} + y_{53}\frac{C_{BR}}{L} + y_{54}\left(\frac{A_T}{B^2}\right)^{-1} + y_{55}\frac{C}{L} + y_{56}\frac{LH_C}{A_L} \tag{32}$$

Each term on C_N is expressed as follows;

$$N_1 = n_{10} + n_{11}\frac{C}{L} + n_{12}\frac{LH_C}{A_L} + n_{13}\left(\frac{A_L}{A_T}\right)^{-1} + n_{14}\frac{C}{H_C} + n_{15}\frac{A_L}{LB} + n_{16}\frac{A_T}{L^2} + n_{17}\left(\frac{A_T}{B^2}\right)^{-1} + n_{18}\frac{C_{BR}}{L} \tag{33}$$

$$N_2 = n_{20} + n_{21}\frac{C_{BR}}{L} + n_{22}\frac{C}{L} + n_{23}\left(\frac{A_{OD}}{A_L}\right)^{-1} + n_{24}\frac{A_T}{B^2} + n_{25}\left(\frac{H_{BR}}{L}\right)^{-1} + n_{26}\left(\frac{BH_{BR}}{A_T}\right)^{-1} + n_{27}\frac{A_L}{LB} + n_{28}\frac{A_L}{L^2} \tag{34}$$

$$N_3 = n_{30} + n_{31}\frac{C_{BR}}{L} + n_{32}\left(\frac{BH_{BR}}{A_T}\right)^{-1} + n_{33}\frac{A_L}{A_T} \tag{35}$$

Each term on C_K is expressed as follows;

$$K_1 = k_{10} + k_{11}\frac{H_{BR}}{L} + k_{12}\frac{A_T}{LB} + k_{13}\frac{LH_C}{A_L} + k_{14}\frac{C}{L} + k_{15}\frac{C_{BR}}{L} + k_{16}\left(\frac{H_{BR}}{B}\right)^{-1} + k_{17}\left(\frac{A_T}{B^2}\right)^{-1} + n_{18}\left(\frac{B}{L}\right)^{-1} \tag{36}$$

Table 2 Correlation table of non-dimensional independent variables

	A_T/L^2	A_L/L^2	A_{OD}/L^2	B/L	H_{BR}/L	Hc/L	C/L	C_{BR}/L	A_L/A_T	A_{OD}/A_L	A_T/B^2	A_T/LB	A_L/LB	H_{BR}/B	C/Hc	LHc/A_L	$H_{BR}C/A_L$	LH_{BR}/A_L	BH_{BR}/A_T
A_T/L^2	1.00																		
A_L/L^2	0.73	1.00																	
A_{OD}/L^2	0.41	0.81	1.00																
B/L	0.78	0.38	0.10	1.00															
H_{BR}/L	0.88	0.75	0.45	0.56	1.00														
Hc/L	0.86	0.93	0.71	0.50	0.88	1.00													
C/L	0.41	0.36	0.19	0.29	0.42	0.41	1.00												
C_{BR}/L	0.52	0.56	0.40	0.25	0.54	0.58	0.77	1.00											
A_L/A_T	−0.37	0.32	0.49	−0.56	−0.21	0.08	0.05	0.09	1.00										
A_{OD}/A_L	0.16	0.53	0.90	−0.12	0.22	0.47	0.09	0.27	0.49	1.00									
A_T/B^2	0.33	0.57	0.49	−0.31	0.53	0.57	0.23	0.43	0.32	0.43	1.00								
A_T/LB	0.88	0.82	0.54	0.41	0.91	0.90	0.39	0.59	−0.12	0.32	0.73	1.00							
A_L/LB	0.32	0.84	0.79	−0.18	0.48	0.70	0.27	0.48	0.70	0.63	0.79	0.62	1.00						
H_{BR}/B	0.32	0.54	0.44	−0.26	0.65	0.57	0.25	0.41	0.29	0.37	0.92	0.68	0.73	1.00					
C/Hc	0.50	0.58	0.35	0.24	0.57	0.59	0.90	0.74	0.18	0.22	0.47	0.58	0.51	0.48	1.00				
LHc/A_L	0.10	−0.35	−0.31	0.15	0.10	−0.01	−0.08	−0.09	−0.59	−0.12	−0.11	0.00	−0.45	−0.04	−0.19	1.00			
$H_{BR}C/A_L$	0.45	0.45	0.27	0.31	0.46	0.48	0.98	0.75	0.10	0.14	0.27	0.45	0.35	0.27	0.95	−0.17	1.00		
LH_{BR}/A_L	−0.26	−0.75	−0.69	−0.01	−0.21	−0.56	−0.26	−0.35	−0.67	−0.54	−0.41	−0.40	−0.79	−0.25	−0.49	0.62	−0.39	1.00	
BH_{BR}/A_T	−0.26	−0.40	−0.37	0.24	−0.15	−0.37	−0.10	−0.31	−0.20	−0.38	−0.70	−0.53	−0.54	−0.39	−0.29	0.12	−0.18	0.55	1.00

$$K_2 = k_{20}+k_{21}\left(\frac{H_{BR}}{B}\right)^{-1}+k_{22}\frac{A_T}{B^2} +k_{23}\left(\frac{LHc}{A_L}\right)^{-1}+k_{24}\frac{C_{BR}}{L}+k_{25}\frac{H_{BR}C}{A_L} +k_{26}\left(\frac{B}{L}\right)^{-1}+k_{27}\left(\frac{A_L}{L^2}\right)^{-1} \quad (37)$$

$$K_3 = k_{30}+k_{31}\left(\frac{A_T}{B^2}\right)^{-1}+k_{32}\frac{C_{BR}}{L}+k_{33}\frac{H_C}{L} +k_{34}\frac{A_T}{LB}+k_{35}\left(\frac{A_L}{LB}\right)^{-1}+k_{36}\frac{A_{OD}}{L^2} \quad (38)$$

$$K_5 = k_{50}+k_{51}\left(\frac{LHc}{A_L}\right)^{-1}+k_{52}\left(\frac{A_{OD}}{A_L}\right)^{-1} +k_{53}\left(\frac{A_L}{A_T}\right)^{-1}+k_{54}\left(\frac{B}{L}\right)^{-1}+k_{55}\frac{A_L}{LB} \quad (39)$$

The coefficients of each term are shown in Table 3. In case that the critical value $F_r = 4.0$ is used for calculation, standard error of the method increases about 27% though number of terms decreases from 96 to 50.

In present equations, two terms of A_L/L^2, which are often used in the past estimation equations as the parameter that represents lift force, are only selected in all equations ((26)-(39)). It is considered that several terms of A_{OD}/L^2, H_C/L, A_T/LB, A_L/LB etc., which have significant correlation for A_L/L^2 (see Table 2), are used in the equation instead of A_L/L^2.

For example, the experiments of rectangular prisms[11] show change of the length and the height influences on X_3, Y_3, that is, increase of L/B influences on X_3 and increase of H/B influences on X_3, Y_3. Since the equations of X_3, Y_3 include the independent variables A_L/A_T that means L/B, A_L/LB that means H/B respectively, it is understood that the estimation equations partly consist of appropriate independent variables. It is not easy, however, to clarify all individual terms in detail in the equations consequentially.

2.4 Accuracy of the estimation method

The present estimation method is examined by comparing with the method of Isherwood[1], Yamano[2] and Yoneta[3] which had already been proposed. Characteristics of each estimation method are shown in Table 4 for the reference. From this table, it is understood that various experimental results including recent ships like LNG, PCC etc. being unique form are collected to make the present method.

As one example, results of estimation on VLCC used in the samples are shown in Figure 7. The wind force coefficients C_X, C_Y and moment coefficients C_N, C_K are respectively shown in the figure. The present method has high accuracy rather than the other methods. Average standard errors of wind force and moment coefficients intended for all sample ships are also shown in Figure 8. The present method is good agreement against experimental results comparing with the other methods. These results show the present method could predict the wind load coefficients well for many kinds of ships.

Table 3 Each coefficient of independent variables

	m=	0	1	2	3	4	5	6	7	8
C_X	x_{0m}	-0.330	0.293	0.0193	0.682					
	x_{1m}	-1.353	1.700	2.87	-0.463	-0.570	-6.640	-0.0123	0.0202	
	x_{3m}	0.830	-0.413	-0.0827	-0.563	0.804	-5.67	0.0401	-0.132	
	x_{5m}	0.0372	-0.0075	-0.103	0.0921					
C_Y	y_{1m}	0.684	0.717	-3.22	0.0281	0.0661	0.298			
	y_{3m}	-0.400	0.282	0.307	0.0519	0.0526	-0.0814	0.0582		
	y_{5m}	0.122	-0.166	-0.0054	-0.0481	-0.0136	0.0864	-0.0297		
C_N	n_{1m}	0.299	1.71	0.183	-1.09	-0.0442	-0.289	4.24	-0.0646	0.0306
	n_{2m}	0.117	0.123	-0.323	0.0041	-0.166	-0.0109	0.174	0.214	-1.06
	n_{3m}	0.0230	0.0385	-0.0339	0.0023					
C_K	k_{1m}	3.63	-30.7	16.8	3.270	-3.03	0.552	-3.03	1.82	-0.224
	k_{2m}	-0.480	0.166	0.318	0.132	-0.148	0.408	-0.0394	0.0041	
	k_{3m}	0.164	-0.170	0.0803	4.92	-1.780	0.0404	-0.739		
	k_{5m}	0.449	-0.148	-0.0049	-0.396	-0.0109	-0.0726			

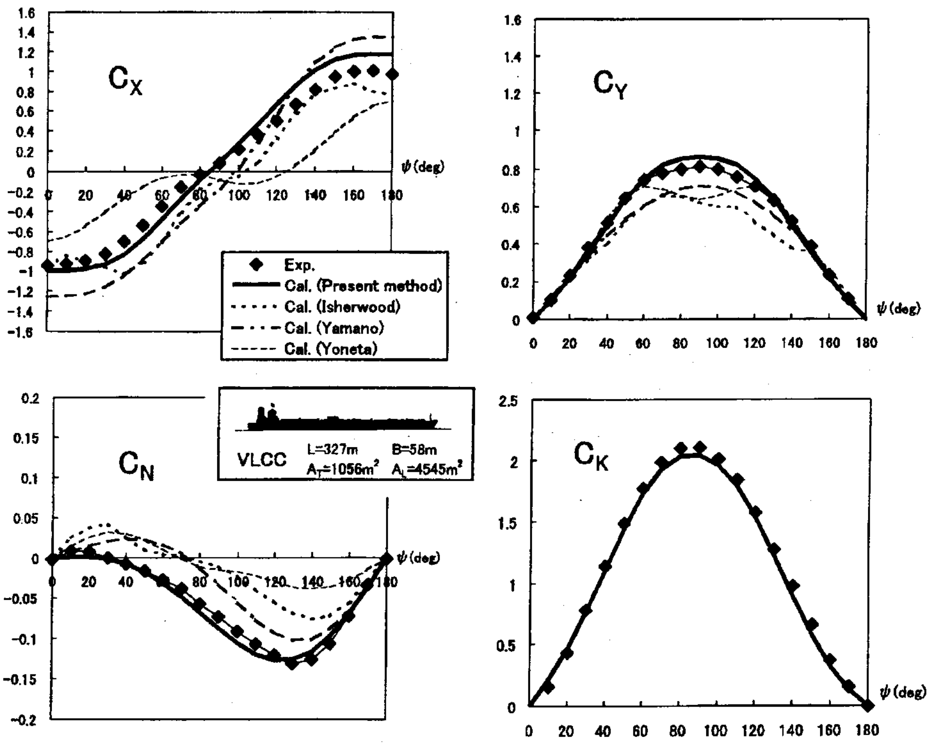


Figure 7 Comparison of experimental results of wind force and moment coefficients with predicted ones

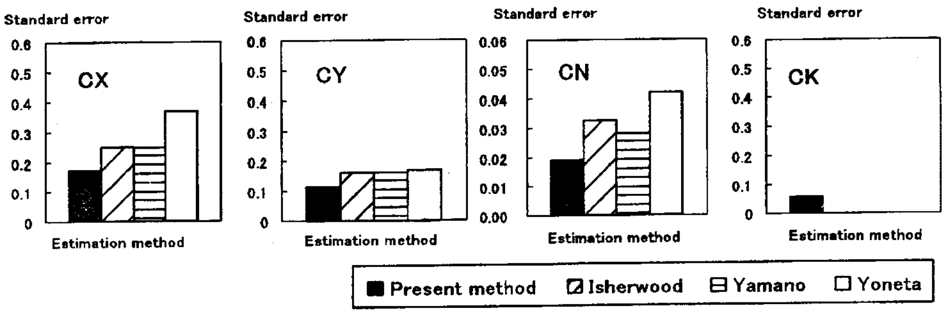


Figure 8 Average standard errors of wind force and moment coefficients for each estimation method

Table 4 Characteristics of estimation methods on wind loads

	Present method	Isherwood	Yamano	Yoneta
Parameters	9	8	5	6
Total number of coefficients on C_X,C_Y,C_N	66 96(including C_K)	219	36	21
Number of samples	68	49	38	68
Samples of experimental results	Tanker Cargo Ship Container Ship Passenger Ship Fishing Boat Research Vessel Tug Boat LNG Carrier PCC Naval Vessel Speed Boat	Tanker Cargo Ship Passenger Ship Fishing Boat Research Vessel Tug Boat Hydrofoil etc.	Tanker Cargo Ship Container Ship Passenger Ship	Tanker Cargo Ship Container Ship Passenger Ship Fishing Boat etc.

3 CONFIRMATION OF EFFECTIVENESS OF THE PRESENT METHOD

Experiments of two kind ships were carried out in wind tunnel of NMRI to confirm effectiveness of the present method. One is a bulk carrier ship that is 185m length, full load condition. The other is a training ship that is 117m length. Effect of boundary layer in experimental condition was modified under uniform flow by using equations (7)-(8).

The comparison the experimental results with calculation ones are shown in Figure 9. The calculation results on C_Y, C_N, C_K agree well with the experimental values. C_X is a little different between experimental results and calculation ones. Since C_X is affected from shape, arrangement of a bridge and equipment on the deck sensitively, these results show difficulty to estimate C_X exactly. It is thought, however, that this method has enough accuracy from the practical viewpoint.

4 CONCLUSIONS

The estimation method of wind forces and moments acting on ship was proposed by using the stepwise method in linear multiple regression analysis. A lot of wind tunnel experimental results of various ships built in recent years were collected as samples and the influence of wind profiles on the experimental results was corrected at the stage of making the equations of the estimation. The

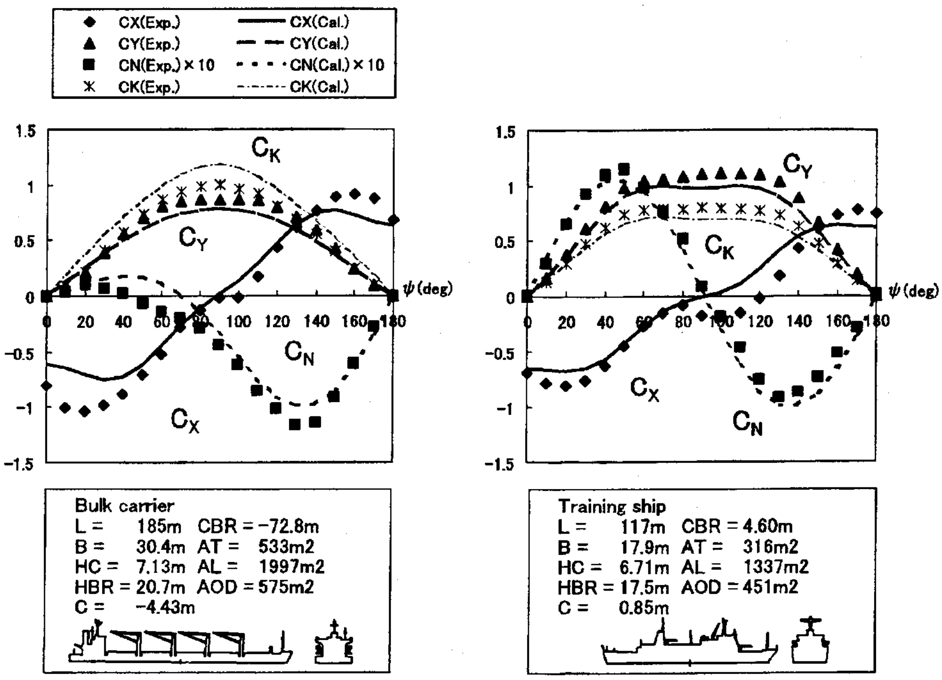


Figure 9 Comparison experimental results with calculation ones on a bulk carrier and a training ship

better independent variables and the regression coefficients in the equations were statistically decided by the stepwise method. As the results, this estimation method can get accuracy results compared with the past estimation methods.

In this paper, effectiveness of the present method is confirmed by using two kinds of different ships. The calculation results agree well with the experimental values. It is thought that this method is useful when manoeuvring performance would be evaluated under strong wind.

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