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A Study of Skin Friction Drag from Realistic Roughness of a Freshly Cleaned and Painted Ship Hull

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A study on the impact of surface roughness from a freshly cleaned and painted ship-hull will be reported. This includes surface scanning and empirical estimation. The overall aim of the investigation is to emphasize that even a recently dry-docked ship, involving cleaning, sand-blasting and repainting still inherently suffers from surface roughness due to the cleaning and painting process. This surface roughness results in a significant drag penalty, which motivates the need to reduce ship-hull roughness in order to reduce fuel expenses. Skin-friction drag that arises from turbulent boundary layers formed over ship hull is one of the primary sources of energy consumption in the maritime sector. It is estimated that up to 80%-90% of the total drag experienced by a large bulk carrier is due to turbulent skin-friction drag. The already high contribution of turbulent skin friction drag is exacerbated by the issue of surface roughness. From a non-hydrodynamic perspective, the hull of a large ship can often seem relatively smooth, particularly in its freshly cleaned and painted state. However, our surface scanning reveals that freshly coated ship surfaces can exhibit an "orange peel" roughness pattern with physical height ranging from 0.1 – 0.5 mm. Such roughness when interacting with the fluid flow will become appreciable in term of viscous length scales. From the surface scan results, we implemented an analytical study to predict skin-friction drag on a full-scale ship. The methods are based on the recent report by Monty et al[1] and Chan et al[2]. Our initial result shows that this seemingly negligible roughness could cause an estimated 31% increase in skin-friction drag compared to the hydrodynamically smooth surface. The results suggest that a better and more careful cleaning and painting during dry-docking is needed in order to lower the drag penalty.

Keywords: Surface roughness, surface scanning, skin-friction drag, turbulent boundary layer

1. Introduction

Shipping is one of the most important modes of transportation and economic engine of the modern world. It is estimated there are more than 100,000 ships operating worldwide, consuming around 200–300 million metric tonnes of fuel annually [3,4]. These fuels are used by the engine and propeller to overcome resistance. An important contribution to this resistance is the skin-friction drag from the turbulent boundary layer that is formed on the ship hull. The energy consumption to overcome skin–friction drag and propelling the ship forward is immensely costly. Up to 80%–90% of the total drag experienced by a large bulk carrier could be due to turbulent skin-friction drag [5,6]. The issue of skin-friction drag on a ship hull is exacerbated by the existence of surface roughness.

Surface roughness on a ship hull is generally associated with the settlement of marine creature on a surface in an aquatic environment, commonly termed biofouling[7-10]. However, many ships that have just recently experienced dry-dock, where the hull is cleaned, sand-blasted, and repainted with anti-corrosion and anti-fouling paints, could still exhibit a noticeable roughness and above the ideal smooth state.

Schultz [10,11] performed towing tank measurement on a flat plate from three different roughness states : unfouled (coated with various antifouling paint), fouled, and cleaned. The results revealed a 3-7% increase in frictional resistance for unfouled coated hull compared to hydraulically smooth surface and an increase of more than 90% for calcareous fouling. Interestingly however, when the fouled surface was cleaned, the skin friction drag reduced, albeit slightly higher than the unfouled state. The higher friction drag of cleaned plate is suspected due to coating deterioration and damage. The towing tank result is later used to predict the full-scale ship drag resistance. The flat plate that Schultz [10,11] used however, is still relatively new and yet to suffer from repeated sand or water blasting. Hence the drag penalty estimation may be lower than the real case scenario.

In this report, a prediction of full–scale ship resistance due to rough-hull from a recently dry-docked ship is made. The hull roughness is obtained via laser surface scanner, allowing a more realistic roughness condition. To estimate the full-scale drag penalty we use empirical methods based on the recent report by Monty et al[1] and Chan et al[2].

2. Turbulent Boundary Layer Over Rough Surface Background

In order to understand the effect of hull-roughness on ship's drag penalty, some background of wall-bounded turbulent boundary layer will be explained here.

The mean velocity profile of wall-bounded flow over a rough wall can be expressed as log law :

$$\frac{U}{U_\tau} = \overbrace{\frac{1}{\kappa}\ln z^{+} + A}^{\text{Log region}} - \Delta U^{+} + \overbrace{\frac{\Pi}{\kappa} W\left(\frac{z}{\delta}\right)}^{\text{Wake function}}, \qquad (1)$$

where for a fully rough surface

$$\Delta U^{+} = \frac{1}{\kappa}\ln k_s^{+} + A - B \qquad (2)$$

is the Hama roughness function[1, 2, 10, 12, 14]. Please refer to nomenclature at the end of this paper for details regarding the equation's parameters. In determining drag penalty of wall bounded flow, one needs to determine the skin–friction velocity U_τ and sand-grain equivalent roughness k_s. These values are later used in an integral formulation of the evolving turbulent boundary layers to calculate the average drag on the rough surfaces[1,12].

The challenge with this method is the cost. To determine k_s, one would firstly need to perform many rough surface wall-normal measurements at different Reynolds number in wind tunnel, towing tank, or water tunnel to obtain various Hama roughness function[1,10]. This method is repeated until C_f (Coefficient of friction) at a given streamwise position becomes invariant with Reynolds number, or fully rough.

In a typical roughness study, for example biofouling on a ship hull, one would need to imprint the biofouling, scaled it to match the viscous scales on the ship, replicate it multiple times (to fill the entire wind tunnel or water tunnel facility), and lay or attach it on wind tunnel. Apart from the large facility needed, and costly manufacturing process, it takes a significant time to perform the actual experiment. For illustration, a standard wall-normal measurement in wind tunnel using Hot-wire Anemometer or Laser Doppler Anemometer, will take around 3-4 hours to perform. The experiment needs to be performed several times to obtain sufficient values of the Hama roughness function to estimate k_s. Please refer to Monty et al[1], Chan et al[2], Jimenez[10], and Hama[14] for further details in finding U_τ, k_s, and Hama Roughness function experimentally.

Our aim is to bypass this costly and lengthy process, and to use empirical roughness model based on the surface scanning to obtain drag prediction for full-scale ship/entire hull.

3. Empirical Roughness Model and Full-Scale Prediction

To obtain a full-scale hull roughness prediction we follow the methodology by Monty et al[1], starting with calculating Reynolds number based on the momentum thickness for a range of viscous scaled boundary layer thickness :

$$Re_\theta = \int_0^{\delta^+} \left(U^+ - \frac{U^{+^2}}{S} \right) dz^+ . \qquad (3)$$

Here S is taken from Jones et al[13] in the form of

$$S = \frac{1}{\kappa} \ln \delta^+ + A - \Delta U^+ - \frac{1}{3\kappa} + \frac{2\Pi}{\kappa}, \qquad (4)$$

where $\Delta U^+ = 0$ for smooth wall case. This yields local skin friction coefficient:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_\infty^2} = \frac{2}{S^2} . \qquad (5)$$

Therefore, for ranges of certain δ^+, one can calculate Re_θ , C_f, and S via the mean momentum integral equation:

$$\frac{d\theta}{dx} = \frac{dRe_\theta}{dRe_x} = \frac{C_f}{2} . \qquad (6)$$

By rearrange Eq. (6), the Reynolds number over certain streamwise location can be obtained from

$$Re_x = \int \frac{2}{C_f} \, dRe_\theta .$$

(7)

Note that Eq.(7) can also be defined as:

$$Re_x = \frac{Ux'}{\upsilon}, \qquad (8)$$

where x' is an intermediate variable coinciding with x – coordinate. Therefore the average skin friction coefficient can be defined as:

$$\overline{C_f} = \frac{1}{x} \int_0^x C_f(x')\, dx' = \frac{1}{Re_x} \int_0^{Re_x} C_f\left(Re_{x'}\right) dRe_{x'} . \qquad (9)$$

Combining the integration of Eq.(6) and Eq.(9) will yield:

$$\overline{C_f} = \frac{2\,\mathrm{Re}_\theta}{\mathrm{Re}_x}, \qquad (10)$$

which can be used to calculate the total integrated ship hull skin friction coefficient.

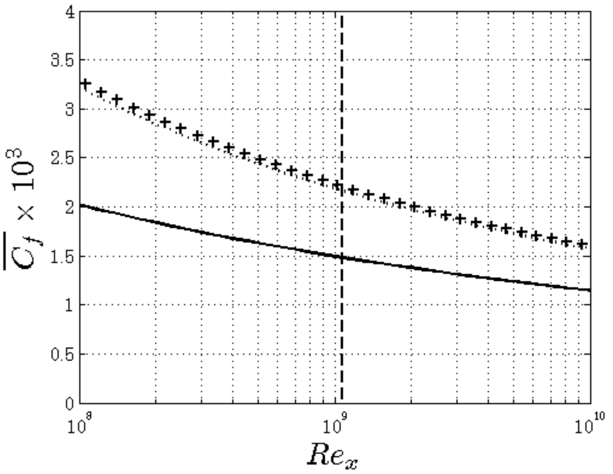

Fig.1 Average skin friction coefficient against Reynolds number for the (black line) smooth surface, (dotted line) tubeworm with experimentally obtained k_s from Monty et al[1], (plus symbol line) identical tubeworm based on scanned surface parameters with empirical calculation of Chan et al [2]. The vertical dashed black line is Reynolds number of FFG-7 frigate at cruise speed from Schultz [11].

For the rough wall case, to solve for Hama roughness function, instead of using equation 2 from the costly obtained k_s, we use empirical model recently reported by Chan et al [2], where

$$\Delta U^+ = \frac{1}{\kappa} \ln k_a^+ + \beta \log ES_x + \gamma . \qquad (11)$$

The empirical model allows us to obtain Hama roughness function directly from the surface scans (via k_a and ES_x). Apart from Eq.(11), the rest of the steps are directly taken from Monty et al[1].

Figure 1 shows average skin friction coefficient against Reynolds number for a smooth surface (black line), Monty et al[1] biofouling experiments (dotted line), and the predictive estimation of Chan et al [2] (plus symbol line) using the same biofouling sample (see table 1 for the biofouling parameters from Monty et al[1]). The plot shows that the empirical estimation is close to the experimental result, and could be effective in predicting the

Hama roughness function for a wide range of surfaces. The vertical black dashed line shows the US Navy {Oliver Hazard Perry class} frigate (FFG-7) from Schultz [11]. The ship has a cruise speed of 7.7 m/s and waterline length of 124.4 m.

Table 1 Biofouling surface roughness parameter from Monty et al[1].

Parameter	Value	Units	Equation
k_a	0.094	mm	$\overline{\lvert z' \rvert}$
k_{rms}	0.144	mm	$\sqrt{\overline{z'^2}}$
k_p	1.630	mm	$\max z' - \min z'$
k_{sk}	2.963	-	$\overline{z'^3}/k_{rms}^3$
k_{ku}	14.180	-	$\overline{z'^4}/k_{rms}^4$
ES_x	0.134	-	$\overline{\lvert dz'/dx \rvert}$

Using the FFG-7 ship as baseline, the full-scale drag penalty from smooth surface is $C_f = 1.484 \times 10^{-3}$ (at the cross between black dashed line and black line), for Monty et al[1] biofouling experiment the C_f is 2.165×10^{-3} (at the cross between black dashed line and dotted line), and from the empirical estimation method of Chan et al [2] the C_f is 2.205×10^{-3} (at the cross between black dashed line and plus symbol line). The average skin friction coefficient difference between biofouling experimentation and empirical method is around 2%. The small difference shows that the empirical method from Chan et al [2] is deemed suitable to be used for estimating the k_s of a scanned surface. In this case (tubeworm fouling), the change in C_f between a biofouled hull and a smooth surface is around 46% – 48%.

4. Surface Scanning of The Recently Cleaned and Painted Ship-Hull

The surface profile of the recently cleaned and painted ship hull is obtained via imprint using silicone rubber (Figure 2). The imprint is then scanned using Keyence™ LK-031 laser triangulation sensor that is attached to a two-axis computer controlled positioning system. The laser has a vertical resolution (z) of 1 μm and the horizontal (x and y) resolution of 60 μm. The horizontal scanning movement covers an area of 50 x 50 mm. Figure 3 shows the resulting “orange-peel” type surface roughness scan with average roughness height k_a = 41.3 μm, and effective slope ES_x = 0.089. Other important parameters are tabulated in table 2. “Orange-peel” is a type of finish quality on a surface where the surface pattern or texture resembles the surface of an orange skin. This type of roughness may arise from the cleaning process and the inconsistency of hull painting.

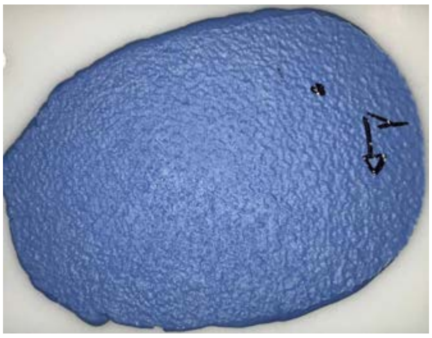

Fig.2 Silicone rubber surface imprint from a recently cleaned and painted ship hull.

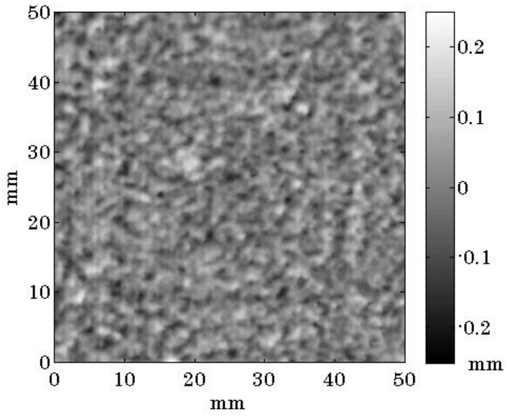

Fig.3 Surface roughness scan result.

The scanning result shows that the roughness from “clean-hull” is larger than that of Schultz [10,11] (approximately 4–6 times larger). From personal communication with anti-fouling producer representatives, this type of hull-roughness is very common for a recently dry-docked ship. A much more severe hull roughness is even regularly found on many recently dry –docked ships.

Table 2 “Orange peel” surface roughness parameter.

Parameter	Value	Units	Equation
k_a	0.0413	mm	$\overline{\lvert z' \rvert}$
k_{rms}	0.0519	mm	$\sqrt{\overline{z'^2}}$
k_p	0.4791	mm	$\max z' - \min z'$
k_{sk}	0.0868	-	$\overline{z'^3}/k_{rms}^3$
k_{ku}	3.0712	-	$\overline{z'^4}/k_{rms}^4$
ES_x	0.0890	-	$\overline{\lvert dz'/dx \rvert}$

5. “Orange Peel” Surface Roughness Drag Penalty Estimation

Figure 4 shows the drag penalty empirical estimation from the “orange-peel” surface roughness (triangular symbol line) compared to the results previously shown in Figure 1. The result shows that the surface finish of a recently dry-docked FFG-7 has a drag coefficient of C_f = 1.948 x 10^{-3}. This when compared to the hydro-dynamically smooth case of C_f = 1.484 x 10^{-3}, displays a drag penalty increase of 31%.

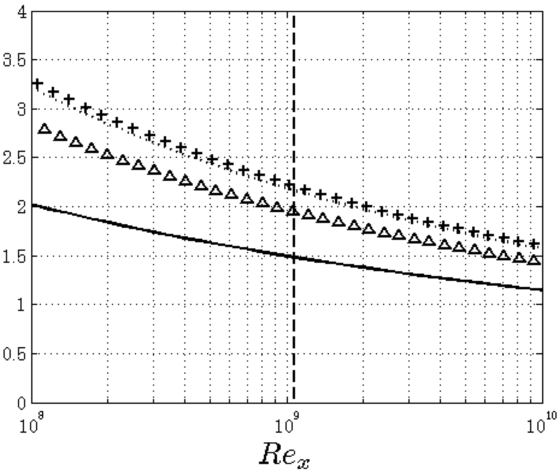

Fig.4 Average skin friction coefficient against Reynolds number for the “orange-peel” surface roughness (triangle symbol line). Other lines are as in Fig.1

The results for “orange-peel” surface roughness lies between the smooth wall and the tubeworm roughness as expected. The result shows the sobering challenges facing the shipping industry in dealing with surface roughness. This means that even a recently dry-docked ship that has been cleaned and painted could potentially already suffer from a considerable drag penalty.

Note however, that the proposed estimation technique still needs further analysis and validation, particularly for other form of roughness. Chan et al [2] have also warned that other parameters may need to be considered (i.e. alignment, sparseness, wavelength, etc). Hence we advise caution when employing this estimation method. The next step will be to experimentally determine k_s for the orange peel surface (following approach of Monty et al [1], and then compare this to the empirical prediction of Chan et al [2])

5. Conclusion

An investigation into the impact of “orange peel” surface roughness pattern from a freshly cleaned and painted ship-hull is discussed. Particular attention is given to surface scanning and empirical drag penalty estimation. Initial results from this study show that even a “clean” baseline hull condition, without suffering any fouling, may already have a substantial drag penalty (estimated at 31% increase compared to the hydrodynamically smooth surface). This empirical prediction result is only serving as a preliminary estimation. Further studies such as wind tunnel experiment (similar to that of Monty et al[1]) and CFD (such as by Chung et al[15]) are needed to confirm the empirical estimation.

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Nomenclature

k		: Roughness height [m]
k_s		: Sand grain equivalent roughness [m]
k_a		: Average roughness height [m]
U		: Velocity [m/s]
U_τ		: Skin friction velocity [m/s]
υ		: Kinematic viscosity [m^2/s]
κ	: 0.4	: Log law constant
A	: 4.17	: Log law constant
Π	: 0.65	: Wake strength
W		: Wake function
z		: Wall normal position (m)
δ		: Boundary layer thickness (m)
ES_x		: Effective slope in streamwise Direction
τ_w		: Wall shear stress
C_f		: Coefficient of friction
ρ		: Density [kg/m^3]
ΔU^+		:Hama roughness function
β	: 1.47	: Roughness empirical constant
γ	: 1.12	: Roughness empirical constant

subscript

a	: Average height
rms	: Root mean square
p	: Difference between maximum and minimum height
sk	: skewness
ku	: kurtosis