THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

RESULTS OF A SERIES OF TESTS WITH A WHOLLY AND PARTIALLY ROUGHENED SHIP MODEL

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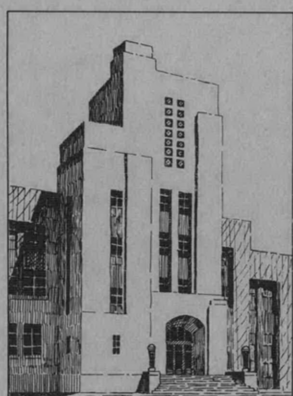

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RESULTS OF A SERIES OF TESTS WITH A WHOLLY AND PARTIALLY ROUGHENED SHIP MODEL

(ERGEBNISSE AUS EINER VERSUCHSREIHE, AUSGEFÜHRT MIT EINEM GANZ UND TEILWEISE RAUH GEMACHTEN SCHIFFSMODELL)

by

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1. INTRODUCTION

In connection with an investigation* carried out by the author of this article to determine the relationship between wake and thrust deduction, a ship model of the single screw freight and passenger vessel SIMON BOLIVAR, whose principal dimensions are given in Table 1, was wholly and partially roughened. Several tests were carried out with this model, and the results of the resistance tests are discussed in the following.

TABLE 1

Dimensions of Ship and Model

		Ship	Model
Length between perpendiculars	L_{bp}	128.013 m	6.0959 m
Length at water line	L_{wl}	128.587 m	6.1232 m
Moulded beam	B	17.832 m	0.8539 m
Draught	T	7.315 m	0.3483 m
Moulded displacement	V	11,906.25 m^3	1.2856 m^3
Wetted surface (including rudder and rudder pintles)	O	3,236.9 m^2	7.3399 m^2
Midship section coefficient	β	0.9745	
Block coefficient	δ	0.7061	
Prismatic coefficient	ϕ	0.7245	
Water line coefficient	α	0.8161	

The roughening was effected by means of sifted sand applied to the model over a coat of paint.

In consecutive order the model was roughened over its entire surface (Condition A_2), then over 20.5 per cent of its length from the after perpendicular (Condition A_3) and finally over 20.5 per cent of its length from the forward perdendicular (Condition D_1).

Since it was originally intended only to cause a change in the frictional wake, no effort was made to grade the sand as to uniformity of grain or to apply it at any particular density.

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* From Report No. 32 of the Netherlands Model Basin at Wageningen, "Analyse der Vortstuwingscomponenten in Verband met het Schaaleffect bij Scheepsmodelproeven " (Analysis of Propulsion Components in Relation to Scale Effect by means of Model Tests), EMB Translation 68.

The results of the resistance tests, which are given in Table 2, are worthy of note. They show that the increase in resistance due to the roughening of the forward body and the increase due to roughening the after body, contrary to expectations, are nearly equal.

TABLE 2

Model Resistances for Various Roughnesses of the BOLIVAR Model at a Corresponding Ship Speed of 13.5 Knots

Condition	1	2	3	4	5
	Temperature of Water degrees C	W_o kg (obs.)	W_r kg (Froude)	W_r kg (Schlichting)	Increase in W_r per cent (Schlichting)
A (smooth overall)	16.9	3.444*	2.590	2.630	
	11.0	3.506	2.657	2.692	
	10.5	3.511	2.662	2.697	
	13.2	3.477	2.632	2.663	
A_2 (rough overall)	11.0	5.690*		4.876	81.2
A_3 (rough aft)	10.5	3.900*		3.086	14.4
D_1 (rough forward)	13.2	3.915*		3.101	16.4

* W_o in Column 2 are the total resistances obtained from the model tests. The first four values in Column 4 are the frictional resistances of the smooth model calculated by Schlichting's formula. The remaining values in this column are the frictional resistances calculated by subtracting the residuary resistance (0.814 kg) of the smooth model from the corresponding W_o values in Column 1. The values in Column 5 express the increase in frictional resistance due to roughness at the temperatures given.

The purpose of the thoughts here developed is to explain this phenomenon by means of the theories given by Schlichting* on the resistance of wholly rough and partially rough plates. In the accompanying paragraphs the various tests are therefore analyzed in detail.

2. APPLICATION OF SCHLICHTING'S METHOD FOR CALCULATING THE RESISTANCE OF A PLATE WITH VARIOUS ROUGHNESSES

The formulas set up by Schlichting, based on roughness tests carried out at Göttingen, are used here. His formula for the total resistance coefficient of a technically smooth plate is

$$\zeta_r = 0.455\ (\log R)^{-2.58} \qquad (10^6 \leqq R \leqq 10^9)$$

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* "Experimentelle Untersuchungen zum Rauhigkeitsproblem" (Experimental Studies on the Roughness Problem), by H. Schlichting, Ingenieur Archiv, vol. VII, No. 1, Feb. 1936.

and for a plate roughened with sand

$$\zeta_r = \left(1.89 + 1.62 \log \frac{l}{k_s}\right)^{-2.5} \qquad \left(2 \cdot 10^2 \leqq \frac{l}{k_s} \leqq 10^6\right)$$

where l is the length of the plate in the direction of motion and k_s is the size (diameter) of the grains of sand.

According to Amtsberg* the form effect (curvature of the surface of the ship) on frictional resistance is slight. However, the increase in frictional resistance on a curved surface as a result of thinning of the boundary layer in moderately full ships, is balanced by the decrease in frictional resistance resulting from the separation of eddies on the afterbody.

The formulas given above, derived from plate tests, may thus prove useful for ship hulls.

Schlichting also gives a method of calculating the resistance of a plate with various degrees of roughness. This method has been applied in analyzing the partially roughened model (Conditions D_1 and A_3).

In this method, a plate of the length l_1' and roughness k_{s_2}, corresponding to the roughness of the after portion of the basic plate (in this case the model), is substituted for the plate or model having a length l_1 and a roughness k_{s_1}. The length l_1' is taken so that the momentum loss in the boundary layer of the forward portion will not change. When the width of the plate b, corresponding to the girth of the model, is constant,

$$W_1 = \rho\, v^2 k_{s_1} b \cdot F(z_1) = \rho \cdot v^2 k_{s_2} b\, F(z_1')$$

where $G(z_1) = \dfrac{l_1}{k_{s_1}}$ and $G(z_1') = \dfrac{l_1'}{k_{s_2}}$

The resistance is given in the form of a parameter (Parameter z).

The relation between $l/k_s = G(z)$ and $F(z)$ can be determined by means of a chart given by Schlichting.

l_1' can now be calculated, since $F(z_1') = k_{s_1}/k_{s_2} \cdot F(z_1)$ and $G(z_1') = l_1'/k_{s_2}$.

The resistance of the second part of the plate with a length l_2 will be

$$W_2 = \rho\, v^2 k_{s_2} b \left[F(z_2) - F(z_1')\right]$$

where $F(z_2)$ is determined by the relation with $G(z_2) = \dfrac{l_1' + l_2}{k_{s_2}}$

The resistance of the whole plate is

$$W = W_1 + W_2 = \rho\, v^2 b\, k_{s_2} F(z_2)$$

The specific frictional resistance ζ_r is

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* "Untersuchungen über die Formabhängigkeit des Reibungswiderstandes " (Investigations of the Dependence of Frictional Resistance on Form), by H. Amtsberg, Jahrbuch der Schiffbautechnischen Gesellschaft, vol. 38, 1937, EMB Translation forthcoming.

$$\frac{W}{\frac{1}{2}\rho v^2 O} = 2\,\frac{k_{s_2}\cdot F(z_2)}{l_1+l_2}$$

This formula will be valid only when the width of the plate is constant. Approximate allowance can be made for the variable width by correcting the calculated resistances W_1 and W_2 in proportion to the mean girths. Herein it is assumed that $F(z)$, or $G(z) = l/k_s$ depends only on the length of the surface. When the width of the surface is variable, this assumption generally is not correct. However, in order to make allowance for the effect of the width on the roughness coefficient l/k_s, the velocity distribution over the surface would have to be known.

Correcting W for the mean girth of the two parts of the surface, we have

$$W = \rho v^2 k_{s_1} b_1 F(z_1) + \rho v^2 k_{s_2}\left[F(z_2) - F(z_1')\right]$$

wherefor

$$\zeta_r = \frac{2}{l_1+l_2}\left[k_{s_1}\frac{b_1}{b}\cdot F(z_1) + k_{s_2}\cdot\frac{b_2}{b}\left[F(z_2)-F(z_1')\right]\right]$$

$$= \frac{2k_{s_2}}{l_1+l_2}\left[\frac{b_2}{b}\cdot F(z_2) - \frac{b_2-b_1}{b}F(z_1')\right]$$

3. MODEL ROUGHENED OVER ITS ENTIRE LENGTH (CONDITION A_2)

Sand with grains of various degrees of fineness was used to roughen the models. It was put through sieves with various sizes of mesh, thus determining the arithmetical average size of grain. The mixture was as follows:

25.6 per cent consisted of grains of 1.32 to 0.78 mm diameter
mean = 1.05 mm (0.041 inch)

71.8 per cent consisted of grains of 0.78 to 0.42 mm diameter
mean = 0.60 mm (0.024 inch)

2.6 per cent consisted of grains of less than 0.42 mm diameter
mean = 0.21 mm (0.008 inch).

The average size of the grains was thus found to be 0.70 mm; they were spread with a density of 140 per square centimeter (900 per square inch).

The roughness thus produced is not directly comparable with that established by Nikuradse in Göttingen. The roughening produced by Nikuradse in the water tunnel was accomplished by applying a layer of sand over a coat of paint and another coat of paint over the sand. The method used on the model under discussion was not the same. In this case, the sand was merely applied over a coat of paint without covering it by another coat. Consequently it is to be expected that the roughness effect will be greater than would follow from the Göttingen roughness values using sand of the same size grains.

Moreover, the size of the grains differs also; the roughness of the larger grains is relatively greater than that of the smaller ones, so that the average roughness also is greater than 0.70 mm.

This is actually evident from the results of the resistance tests with the smooth model (A) and with the wholly roughened model (A_2).

Taking k_s = 0.70 we find by Schlichting's formula

$$\zeta_r = \left(1.89 + 1.62 \log \frac{l}{k_s}\right)^{-2.5} = 5.080 \cdot 10^{-3}$$

wherein

$$\frac{l}{k_s} = \frac{6.096}{7 \cdot 10^{-4}} = 0.871 \cdot 10^4$$

For the smooth model we find, at the temperature for Condition A_2 (11 degrees Centigrade),

$$\zeta_r = 0.455 (\log R)^{-2.58} = 0.455 \log \left(\frac{1.515 \cdot 6.096}{1.272 \cdot 10^{-6}}\right)^{-2.58} = 3.164 \cdot 10^{-3}$$

The increase in frictional,resistance thus obtained amounts to only 60.5 per cent, while the measured increase was 81.2 per cent (see Table 2).

In order to obtain an increase of 81.2 per cent in resistance, it will be necessary to assume the size of the grains as k_s = 1.22 mm. This size of grain was adhered to in calculating the increase in frictional resistance for the partially roughened model.

TABLE 3

Distribution of the Frictional Resistance over the Surface

Portion of Length being Investigated x	$\frac{x}{l}$	Specific Frictional Resistance $\zeta_r(x)$	$\frac{W_x}{W}$		$\frac{O_x}{O}$		$\frac{W'_x}{W}$	
Forward 1	0.1	10.18×10^{-3}	0.1777	0.2946	0.0589	0.1484	0.1046	0.2187
2	0.2	8.44	0.1169		0.0895		0.1141	
3	0.3	7.62	0.1043	0.2004	0.1106	0.2317	0.1259	0.2513
4	0.4	7.092	0.0961		0.1211		0.1254	
5	0.5	6.72	0.0912	0.1791	0.1221	0.2442	0.1190	0.2310
6	0.6	6.44	0.0879		0.1221		0.1120	
7	0.7	6.21	0.0842	0.1667	0.1200	0.2300	0.1050	0.1970
8	0.8	6.025	0.0825		0.1100		0.0920	
9	0.9	5.87	0.0807	0.1590	0.0858	0.1457	0.0650	0.1020
Aft 10	1.0	5.732	0.0783		0.0599		0.0370	

In Table 3 the distribution of the frictional resistance over the length of the model for uniform and non-uniform distribution of the surface is given. When the surface is uniformly distributed over the length we have

$$\frac{W_x}{W} = \frac{\frac{x}{10}\cdot\zeta_r(x) - \frac{x-1}{10}\zeta_r(x-1)}{\zeta_r}$$

When the surface is not uniformly distributed, we have

$$\frac{W_x'}{W} = \frac{(O_x + O_{x-1} + \cdots)\,\zeta_r(x)\quad(O_{x-1} + O_{x-2} + \cdots)\,\zeta_r(x-1)}{O\cdot\zeta_r}$$

It follows from Table 3 that with uniform distribution of the roughness over 20 per cent of the length from the forward perpendicular the resistance is about 12 per cent of the total frictional resistance higher than when the model is roughened over 20 per cent of its length from the after perpendicular, since the distribution of the surface is also taken into account. Without this correction, this percentage will be 14 per cent.

It is not permissible, however, to conclude from these data that a given increase in roughness of the afterbody will lead to a much smaller increase in resistance than the same increase in roughness of the forebody. When various degrees of roughness exist in the case of a model or a ship, conditions will be entirely different. This will be investigated in greater detail by means of tests of the partially roughened model.

4. MODEL ROUGHENED OVER 20.5 PER CENT OF ITS LENGTH FROM THE FORWARD PERPENDICULAR (CONDITION D_1)

In order to permit determining the resistance of the partially roughened model, the smooth portion of the model was also regarded as roughened surface. The roughness coefficient of the smooth model at a temperature coinciding with that for Condition D_1 amounts to 3.130×10^{-3}. The corresponding roughness k_s will be 0.0567 mm.

The ratio of the average width b_1 of the surface over 20.5 per cent of the length of the model l_1 to the mean width b of the whole surface is $b_1/b = 0.749$.

For the remaining portion of the length l_2 this ratio is $b_2/b = 1.065$.

However, for the calculation of $F(z')$, the width is assumed to be constant and equal to b (see Section 1).

Then we have

$$k_{s_1} = 1.22\,\text{mm} \qquad k_{s_2} = 0.0567\,\text{mm}$$

$$l_1 = 1.25\,\text{m} \qquad l_2 = 4.846\,\text{m}$$

$$G(z_1) = \frac{l_1}{k_{s_1}} = 1.025\cdot 10^3 \text{ gives } \quad F(z_1) = 4.32$$

$$F(z_1') = \frac{k_{s_1}}{k_{s_2}}\cdot F(z_1) = 92.95 \qquad G(z_1') = 5.24\cdot 10^4 \qquad l_1' = 2.96\,\text{m}$$

$$G(z_2) = \frac{l_1' + l_2}{k_{s_2}} = 1.377\cdot 10^5 \qquad F(z_2) = 207$$

When the surface is uniformly distributed we will have

$$\zeta_r\,(l_1 + l_2) = 2 \cdot \frac{k_{s_2} \cdot F(z_2)}{l_1 + l_2} = 3.85 \cdot 10^{-3}$$

$$\zeta_r \text{ smooth} = 3.13 \cdot 10^{-3}$$

The increase in resistance thus will be 23 per cent, while measurement gave 16.4 per cent.

Considering non-uniform distribution of the surface we have

$$\zeta_r(l_1 + l_2) = \frac{2\,k_{s_2}}{l_1 + l_2}\left[\frac{b_2}{b} \cdot F(z_2) - \frac{b_2 - b_1}{b}\,F(z_1')\right]$$

$$= \frac{2 \cdot 5.67 \cdot 10^{-5}}{6.096}[1.065 \cdot 207 - (1.065 - 0.749) \cdot 92.95]$$

$$= 3.555 \cdot 10^{-3}$$

Now the increase in resistance is 13.6 per cent.

If we consider the assumption that k_s is dependent only upon the length of the surface and not on the variable width, the agreement between the calculated and the measured percentage is very good.

According to Table 3, the increase in resistance of the same part of the surface in the case of the wholly roughened model is 0.2245 x 81.2 = 18.2 per cent.

The resistance component due to the roughened parts is $3.952 \times 10^{-3} \cdot \rho b v^2$, while that of the smooth parts amounts to $6.885 \times 10^{-3} \cdot \rho b v^2$.

5. MODEL ROUGHENED OVER 20.5 PER CENT OF ITS LENGTH FROM THE AFTER PERPENDICULAR (CONDITION A_3)

The resistance coefficient of the smooth model at a temperature corresponding to that for Condition A_3 is 3.172×10^{-3}.

The corresponding roughness k_s amounts to 0.0603 mm. The ratio of the mean width b_1 of the surface over 79.5 per cent of the length of the model from the forward perpendicular l_1 to the mean width b of the entire surface is $b_1/b = 1.067$.

For the rest of the length l_2 this ratio is $b_2/b = 0.739$.

Now we have

$$k_{s_1} = 0.0603\,\text{mm} \qquad k_{s_2} = 1.22\,\text{mm}$$

$$l_1 = 4.846\,\text{m} \qquad l_2 = 1.25\,\text{m}$$

$$G(z_1) = \frac{l_1}{k_{s_1}} = 8.04 \cdot 10^4 \text{ gives } F(z_1) = 1.327 \cdot 10^2$$

$$F(z_1') = \frac{k_{s_1}}{k_{s_2}} \cdot F(z_1) = 6.56 \qquad G(z_1') = 1.798 \cdot 10^3 \qquad l_1' = 2.193\,\text{m}$$

$$G(z_2) = \frac{l_1' + l_2}{k_{s_2}} = 2.823 \cdot 10^3 \qquad F(z_2) = 9.24$$

When the surface is uniformly distributed, we have

$$\zeta_r(l_1 + l_2) = 2\frac{k_{s_2} \cdot F(z_2)}{l_1 + l_2} = 3.698 \cdot 10^{-3}$$

$$\zeta_r \text{ smooth} = 3.172 \cdot 10^{-3}$$

The resistance distribution thus will be 16.6 per cent, while 14.4 per cent was measured.

Again considering non-uniform distribution of the surface, we have

$$\zeta_r(l_1 + l_2) = \frac{2k_{s_2}}{l_1 + l_2}\left[\frac{b_2}{b} \cdot F(z_2) - \frac{b_2 - b_1}{b} F(z_1')\right]$$

$$= \frac{2 \cdot 1.22 \cdot 10^{-3}}{6.096}[0.739 \cdot 9.24 - (0.739 - 1.067) \cdot 6.56]$$

$$= 3.593 \cdot 10^{-3}$$

The increase in resistance now is 13.3 per cent.

According to Table 3, the increase in resistance of the same part of the surface with the whole model roughened is 0.1053 x 81.2 = 8.5 per cent.

The resistance component due to the roughened portion of the surface is 2.417 x 10^{-3} $\rho b v^2$, while the component due to the smooth portion of the surface is 8.53 x 10^{-3} $\rho b v^2$.

Although the resistance of the roughened part of the model in this case is considerably less than for Condition D_1, due to the thicker boundary layer in the region of the rough surface, the resistance of the smooth portion is so much greater, on the other hand, that the total resistance according to calculation has undergone practically no change.

It is evident from the tests that the increase in resistance in this case (A_3) is somewhat lower, which may be explained by the eddy separation on the afterbody. Due to this, the velocities along the afterbody will be low or even negative, and the frictional resistance thereby reduced.

According to the calculations and measurements given, the decrease in frictional resistance due to eddy separation in this case amounts to about 2 per cent.

6. CONCLUSIONS

1. The results of the tests cited are in agreement with Schlichting's theory regarding the increase in resistance of partially roughened plates or ship models when in the case of the latter the distribution of surface over the length is considered.

2. It is not true that a roughness of the forebody always leads to a noticeably greater total resistance than a roughness of the afterbody (of approximately the same area), as would follow from Table 3 if the effect of eddy separation on frictional resistance were disregarded.

In the cases discussed under Sections 3 and 4, where 20.5 per cent of the length from the forward perpendicular, or respectively the after perpendicular were roughened (size of grains = 1.22 mm) the increase in resistance by calculation amounted to 13.7 per cent and 13.3 per cent respectively (measured increases were 16.4 per cent and 14.4 per cent respectively). On the other hand, if 79.5 per cent from the forward perpendicular, or respectively the after perpendicular is roughened, then these percentages (size of grains being the same) will be 72.2 per cent or 65 per cent respectively. It is only when the roughened zones are longer that the difference between these percentages will be larger. The length over which the roughness extends here has an effect.

Kempf's conclusion that particularly the forebody should be as smooth as possible thus loses some of its importance. In order to obtain a low frictional resistance, requisite attention must also be given the remaining part of the surface.

3. The results of the tests discussed confirm Amtsberg's conclusion that the form effect on frictional resistance is small and nearly negligible.

4. By roughening various lengths of the model from the forward perpendicular and calculating the corresponding roughnesses from the measured increases in resistance by Schlichting's method, it is possible, by comparing the calculated resistance with the measured resistance of the completely roughened model, to determine the effect of eddy separation on the frictional resistance.

In this way the form resistance due to eddy separation of submerged double models or bodies of rotation can likewise be determined, by finding the difference between the total measured resistance and the frictional resistance calculated by Schlichting's method, and correcting the latter for eddy separation.