Approximate Calculation of Ship Frictional Resistance Increase due to Surface Roughness

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Summary

In order to calculate frictional resistance increase due to surface roughness of a ship, a two-dimensional turbulent boundary layer theory for rough surface was applied to potential streamlines over the hull surface. In the calculation, Karlsson's roughness functions for full-scale ships were used. The calculated results were compared with those calculated by replacing a ship with a flat plate, and compared with the experimental data. The frictional resistance increase calculated by the present method is a little larger than that of flat plate approximation. Further, a fairly good correlation between calculated results and experimental data was obtained when they were plotted with respect to the mean apparent amplitude.

1. Introduction

Hull roughness is closely related to the propulsive performance of a ship in operation. Therefore, in the days of uprising fuel oil cost, prediction of frictional resistance characteristics due to hull roughness has become one of the major topics in ship hydrodynamics. In the recent years, it has become possible to determine roughness function, i.e. downward velocity shift $\Delta U_1/U_*$ due to surface roughness in logarithmic velocity profile for full-scale ship as shown in Fig. 1. For instance, Karlsson developed a wind tunnel floating element drag measurement technique and gave roughness function data for replicas of surface roughnesses of full-scale ships¹⁾. Musker and Lewkowicz developed a method to transfer copies of ship hull roughness onto the inside a pipe-line, and gave roughness function data²⁾. Making use of such roughness functions we may predict ship frictional resistance increase based on the turbulent boundary layer theory for rough surface.

As far as the theory for rough surface is concerned, three-dimensional theory for ship form has not been developed yet. A ship is usually replaced by a flat plate with the same length and speed, and two-dimensional theory is applied on the equivalent plate^{1,3,4)}. In the present study, an attempt is made to develop an approximate three-dimensional method of calculation. Namely

Fig. 1 Velocity profile for rough surface

a two-dimensional turbulent boundary layer theory for rough surface was applied to the double-body potential streamlines over the hull surface of a full ship so that the longitudinal pressure gradients along the streamlines might be taken into account.

The calculated results were compared with those calculated by replacing a ship with a flat plate. In this calculation the roughness functions provided by Karlsson for full-scale ship were used.

2. Nomenclature

- B : beam of ship
- C_b : block coefficient of ship
- C_f : total skin friction coefficient
- ΔC_f : increment in C_f due to surface roughness
- C_f' : local skin friction coefficient
 $= \tau_w / (1/2) \rho U^2$

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- C_i : constants in Eq. (4)
 C_p : pressure coefficient
 d : draft of ship
 F : Head's entrainment function
 G : pressure gradient parameter
 H : shape factor $= \delta^*/\theta$
 $H_{\delta-\delta^*}$: shape factor $= (\delta - \delta^*)/\theta$
 k : characteristic roughness height
 k_s : sand roughness height
 L : length of ship
 MAA : mean apparent amplitude of surface roughness
 R_k : roughness Reynolds number $= U_* k / \nu$
 s : coordinate in streamwise direction
 u : velocity in boundary layer
 U : local velocity outside the boundary layer
 U_0 : free stream velocity
 U_* : friction velocity $= \sqrt{\tau_w / \rho}$
 $\Delta U_1 / U_*$: roughness function
 $\Delta U_2 / U_*$: pressure gradient contribution to velocity defect law
 y : distance from wall
 α : MAA
 δ : boundary layer thickness
 δ^* : displacement thickness
 θ : momentum thickness
 ν : kinematic viscosity
 ρ : density of fluid
 τ_w : local wall shear stress
Subscripts
 m : ship model
 s : ship

3. Outline of the theory

In 1969 Uberoi applied a two-dimensional turbulent boundary layer theory to the streamlines over smooth hull surface and calculated viscous resistance of a ship for the first time.⁵⁾ In the present study the same method was applied to calculate the turbulent boundary layer for rough surface so as to take into account the influence of the longitudinal pressure gradients along the streamlines. In this calculation, therefore, neither the cross-flow nor the streamline convergence was taken into account for the sake of simplicity. Streamlines and pressure distribution over the hull surface were calculated by the potential theory.⁶⁾ In this calculation the free-surface elevation is neglected.

Calculation of boundary layer parameters on each streamline are based on the following equations. Momentum integral equation was used as the basic equation, viz.,

$$\frac{d\theta}{ds} = \frac{C_f'}{2} - (H+2) \cdot \frac{\theta}{U} \frac{dU}{ds} \quad (1)$$

and entrainment equation was used as the auxi-

liary equation

$$\frac{d}{ds}(\delta - \delta^*) = F(H_{\delta-\delta^*}) - \frac{\delta - \delta^*}{U} \frac{dU}{ds}, \quad (2)$$

where $F(H_{\delta-\delta^*})$ is the Head's entrainment function.

Relationship between Head's entrainment function F and shape factor H is common to both smooth and roughened surfaces.

As the skin friction law for smooth and roughened surface, Clauser's formula was used.⁷⁾

$$\sqrt{\frac{2}{C_f}} = 5.6 \log_{10} \frac{U \delta^*}{\nu} + 4.3 - \frac{\Delta U_1}{U_*} + \frac{\Delta U_2}{U_*}, \quad (3)$$

where $\Delta U_1 / U_*$ is the roughness function, which was approximated by a function of $U_* k / \nu$:

$$\frac{\Delta U_1}{U_*} = C_0 + C_1 R_k + \sum_{i=2}^n C_i (\ln R_k)^{i-1}, \quad (4)$$

where $R_k = U_* k / \nu$ and C_i ($i=0, n$) are constants which are determined so as to fit the experimental values of $\Delta U_1 / U_*$, and for smooth surface $\Delta U_1 / U_* = 0$. $\Delta U_2 / U_*$ represents the contribution of pressure gradient to velocity defect law,

$$\begin{aligned} \frac{\Delta U_2}{U_*} &= 1.253(G-6.7) & G \geq 6.7, \\ &= 0.404(G-6.7) & G < 6.7, \end{aligned} \quad (5)$$

where

$$G = \sqrt{\frac{2}{C_f}} \cdot \frac{H-1}{H}.$$

Equations (1) and (2) can be integrated simultaneously by Runge-Kutta-Gill method with the skin friction coefficient being determined numerically at each step from equations (3) through (5) by iterative method.

4. Calculation of frictional resistance increase for a full-scale ship

4.1 Calculation for a full ship form of $C_b = 0.84$

Two-dimensional theory for rough surface explained in the previous section was applied to the potential streamlines over a full ship form with the following principal particulars:

$$\begin{aligned} L_{pp} &= 220 \text{ m}, & C_b &= 0.84 \\ L_{pp}/B &= 5.96, & B/d &= 2.62 \end{aligned}$$

Fig. 2 shows the body plan. The calculation was

Fig. 2 Body plan and potential streamlines

Table 1 Frictional resistance increase for a full form of 220 m at 15 kn

Karlsson's rough surfaces			$10^3 \times \Delta C_f$	
Surface Number	Peak to valley height (μm) in 52.5 mm length	RMS amplitude (μm)	Calculations along Streamlines	Calculations for Flat plate
1	132	31	0.120	0.110
2	344	65	0.211	0.198
3	825	183	0.513	0.491
4	154	29	0.090	0.081

made on twelve potential streamlines over the hull surface. Some of them are shown in the body plan.

In the calculation Reynolds number is 1.43×10^9 (ship speed is 15 knots and kinematic viscosity $\nu = 1.1873 \times 10^{-6} \text{ m}^2/\text{sec}$). Initial values of momentum thickness θ_0 and shape factor H_0 were given at the position of 3 percent of ship length aft from fore perpendicular by use of flat plate approximation for smooth surface.^{8,9)} For the calculation of frictional resistance for rough surface, four different roughness functions prepared by Karlsson¹⁾ were used. They are mathematically expressed in a form of the expression (4) in the previous section.

Table 1 shows the results of calculations made by the present method. Calculations were also made by using equations (1) through (5) when the ship is replaced by a flat plate with the same length and speed. The frictional resistance increase calculated along streamlines gives a little higher values than those of flat plate calculation.

4.2 Effect of pressure gradient

In the previous section only a small difference was observed between the frictional resistance increase based on calculations along streamlines and flat plate. In order to know the effect of pressure gradient a comparison was made for boundary layer parameters by use of Karlsson's rough surface No. 3. Fig. 3 shows the comparisons of the pressure distributions and boundary layer parameters, i.e. local skin friction co-

efficient C_f' , shape factor H and momentum thickness θ for both methods. It is clear that the flat plate calculation gives rather monotonous change of these parameters. On the other hand, the calculation along streamline shows an influence of pressure gradient.

For the consideration of local characteristics of flow around a ship due to roughness, the present method of calculation may give more rational information. However, the integrated values, that is, the total skin friction resistance for both methods comes close each other.

5. Relation between ΔC_f and surface roughness

5.1 Resistance test data of flat plates with various surface roughnesses

In the previous section calculations of frictional resistance increase due to surface roughness were made by use of roughness functions corresponding to full-scale ships. In the present section these calculated results are compared with existing towing test data of flat plates whose surfaces were finished by use of conventional paints for ship hull surface.

At present, following test results are available to the authors:

	Method of test	Length of test plate	Test speed
Todd ¹⁰⁾	Towing test of planks	6.4 m	<7.13 m/sec
Townsin et al. ¹¹⁾	Flume test of plates	1.0 m	7.50 m/sec

Fig. 3 Effect of pressure gradient on boundary layer parameters for rough surface

Present authors Towing test of flat plates 3.0 m <9.0 m/sec

These experimental data were extrapolated to full-scale condition by making use of Sasajima and Himeno's scaling law for frictional resistance increase due to surface roughness¹²⁾

$$\Delta C_{fs} = \Delta C_{fm} \cdot \left(\frac{C_{fs}}{C_{fm}} \right)^2 \quad (6)$$

with roughness Reynolds number $U_0 k / \nu = \text{constant}$. This formula can be applied to any kind of roughness provided that $U_0 k / \nu < 1 \times 10^5$. The validity of this formula was examined by the authors by use of 7 m and 4.2 m length geosims whose surfaces were artificially roughened⁴⁾.

In the followings, ΔC_{fs} values extrapolated by Eq. (6) from model tests to a ship of 220 m in length at 15 knots are shown.

**Todd's data (Plank length=6.4 m,
speed=7.13 m/sec)**

Kinds of paint	Peak to valley height*	$10^3 \Delta C_{fm}$	$10^3 \Delta C_{fs}$
Hot plastic	508 μm	0.900	0.347
Anti-corrosive	76	0.240	0.093
Cold plastic	51	0.040	0.015
Zinc chromate	54	0.040	0.015

$\Delta C_{fs} = (C_{fs}/C_{fm})^2 \Delta C_{fm} = 0.386 \Delta C_{fm}$ based on Schoenherr line.

* Reading from the roughness recordings shown in Fig. 11 (a) to (d) of Ref. (10).

**Townsin et al.'s data (Plate length=1.0 m,
Speed=7.50 m/sec)**

MAA Roughness	Drag at $U_0=7.5$ m/sec	$10^3 C_{fm}$	$10^3 \Delta C_{fm}$	$10^3 \Delta C_{fs}$
Smooth	3.33 kg	2.903		
46 μm	3.80	3.313	0.410	0.084
54	3.70	3.225	0.322	0.066
351	4.70	4.097	1.195	0.243
113	4.20	3.661	0.758	0.155

Fig. 4 Arrangement of test apparatus for 3 m flat plate resistance test

415	5.20	4.533	1.630	0.332
95	3.96	3.452	0.549	0.112
654	5.65	4.925	2.022	0.412
136	4.25	3.705	0.802	0.164

C_{fm} for smooth surface is closed to Hughes friction line. $\Delta C_{fs} = 0.204 \Delta C_{fm}$ based on Hughes friction line.

Tokunaga and Baba (Plate length=3.0 m, Speed=7.60 m/sec)

Test arrangement is shown in Fig. 4. Water temperature = 14.0°C. $U_{0\text{model}} = U_{0\text{ship}} \times (\nu_{\text{model}} / \nu_{\text{ship}} \text{ at } 15^\circ\text{C}) = 7.60 \text{ m/sec}$.

MAA			
Roughness	$10^3 C_{fm}$	$10^3 \Delta C_{fm}$	$10^3 \Delta C_{fs}$
Schoenherr friction line	2.638		
96 μm	2.815	0.177	0.055
48	2.600	-0.038	-0.012

$\Delta C_{fs} = 0.308 \Delta C_{fm}$ based on Schoenherr line.

Resistance was determined from the difference of resistance measured at two different drafts (0.5 m and 0.3 m) of the plates so as to eliminate the effect of spray resistance, wind resistance of supporting apparatus and other experimental errors.

5.2 Comparison of calculated ΔC_f with experimental data

In Fig. 5 extrapolated experimental data of Todd, Townsin et al. and the present authors are plotted versus mean apparent amplitude α , which is defined as the mean of peak to valley heights in 50 mm interval as proposed by BSRA. This figure shows also the present authors' calculations which were made along streamlines and those of flat plate approximation. In addition to them ΔC_f read off Karlsson's charts are also shown. In Karlsson's calculation a ship is replaced by a flat plate, and the effect of upstream boundary layer growth on the downstream part has not been considered, while this effect is taken into account in the authors' calculation.

Though the methods of resistance measurements are different, experimental data come close together after the application of Sasajima and Himeno's scaling law. Further, calculated ΔC_f are also close to the experimental data. The plotted data seem to be proportional to the mean apparent amplitude. This is an important result for practical purpose to know quickly the order of magnitude of ΔC_f versus roughness height.

Nextly, equivalent sand roughness height was read off Nikuradse-Schlichting resistance diagram for sand-roughened plate⁸⁾.

Fig. 5 Relationship between ΔC_f and roughness height

Readings from Nikuradse-Schlichting resistance diagram

L/k_s	k_s ($L=220$ m)	α (MAA)		$10^3 \Delta C_f$ at $U_0 L/\nu = 1.43 \times 10^9$
		$\alpha=4 k_s$	$\alpha=5 k_s$	
2×10^6	110 μ m	440 μ m	550 μ m	0.35
1.5×10^6	147	587	735	0.44
1×10^6	220	880	1100	0.66
7.5×10^5	293	1172	1465	0.80

As shown in Fig. 5 the plotted data approximately correspond to the sand roughness height k_s in between $(1/4)\alpha$ and $(1/5)\alpha$.

For reference, 1978 ITTC correlation formula:

$$10^3 \Delta C_f = 105 \left(\frac{\alpha}{L} \right)^{1/8} - 0.64$$

is also shown in this figure. This formula was derived based on the analyses of a number of ship trials and their model experiments.¹³⁾ Therefore, effects of structural roughness, effect of roughness on viscous pressure resistance and other factors related to full-scale trials are included. The comparison of this correlation formula with the data prepared in the present study may give an idea about the order of magnitude of these effects which were not considered in the present study. It is noted that the rate of increase of ΔC_f in the present study with respect to the mean apparent amplitude α is less than that of ITTC correlation formula.

6. Conclusion

An approximate calculation method of ship frictional resistance increase due to surface roughness was presented by applying two-dimensional turbulent boundary layer theory for rough surface to the potential streamlines over ship hull surface. Numerical calculations of the frictional resistance increase due to surface roughness were carried out by use of Karlsson's roughness functions corresponding to the actual hull surface and compared with the experimental data. The following conclusions are derived.

(1) Calculated frictional resistance increase by the present method is a little larger than that of flat plate approximation. Therefore the flat plate approximation presented here may serve as a practical tool to predict ship frictional resistance increase due to surface roughness within acceptable accuracy.

(2) A fairly good correlation between calculated results and experimental data was obtained when they were plotted with respect to the mean apparent amplitude.

(3) In the present study only frictional resistance increase due to surface roughness was considered. However in order to predict ship viscous resistance increase due to surface roughness more

accurately, it is also necessary to calculate the viscous pressure resistance increase due to surface roughness.

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