Wind Resistance of Merchant Ships

by R. M. Isherwood M.A.,* (Junior Member)

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SUMMARY: Previous published results of attempts to predict the wind resistance of merchant ships have been incomplete. The paper describes and gives the results of an analysis of wind resistance experiments carried out at several different test establishments on models covering a wide range of merchant ships. Equations are given for estimating the components of wind force and the wind-induced yawing moment on any merchant ship form for a wind from any direction. The equations are shown to apply to independent data.

SYMBOLS

A_L = Lateral projected area
A_T = Transverse projected area
A_{SS} = Lateral projected area of superstructure
B = Beam
C = Distance from bow of centroid of lateral projected area
C_N = Yawing moment coefficient
C_X = Fore and aft wind force coefficient
C_Y = Lateral wind force coefficient
F_X = Fore and aft component of wind force
F_Y = Lateral component of wind force
h = Height to top of superstructure
L_{OA} = Length overall
M = Number of distinct groups of masts or kingposts seen in lateral projection
N = Yawing moment
S = Length of perimeter of lateral projection of vessel excluding waterline and slender bodies such as masts and ventilators
V_R = Wind speed relative to ship
v_R = Relative wind speed at height z
z = Distance above sea surface
γ_R = Angle of relative wind off bow
ρ = Density of air

1. INTRODUCTION

A number of methods have been suggested for estimating the wind resistance of ships without recourse to direct model testing and those known to the author are described in Refs. 1 to 6. None of these methods covers the whole range of merchant ships and five are concerned only with the fore and aft component of wind force which, as Wagner (Ref. 7) has shown, may be only a small part of the total resistance due to wind. This report gives equations for estimating both fore and aft and lateral components of wind force and the moment of that force about amidships for any merchant ship form.

2. BASIC DATA

A search of the literature revealed the results of 107 tests of complete models of conventional merchant ships and, in addition, two tests of a hydrofoil boat, a number of tests on hulls without superstructures and some repeated tests on models with varying quantities of rigging and small fittings. For consistency only those data for single models of complete ships tested in nominally uniform flow in wind tunnels have been accepted for analysis.

A further 8 sets of model results had to be rejected due to lack of adequate drawings or photographs of the models, reducing the acceptable data to 49 sets given in Refs. 8 to 14.

3. ANALYSIS PROCEDURE

The experiment results were expressed in the form of coefficients as follows:

(i) Coefficient of fore and aft component of wind force

$$C_X = \frac{F_X}{\frac{1}{2}\rho V_R^2 A_T} \tag{1}$$

where F_X is the fore and aft component of wind force, considered positive when directed from bow to stern, ρ is the density of air, V_R is the relative wind speed and A_T is the transverse projected area of the model.

(ii) Coefficient of lateral component of wind force

$$C_Y = \frac{F_Y}{\frac{1}{2}\rho V_R^2 A_L} \tag{2}$$

where F_Y is the lateral component of wind force, considered positive when directed away from the wind, and A_L is the lateral projected area of the model.

(iii) Coefficient of wind-induced yawing moment

$$C_N = \frac{N}{\frac{1}{2}\rho V_R^2 A_L L_{OA}} \tag{3}$$

where N is the wind-induced yawing moment about amidships overall, considered positive when tending to turn the bow away from the wind, and L_{OA} is the overall length of the model.

Even in nominally uniform flow in a wind tunnel a residual boundary layer is always present and to take account of this the value of V_R^2 used in equations (1) to (3) was the mean square given by

$$V_R^2 = \frac{1}{h}\int_0^h v_R^2 dz \tag{4}$$

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* Vickers Limited Ship Model Experiment Tank, St. Albans.

where v_R is the relative wind speed at height z and h is the height to the top of the superstructure excluding masts and funnels. The values of V_R^2 calculated by equation (4) differed from the squares of the free stream wind speeds by up to 8%.

The data were analysed by multiple regression techniques using as independent variables functions of the following eight parameters:

L_{OA} = length overall

B = beam

A_L = lateral projected area

A_T = transverse projected area

A_{SS} = lateral projected area of superstructure

S = length of perimeter of lateral projection of model excluding waterline and slender bodies such as masts and ventilators

C = distance from bow of centroid of lateral projected area

M = number of distinct groups of masts or kingposts seen in lateral projection; kingposts close against the bridge front are not included.

The first four parameters were given by the original experimenters for all the models considered and the last four were measured from drawings or photographs by the present author.

It was found that the data were best fitted by equations of the following forms:—

(i) Fore and aft force coefficient

$$C_X = A_0 + A_1 \frac{2A_L}{L_{OA}^2} + A_2 \frac{2A_T}{B^2} + A_3 \frac{L_{OA}}{B} + A_4 \frac{S}{L_{OA}} + A_5 \frac{C}{L_{OA}} + A_6 M \tag{5}$$

(ii) Lateral force coefficient

$$C_Y = B_0 + B_1 \frac{2A_L}{L_{OA}^2} + B_2 \frac{2A_T}{B^2} + B_3 \frac{L_{OA}}{B} + B_4 \frac{S}{L_{OA}} + B_5 \frac{C}{L_{OA}} + B_6 \frac{A_{SS}}{A_L} \tag{6}$$

(iii) Yawing moment coefficient

$$C_N = C_0 + C_1 \frac{2A_L}{L_{OA}^2} + C_2 \frac{2A_T}{B^2} + C_3 \frac{L_{OA}}{B} + C_4 \frac{S}{L_{OA}} + C_5 \frac{C}{L_{OA}} \tag{7}$$

The constants A_0 to A_6, B_0 to B_6 and C_0 to C_5 are tabulated together with the residual standard errors in Tables I to III at $\gamma_R = 0°, 10° \ldots\ldots 180°$, where γ_R is the angle of the relative wind off the bow. The mean values of residual standard error shown by the regression equations for all values of γ_R are 0·10 for C_X, 0·04 for C_Y and 0·013 for C_N.

TABLE I. Fore and aft component of wind force

$$C_X = A_0 + A_1 \frac{2A_L}{L_{OA}^2} + A_2 \frac{2A_T}{B^2} + A_3 \frac{L_{OA}}{B} + A_4 \frac{S}{L_{OA}} + A_5 \frac{C}{L_{OA}} + A_6 M \pm 1{\cdot}96 \text{ S.E.}$$

γ_R°	A_0	A_1	A_2	A_3	A_4	A_5	A_6	S.E.
0	2·152	−5·00	0·243	−0·164	—	—	—	0·086
10	1·714	−3·33	0·145	−0·121	—	—	—	0·104
20	1·818	−3·97	0·211	−0·143	—	—	0·033	0·096
30	1·965	−4·81	0·243	−0·154	—	—	0·041	0·117
40	2·333	−5·99	0·247	−0·190	—	—	0·042	0·115
50	1·726	−6·54	0·189	−0·173	0·348	—	0·048	0·109
60	0·913	−4·68	—	−0·104	0·482	—	0·052	0·082
70	0·457	−2·88	—	−0·068	0·346	—	0·043	0·077
80	0·341	−0·91	—	−0·031	—	—	0·032	0·090
90	0·355	—	—	—	−0·247	—	0·018	0·094
100	0·601	—	—	—	−0·372	—	−0·020	0·096
110	0·651	1·29	—	—	−0·582	—	−0·031	0·090
120	0·564	2·54	—	—	−0·748	—	−0·024	0·100
130	−0·142	3·58	—	0·047	−0·700	—	−0·028	0·105
140	−0·677	3·64	—	0·069	−0·529	—	−0·032	0·123
150	−0·723	3·14	—	0·064	−0·475	—	−0·032	0·128
160	−2·148	2·56	—	0·081	—	1·27	−0·027	0·123
170	−2·707	3·97	−0·175	0·126	—	1·81	—	0·115
180	−2·529	3·76	−0·174	0·128	—	1·55	—	0·112
						Mean Standard Error		0·103

TABLE II. Lateral component of wind force

$$C_Y = B_0 + B_1 \frac{2A_L}{L_{OA}^2} + B_2 \frac{2A_T}{B^2} + B_3 \frac{L_{OA}}{B} + B_4 \frac{S}{L_{OA}} + B_5 \frac{C}{L_{OA}} + B_6 \frac{A_{SS}}{A_L} \pm 1{\cdot}96 \text{ S.E.}$$

γ_R°	B_0	B_1	B_2	B_3	B_4	B_5	B_6	S.E.
10	0·096	0·22	—	—	—	—	—	0·015
20	0·176	0·71	—	—	—	—	—	0·023
30	0·225	1·38	—	0·023	—	−0·29	—	0·030
40	0·329	1·82	—	0·043	—	−0·59	—	0·054
50	1·164	1·26	0·121	—	−0·242	−0·95	—	0·055
60	1·163	0·96	0·101	—	−0·177	−0·88	—	0·049
70	0·916	0·53	0·069	—	—	−0·65	—	0·047
80	0·844	0·55	0·082	—	—	−0·54	—	0·046
90	0·889	—	0·138	—	—	−0·66	—	0·051
100	0·799	—	0·155	—	—	−0·55	—	0·050
110	0·797	—	0·151	—	—	−0·55	—	0·049
120	0·996	—	0·184	—	−0·212	−0·66	0·34	0·047
130	1·014	—	0·191	—	−0·280	−0·69	0·44	0·051
140	0·784	—	0·166	—	−0·209	−0·53	0·38	0·060
150	0·536	—	0·176	−0·029	−0·163	—	0·27	0·055
160	0·251	—	0·106	−0·022	—	—	—	0·036
170	0·125	—	0·046	−0·012	—	—	—	0·022
						Mean Standard Error		0·044

TABLE III. Wind induced yawing moment

$$C_N = C_0 + C_1 \frac{2A_L}{L_{OA}^2} + C_2 \frac{2A_T}{B^2} + C_3 \frac{L_{OA}}{B} + C_4 \frac{S}{L_{OA}} + C_5 \frac{C}{L_{OA}} \pm 1{\cdot}96 \text{ S.E.}$$

γ_R°	C_0	C_1	C_2	C_3	C_4	C_5	S.E.
10	0·0596	0·061	—	—	—	−0·074	0·0048
20	0·1106	0·204	—	—	—	−0·170	0·0074
30	0·2258	0·245	—	—	—	−0·380	0·0105
40	0·2017	0·457	—	0·0067	—	−0·472	0·0137
50	0·1759	0·573	—	0·0118	—	−0·523	0·0149
60	0·1925	0·480	—	0·0115	—	−0·546	0·0133
70	0·2133	0·315	—	0·0081	—	−0·526	0·0125
80	0·1827	0·254	—	0·0053	—	−0·443	0·0123
90	0·2627	—	—	—	—	−0·508	0·0141
100	0·2102	—	−0·0195	—	0·0335	−0·492	0·0146
110	0·1567	—	−0·0258	—	0·0497	−0·457	0·0163
120	0·0801	—	−0·0311	—	0·0740	−0·396	0·0179
130	−0·0189	—	−0·0488	0·0101	0·1128	−0·420	0·0166
140	0·0256	—	−0·0422	0·0100	0·0889	−0·463	0·0162
150	0·0552	—	−0·0381	0·0109	0·0689	−0·476	0·0141
160	0·0881	—	−0·0306	0·0091	0·0366	−0·415	0·0105
170	0·0851	—	−0·0122	0·0025	—	−0·220	0·0057
					Mean Standard Error		0·0127

4. COMPARISON WITH PUBLISHED PREDICTORS

Fig. 1 compares measured values of C_X at $\gamma_R = 0°$ with values predicted from Refs. 1, 3, 5 and 6 and from equation (5). The data considered are those used in the derivation of the regression equations and the predictions have been made e-uniform flow where the method allows for the effects of velocity gradient. The method of Ref. 2 could not be use since information is required which was not available f most of the models; furthermore this method, provides

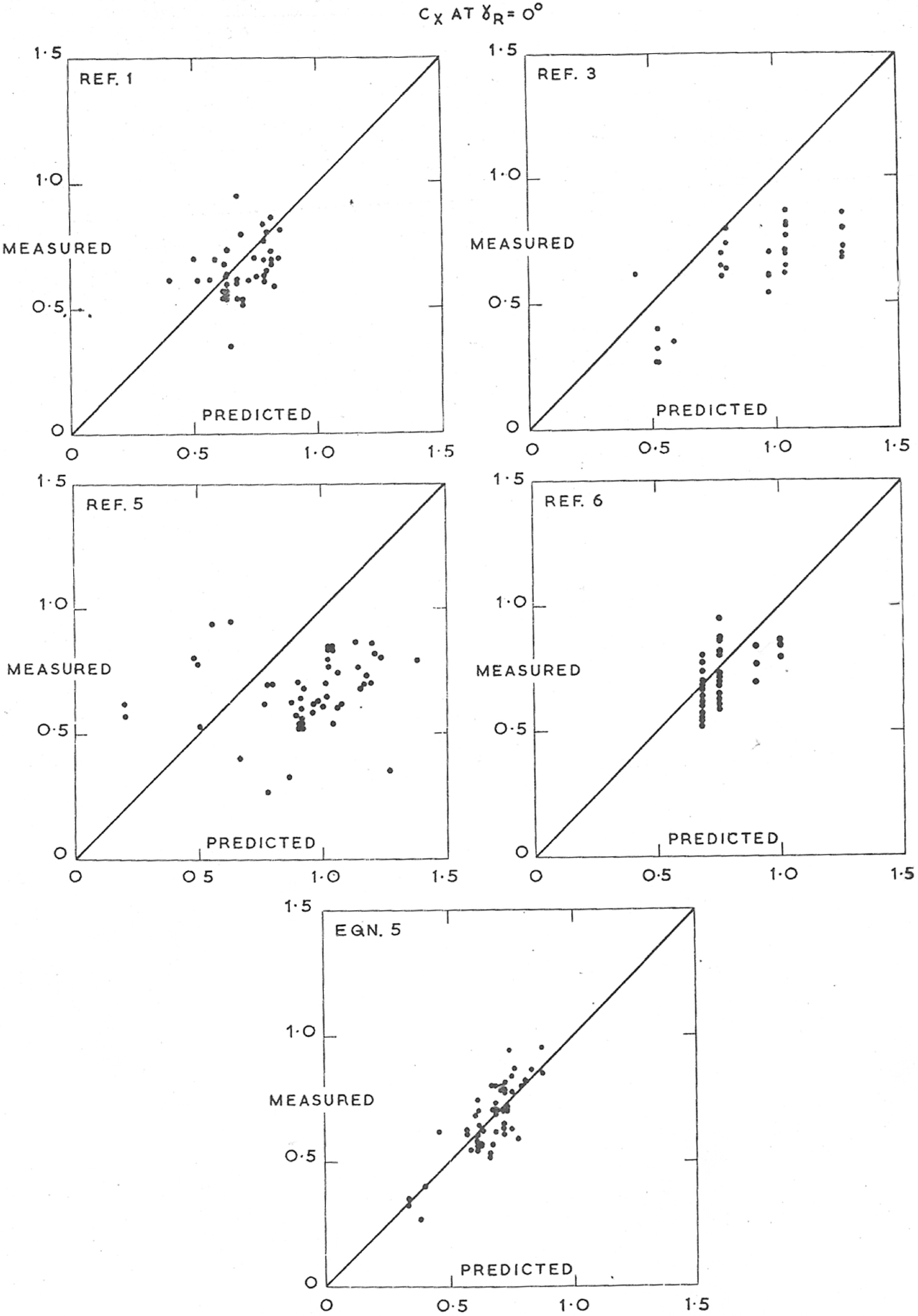

Fig 1. Comparison of measured wind forces with predictions by various methods for data used in analysis

dictions of C_X at $\gamma_R = 0°$ only and is therefore of little practical use. The method of Ref. 4 is substantially the same as that of Ref. 3 and may be expected to be of similar accuracy.

It is evident from Fig. 1 that the methods of Refs. 3 and 5 are very inaccurate and the method of Ref. 1 leads to appreciably greater scatter than Ref. 6 or equation (5). The method of Ref. 6 has the virtue of extreme simplicity but depends for its accuracy on the existence of sufficient model data to provide reliable average values. Ref. 6 gives predictions of C_X only for general cargo ships and tankers in load and ballast conditions; extension to C_Y and C_N for such vessels is simple but extension to other ship types is dependent on the availability of sufficient model data for each type of vessel to give a reliable mean. This condition is at present fulfilled only for passenger ships. The regression equations given in Section 3 are more complicated in use than the method of Ref. 6 but have the great advantage of applying to any merchant ship form having values of the independent variables within the ranges covered by the original data; these ranges are given in Table IV.

The equations are intended to provide estimates of the wind forces and moments on a ship for use in trials and voyage analysis where no wind tunnel results are available. Greatest accuracy may be expected when accurate values of the independent variables are used but in practice some of the necessary figures may not be readily available or an estimate may be required quickly with no time to measure areas, centroid of lateral area etc. Mean values of these parameters are therefore given in Table IV for the principal ship types and loading conditions found in the data analysed. The ship types are numbered in the Table as follows:—

1\. Passenger ships and ferries,

2\. Cargo ships with engines amidships, load,

3\. Cargo ships with engines amidships, ballast,

4\. Cargo ships with engines aft, load,

3\. Cargo ships with engines aft, ballast,

4\. Tankers and ore carriers with bridge amidships, load,

5\. Tankers and ore carriers with bridge amidships, ballast,

o. Tankers and ore carriers with bridge aft, load,

9\. Tankers and ore carriers with bridge aft, ballast,

10\. Stern trawlers,

11\. Tugs.

In view of their much wider applicability than the only alternative of comparable accuracy it is suggested that equations (5), (6) and (7) of the present paper be used for predictions of wind forces and moments, if necessary using mean values of independent variables from Table IV.

5. COMPARISON WITH INDEPENDENT MODEL DATA

A re-examination of the rejected model data showed that for five models, one run in two conditions of loading, sufficient material was available to allow approximate values of the independent variables to be obtained and these six sets of measurements were used to provide an independent check of the validity of the regression equations. The data were obtained from Refs. 15 and 16.

Fig. 2 shows measured force and moment coefficients plotted against predictions from equations (5), (6), and (7). With the exception of those spots marked with tails, which are for the factory trawler 'Tropik' (Ref. 15) the agreement between measurement and prediction is very close; the spots lie almost entirely within ± 1·96 times mean standard error from the 45° line as shown by the broken lines. Even the results for 'Tropik' do not show very large discrepancies except for C_X at γ_R greater than 90° (negative C_X values). The C_X measurements in this region reach much greater negative values than any recorded in the main data sample, −1·27 compared with a maximum negative value in the main sample of −0·98, which throws some doubt on the measured values for this model. It is therefore concluded that Fig. 2 gives no reason to doubt the general applicability of the predicting equations.

6. EFFECTS OF VELOCITY GRADIENTS

As was noted in Section 2 experiments carried out in velocity gradients appreciably different from uniform flow were not considered in the main analysis but the effects of a velocity gradient have been investigated and the results are presented in this section.

TABLE IV. Values of independent variables

Variable	$\frac{2A_L}{L_{OA}^2}$	$\frac{2A_T}{B^2}$	$\frac{L_{OA}}{B}$	$\frac{S}{L_{OA}}$	$\frac{C}{L_{OA}}$	$\frac{A_{SS}}{A_L}$	M
Maximum	0·246	2·32	9·75	1·97	0·619	0·595	7
Minimum	0·072	0·88	4·00	1·23	0·401	0·138	1
Mean	0·143	1·78	7·39	1·51	0·506	0·246	4
Ship type							
1	0·192	1·95	7·66	1·44	0·492	0·398	2
2	0·111	1·67	7·80	1·51	0·490	0·258	4
3	0·149	2·04	7·80	1·58	0·489	0·188	4
4	0·122	1·75	7·80	1·51	0·550	0·253	5
5	0·151	2·06	7·80	1·58	0·526	0·175	5
6	0·076	1·03	7·46	1·33	0·547	0·252	3
7	0·117	1·43	7·46	1·40	0·522	0·161	3
8	0·100	1·59	7·46	1·33	0·568	0·211	3
9	0·121	1·68	7·46	1·40	0·537	0·139	3
10	0·166	1·80	6·47	1·45	0·476	0·229	2
11	0·236	1·43	4·05	1·86	0·405	0·396	1

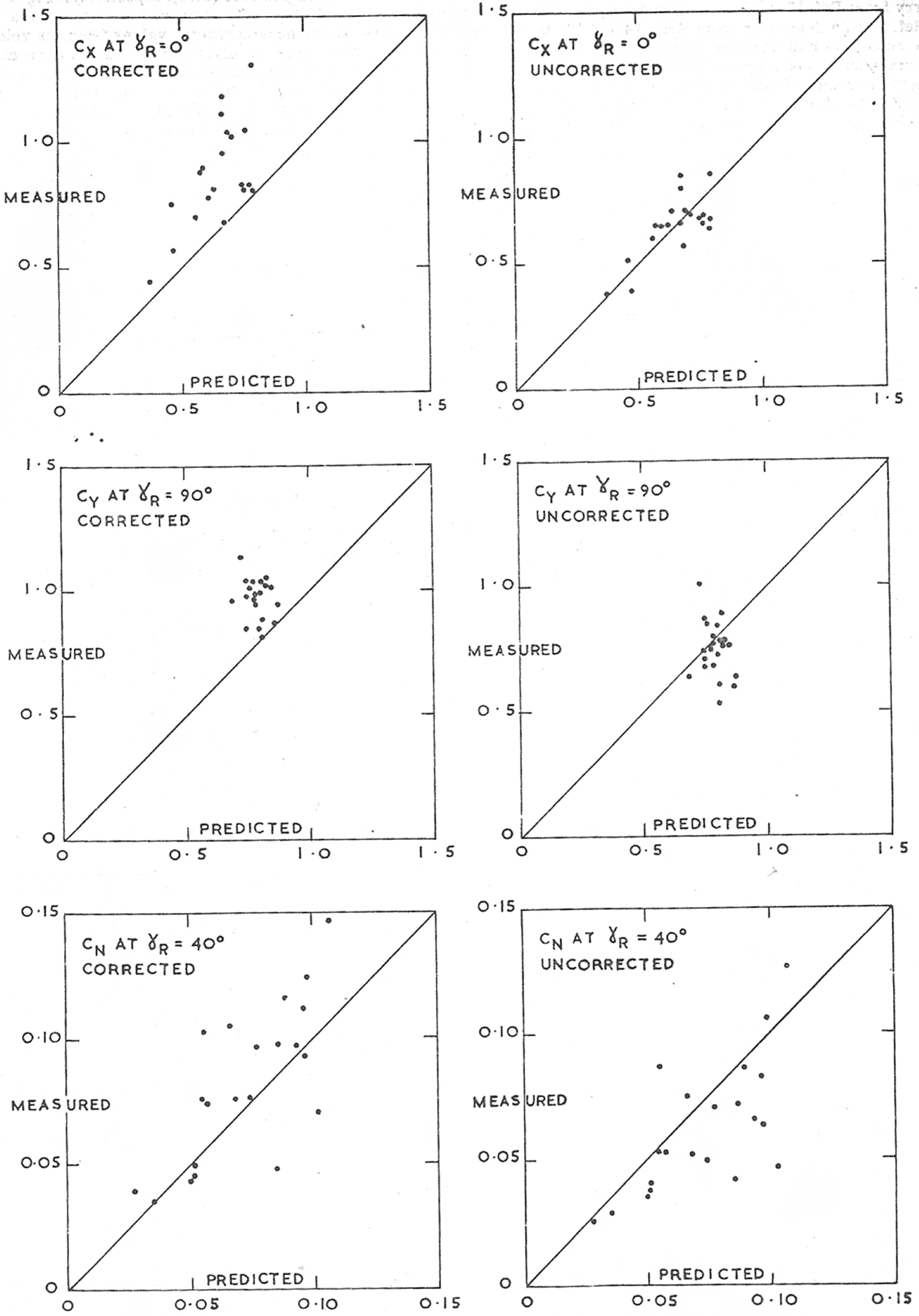

Fig 4. Comparison of measurements in velocity gradients with predictions from regression equations. Corrected coefficients based on mean square wind speed. Uncorrected coefficients based on free stream wind speed

A further comparison has been made between results for twenty two models run in velocity gradients only, for which adequate drawings were available, and predictions from equations (5), (6) and (7). The model results were obtained from Refs. 13, 18 and 19. The values predicted from the regression equations are for uniform flow and again measured values have been obtained based on a mean square wind speed from equation (4), referred to as corrected, and on the nominal free stream wind speed, referred to as uncorrected. Fig. 4 shows the measured values of C_X at $\gamma_R = 0°$, C_Y at $\gamma_R = 90°$ and C_N at $\gamma_R = 40°$ plotted against the predicted values; the γ_R values were selected merely to give large positive values of the coefficients. It is evident from Fig. 4 that the uncorrected measurements agree more closely with the predictions than the corrected values, implying that the use of a mean square wind speed calculated from equation (4) over-corrects for the effects of a velocity gradient. This is in direct contradiction to Fig. 3.

No final conclusion can therefore be reached on the effects of a velocity gradient and the question must remain open until sufficient new data have been published to allow a fuller investigation to be carried out. It is suggested that until this matter is fully investigated routine wind tunnel tests on ships models should be carried out in uniform flow to simplify comparison with existing data.

Similarly, it is not possible to say at present how model results obtained in uniform flow or predictions from equations (5), (6) and (7) should be applied to ships which are, in general, subject to velocity gradients. Fig. 3 implies that a mean square wind speed should be used while Fig. 4 suggests that a nominal free stream wind speed would give more accurate results. In light winds the two approaches lead to negligible differences in estimated total power but the differences may be important in strong winds, the use of a nominal wind speed leading to higher estimates of total power requirements. Until the difficulty is resolved it is suggested that a nominal wind speed be used for simplicity.

7. CONCLUSIONS AND RECOMMENDATIONS

(i) The equations and coefficients given in Tables I to III provide the best available means of estimating fore and aft and lateral components of wind force and wind-induced yawing moments for any merchant ship at any angle to the wind. Where measured values of any of the independent variables are not available appropriate mean values from Table IV may be used.

(ii) The correlation between tests in uniform flow and in velocity gradients is not clear and requires further investigation. For the time being it is recommended that routine wind tunnel tests on ship models be carried out in uniform flow conditions to simplify comparison with existing data.

(iii) The effect of a velocity gradient on ship wind resistance is at present unknown. For the time being it is recommended that wind forces and moments be obtained from the appropriate coefficients using the nominal wind speed; it should, however, be borne in mind that total power requirements in strong winds may be overestimated by this means.

8. ACKNOWLEDGEMENT

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WRITTEN DISCUSSION

Mr. J. W. English, B.Sc., Ph.D. (Fellow): The flow of air over ships in the heading range 0 to 180° is complicated as will be seen by reading accounts of flow observations such as those described in Ref. 3. It is questionable, therefore, if it is reasonable to put 49 sets of data from an unspecified number of ship types through a regression analysis and then expect to predict wind forces and moments for most ships. Until individual users have had time to correlate predictions using equations (5), (6) and (7) from this paper with methods they have used in the past it would seem premature to suggest that they should switch over.

Perhaps the author could clarify the information given in Fig. 1. For instance in each diagram which measured data have been included and are the predictions based on prediction methods which are independent of the measured data in each diagram? Has Ref. 3 been used to predict information for ship model tests not included in Ref. 3, and which measurements were used with equation (5)? In connection with this figure it should be pointed out that the flow conditions at $\gamma_R = 0°$ are fairly well behaved because the hull offers a streamlined shape, and comparisons at this single condition are not necessarily representative of the complete range.

In a paper dealing with resistance the author does not mention Reynolds number. This could imply that the data from different sources were obtained at about the same Rn. Perhaps the author would comment on this point.

Mr. H. L. Dove, M.B.E. (Fellow): The author has used data provided by earlier experimenters and has derived equations which, it is claimed, fit the data more satisfactorily than those used by these earlier authors and experimenters. This is a worthwhile achievement. Whilst it does not obviate the need to carry out further experiments, eg where the observations of wind currents around specific items such as bridge superstructures are required or of smoke trials from funnels are concerned, it does provide a means of assessing wind resistance during ships' speed trials, so that determination of the elusive $\Delta\delta C_t$ can be that much more accurately determined.

It would be wrong in this case to place too high a value on the accuracy required, eg the total wind resistance is unlikely to exceed 5% of the total trial resistance, so that even if the wind resistance error reaches 20%, the overall effect on the trial analysis will only be 1%.

With this in mind the writer is surprised at the author's statement that the method of Ref. 1 leads to appreciably greater scatter than that of Ref. 6 or of the author's equation (5), for if a 20% error line is drawn on Fig. 1 for Refs. 1 and 6 and equation (5), it will be seen that there is very little difference between the scatter of Ref. 1 and equation (5), and that the scatter of Ref. 6 is slightly less, merely because of the smaller number and range of the data used.

The writer, in Ref. 2, introduced the 'roughness' parameter to allow for the irregularities in the ships' profiles and this had the advantage of reducing the scatter. The author has used this parameter in the present paper.

The author gives deduced values for the constants of his equations in Tables I-III and for the mean values of the independent variables in Table IV. It is not clear why there are so many gaps in Tables I-III. Could the author explain please?

If we apply the mean values of Table IV to the constants, say for 30° in Table I, we find that

$$C_X = 1{\cdot}965 - 0{\cdot}688 + 0{\cdot}433 - 1{\cdot}138 + 0 + 0 + 0{\cdot}164 \pm 0{\cdot}229$$

ie it consists of large positive terms and large negative terms, which approximately balance, and finally C_X approximates to 0·965 or 0·507, hence the 'error' is a large part of the final answer, whichever is taken. The randomness of these terms both in magnitude and sign should indicate the care with which such equations should be applied.

Whilst the author has indicated that these equations and constants allow answers to be deduced, close to those measured, it should be pointed out that, in fact, the data can only apply over a range of ship parameters within the range of those used to compile the equations, and it would be a mistake to assume otherwise. This is, unfortunately, a fundamental feature of multiple regression analysis—it can be quite misleading.

Considering the effects of velocity gradients, the author has assumed a gradient given in his equation (4). Was any check made that this gradient did, in fact, apply? It would surely be an amazing fact that the boundary layer did just extend to the 'top of the superstructure' in each case tested. The implications of the author's remarks are that more accurate ship resistance would be obtained if the 'corrected' values were used. Does the author expect the boundary layer of the ship to be 'correspondingly' large? The fact that the velocity gradient 'corrections' do not appear to apply to Refs. 13, 18 and 19 may well be explained by the corrections already applied and did the author check this?

Mr. B. S. Bowden, B.Sc. (Member): Mr. Isherwood's paper seems to leave the estimation of wind resistance up in the air. It is all very well deriving regression equations to estimate wind resistance coefficients in uniform flow but, as Mr. Isherwood has noted in his paper, the natural wind over a ship has a velocity gradient. Mr. Isherwood states in his conclusions that the effect of a velocity gradient is at present unknown and he chooses to ignore it. However, as he also indicates in the paper, if the natural wind speed is high in relation to the ship speed, the wind resistance could be grossly over-estimated by assuming uniform flow conditions. White's method, as given in Ref. 4, is cursorily dismissed by the author in spite of the fact that the method recognises the effect of a wind velocity gradient and makes an allowance for it in estimating the ship wind resistance. We may not yet have a complete understanding of the effect of velocity gradients but there is considerable justification for making an allowance rather than adopting Mr. Isherwood's approach of completely neglecting the effect.

It would be appreciated if the author would expand his comments on the comparisons shown in Fig. 1. The lower diagram seems to be a comparison of C_X values determined from his regression equation with the measured values for the forty-nine sets of data used in the derivation of the equation. As I see it, this means that Mr. Isherwood has fitted a sample of data and then rejected the other four methods shown in Fig. 1 because they do not give such a good fit for his data. Surely the comparisons shown in Fig. 1 should be made for independent model data which had not been used in the derivation of the regression equations.

Mr. Isherwood may have given himself a head-start but his comments on Fig. 1 are still questionable. Refs. 3 and 5 give methods for predicting wind resistance as well as including resistance data which have been measured for various types of ships. Mr. Isherwood is not justified in stating that the methods given in these two references are very inaccurate, since he has undertaken an assessment of the data and not the methods. The data given in these references may be limited but there is no reason why the methods which they present should not be used in conjunction with data taken from other published sources. For example, resistance coefficients obtained from Mr. Isherwood's regression equations could be used with either Refs. 3 or 5.

The author states that the data of Ref. 1 lead to appreciably greater scatter than his equation (5). On the basis of the comparisons shown in Fig. 1 there seems to be little to choose between the data for Refs. 1 or 6 and equation (5).

In Figs. 3 and 4 the author attempts to reconcile the differences between resistance coefficients determined for uniform flow and for velocity gradients. The concept of using mean square wind speed has been suggested by several investigators, including Gould in Ref. 5. Mr. Isherwood confirms its usefulness in Fig. 3 on the basis of comparisons for measured values and yet rejects it when using coefficients estimated from his regression equations. In this context, probably more significance should be attached to the comparisons for the measured values rather than the predicted coefficients. For the data used in Fig. 3, it would be interesting to see comparisons of (a) the velocity gradient coefficients based on free-stream speed and the predicted uniform flow coefficients, (b) the velocity gradient coefficients based on mean-square speed and the predicted uniform flow coefficients, (c) the uniform flow coefficients as measured and as predicted.

Professor G. Aertssen (Fellow): It is gratifying that the model tests carried out in the wind tunnel of the von Karman

Institute for Fluid Dynamics could be of some use in establishing the components of wind forces and the wind induced yawing moment. The results of the tests published by A.T.M.A., Ref. 13, are compared with data obtained from Isherwood's equations. Moreover, since the distribution of the preprints of Isherwood's study some other data were issued by the von Karman Institute and published in the R.I.N.A. Transactions, Ref. 20, on the wind resistance of the containership DART EUROPE, the wind data of this ship are added for comparison in Table V. The model of the container ship, 218 m in length, was tested at 26 ft draft in three conditions of deck load: no containers, one layer and three layers of containers. The transverse projected area is 740, 744 and 760 m^2 and the lateral projected area 3080, 3375 and 3700 m^2 respectively for the three deck load conditions.

It must be said that the von Karman Institute's data in uniform flow were obtained without correction for the residual boundary layer of the wind tunnel, i.e. the forces and moments are divided by the nominal air velocity squared and not by a corrected V_R^2 as obtained from equation (4). This means that these data are perhaps 10% low due to neglecting this boundary layer correction. Using Isherwood's equations the wind resistance components are calculated for the five merchant ships, subtracted from the model data and the differences are given as percentages of the model data in Table V. The comparison is restricted to three wind directions 0°, 30° and 180° off bow for the fore and aft component, to three directions 60°, 90° and 120° off bow for the lateral component, and to two directions 40° and 140° off bow for the yawing moment. Mean values are given, on the one hand for each ship the mean value for all components and all headings, on the other hand the mean value for all ships together but for one component and one heading. The total mean percentage is 2.

REFERENCE

20. Aertssen, G. and van Sluys, M. F.: 'Service Performance and Seakeeping Trials on a Large Container Ship. RINA Journal, October, 1972, p. 433.

Dr. Nils H. Norrbin (Member): This paper is welcomed by all of us who are involved in the prediction of ship speed and motion in winds. The results tend to verify that a set of inhomogeneous force and moment scale model data collected from different publications lends itself to a consistent regression analysis. In recent years a large number of ship problems have been handled with the attractive technique of stepwise regression, with which, however, a mathematical model is too often derived in ignorance of simple physical relations.

The forces on a ship's hull and superstructure in a unit relative wind depend on a matrix of geometry and orientation. The author has chosen to base each set of his regression equations on measurements (and interpolations?) for a certain angle γ_R and so to derive a number of unrelated models for the geometry dependence. In an application, where the ship turns through the wind, the computer has to make a continuous interpolation for the values of seven coefficients. The writer will confine a limited analysis—and, hopefully, some constructive criticism—to the presentation of lateral force and moment at angles between 0° and 90° off the bow.

From the obvious analogy between the naked hull (with freeboard F) and a well-behaved slender body we expect a contribution to C_Y as given by

$$k_0 C_D \sin^2\gamma_R + k_1 \frac{F}{L} \sin 2\gamma_R \qquad (8)$$

which suggests that these are essentially the first two terms of the author's equation (6). (For $\gamma_R = 30°$ these two terms contribute some 98% of the total lateral force.) In Fig. 5 the writer has plotted B_0 as a function of $\sin^2\gamma_R$ and B_1 as a function of $\sin 2\gamma_R$. The deviations from the straight sloping lines consistent with the analogy are locally violent but moderate in the mean. (The most marked breaks are associated with the introduction of additional terms in the model for the neighbouring angle.) The writer believes that the trigonometric dependence could be adopted as a matrix restraint in the regression analysis simultaneously applied to the total set of data; certain functions can be formulated to simulate the fore-and-aft asymmetry, whereas some of the remaining terms can be looked upon as corrections to the basic B_0 and B_1 relations.

Yet another constraint would serve to define a progressive shift of centre of pressure with angle of attack. From Tables II and III the force contribution proportional to $2A_L/L_{0A}^2$ acts at a distance C_1/B_1 forward of amidships, which distance varies here in an unpredictable manner.

It is hard to see how the distance from the bow to the centroid of lateral projected area can affect the lateral force in the way it appears from the B_5-term of the regression analysis. On the other hand, the distance as measured from amidships will certainly have an important bearing on the moment about amidships.

AUTHOR'S REPLY

Dr. English's first paragraph contains two fallacies. First, the fact that a problem is complex is no reason for rejecting regression analysis and, secondly, the test of a predictor is correlation with measured data, not with results from other, possibly erroneous, predictors. Fig. 1 indicates that a comparison of predictions from the regression equations

TABLE V Per cent difference on model results of the data obtained from Isherwood's equations

	Fore and aft deg off bow			Lateral deg off bow			Yawing moment deg off bow		Mean
Ship's Name	0	30	180	60	90	120	40	140	
LUKUGA I	–21	–10	–23	–12	–15	–15	– 7	+ 5	–12
LUKUGA II	–12	– 9	–22	–18	–26	–19	– 7	+11	–13
JORDAENS I	–20	–10	–18	0	+ 3	+ 5	+13	+18	– 1
JORDAENS II	–13	–13	–16	+ 2	0	+ 1	+10	+27	0
CAR-FERRY	–25	–18	–29	– 6	+ 4	+ 4	+10	– 5	– 8
FRUIT CARRIER	–14	– 9	–	+14	+ 6	–	– 3	–	– 1
DART EUROPE I	+12	+36	+12	+32	+27	+38	+37	+ 7	+25
DART EUROPE II	+25	+37	+ 2	+10	– 1	+22	+ 8	+ 2	+13
DART EUROPE III	+27	+41	+ 9	+ 8	– 2	+14	+15	+ 4	+14
Mean	– 5	+ 5	–10	+ 3	0	+ 6	+ 8	+ 9	2 \ 2

LUKUGA I = light load
LUKUGA II = heavy load
JORDAENS I = light load
JORDAENS II = heavy load

DART EUROPE I = no containers on deck
DART EUROPE II = one layer of containers
DART EUROPE III = three layers of containers

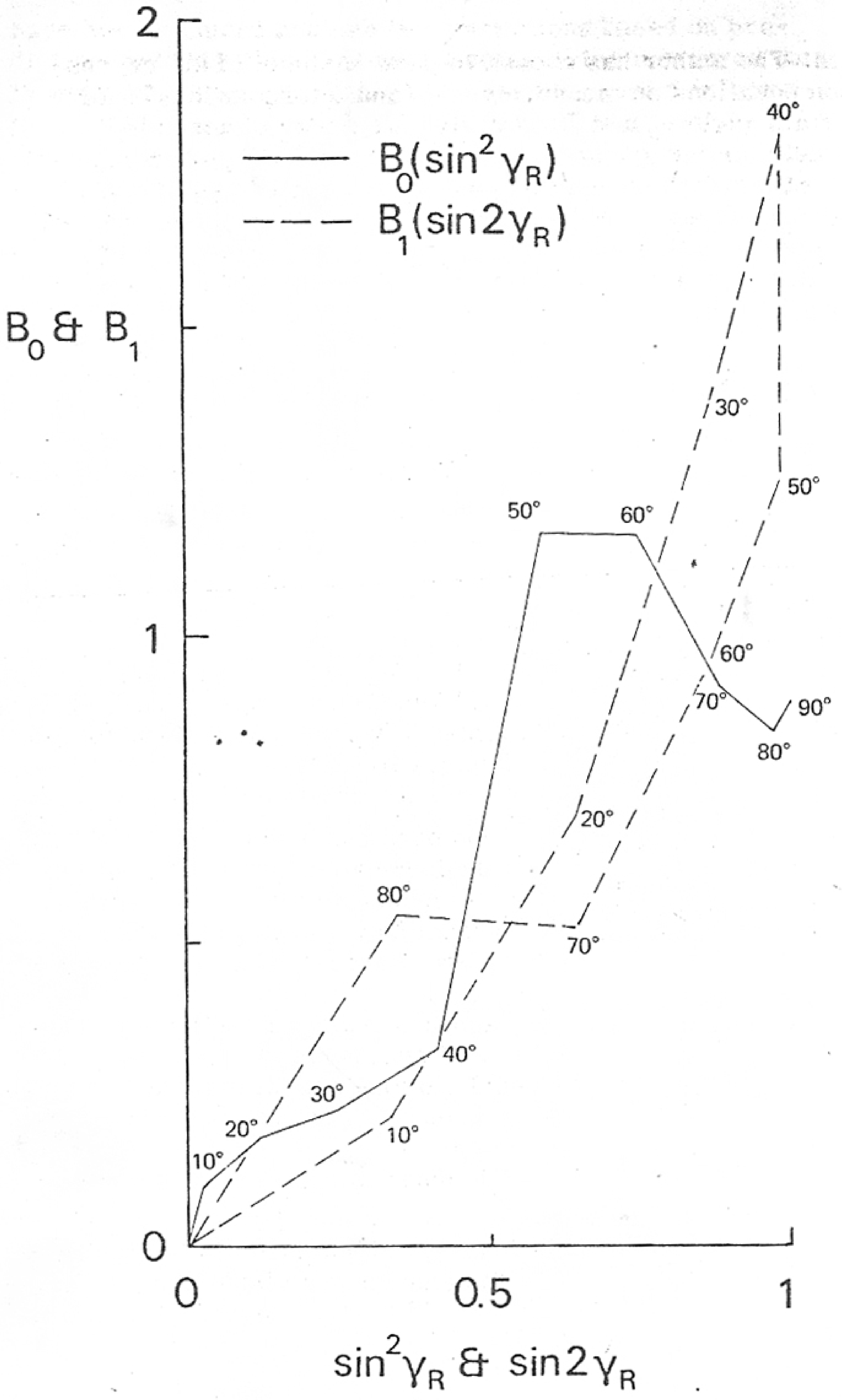

Fig. 5. Testing of results from lateral force regression analysis

with predictions from other available methods could be highly misleading to someone of Dr. English's persuasion.

Dr. English asks which measured data have been included in the diagrams in Fig. 1. In each case predictions were made for those models to which the method under consideration applied. Ref. 1 gives a curve of C_X against A_L/L_{OA}^2 for A_L/L_{OA}^2 in the range 0·04 to 0·09 ($0{\cdot}08 \leqslant 2A_L/L_{OA}^2 \leqslant 0{\cdot}18$) and models in this range only were considered. For Ref. 3, models similar in general appearance to those in the report were used. Ref. 5 gives a straight line relationship between C_X and $2A_L/L_{OA}^2$ at $\gamma_R = 0°$ and this line was used to predict for all the data. Ref. 6 is restricted to general cargo ships and tankers and that restriction was observed. These selections were made to ensure fairness of comparison between the five parts of Fig. 1. General insertion of all the data plotted in the 'Equation (5)' plot would clearly have been unfair.

The model data used in deriving the regression equations were all obtained at Reynolds numbers in the range 2 to 5 million. This was not mentioned in the paper because ship shapes above water are sufficiently irregular for no R_n scale effect to be anticipated.

I agree with Mr. Dove that it is not necessary to strive after great accuracy in estimating wind forces but when an improvement is available it would seem perverse not to accept it. In fact the standard error of the estimates from Ref. 1 plotted in Fig. 1 is about 60% greater than the corresponding standard error for equation (5).

The gaps in Tables I to III correspond to terms in the regression equations which were found not to be statistically significant. In such cases one is faced with the alternatives of leaving the terms in and stating that they are not significant or repeating the regression with non-significant terms omitted. I chose the latter course to reduce the labour of calculating wind forces.

Mr. Dove's examination of equation (5) for $\gamma_R = 30°$ is dangerously superficial. A better insight into the meaning of the equations can be obtained by considering the variation in forces and moments represented by changing each independent variable from the maximum to the minimum value given at the head of Table IV. Such an examination will show the relative importance of each term in the equations.

Mr. Dove is also helping to perpetuate a piece of statistical nonsense. Regression equations can, and often do, apply outside the ranges of data used to derive them. That they do not is not a 'fundamental feature of multiple regression analysis'.

Mr. Dove appears to have misunderstood equation (4). The equation involves no assumptions as to velocity gradient or thickness of boundary layer; it is merely a mathematical statement that the value of V_R^2 used in equations (1) and (3) was the mean square evaluated over the (arbitrary) height, h. The height, h, was defined as in the paper because it seemed both reasonable and conducive to simplicity to do so.

Mr. Bowden's chief complaints appear to be that I have not recommended a way of allowing for wind velocity gradient and that I claim that equations (5), (6) and (7) provide a better and more complete method of predicting wind forces and moments than other available methods. On the first point, having found the evidence inconclusive I prefer to admit my ignorance and adopt the simpler and more cautious course. I have no desire to be dogmatic, however, and Mr. Bowden, and any others who share his view, are entirely free to allow for wind gradients as they choose. On the second point, Mr. Bowden offers no evidence such as to persuade me to amend my claim, and, I must admit, the logic of much of what he has written escapes me.

Professor Aertssen's contribution is interesting but calls for little comment. Some of the individual comparisons he presents show larger discrepancies than one would like but all those for which measured data have been published lie within the range ± 1·96 times standard error. The percentage errors are large because the absolute values of the coefficients are small.

Dr. Norrbin's approach is an interesting one and his Fig. 5 is prima facie evidence that such an approach is applicable. However a different mathematical model would be required for C_Y for γ_R in the range 90° to 180° where no term in $2A_L/L_{OA}^2$ is present in the regression equations. There may also be difficulties in extending the approach to C_X and C_N where the data are much more scattered. Nevertheless Dr. Norrbin's suggestion should be considered in any future analysis.

In his second paragraph, Dr. Norrbin implies that for γ_R values between those for which coefficients are given, the computer program he uses interpolates for the values of the coefficients in the regression equations and uses these to calculate the forces and moments. I suggest it would be preferable to calculate values of C_X, C_Y and C_N at $\gamma_R = 0°$, 10°, 20° and so on as a first step and interpolate for values at other γ_R as required. On the other hand, since wind direction is always subject to short term fluctuations, it is debatable whether it is worth interpolating at all.

It is perhaps not sufficiently emphasised in the paper that the claims of the regression equations to general use are based on two main grounds. Not only do they provide more accurate estimates of wind forces than other available methods but they are more widely applicable both in the range of ships to which they apply and in the fact that they provide estimates of two forces and one moment compared with the single force given by most other methods. The second point appears to have escaped the notice of some discussers.

It remains for me to thank the contributors for a stimulating discussion.