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Uncovering the origin of the out-of-dry-dock drag penalty of a tanker ship

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1 Introduction

Biofouling-induced roughness is widely known to substantially increase friction-induced resistance, and therefore the fuel consumption, of ships (Townsin, 2003). However, significantly less investigation has been dedicated to the frictional drag penalty originating from sources of roughness on a "clean" hull such as paint-induced roughness, unpainted regions under the docking blocks, and weld seams. Recent work, measuring the drag penalty of an operational tanker ship, has shown that for a "clean" ship, fresh from dry-dock, the frictional drag is already 26% higher than that of a hydrodynamically smooth hull of equivalent length (Will, *et al.*, 2023). Importantly, with ever-improving anti-fouling coatings, this "clean" state describes the hull condition for a large part of the dry-docking cycle and therefore represents a state where substantial reductions in fuel consumption and emissions can be made. With that in mind, it is especially important to determine what aspect of the hull state contributes to this initial increase in hydrodynamic resistance. To obtain such an answer, it is necessary to isolate each potential drag source and investigate them independently. The present work aims to investigate the drag of the underlying paint roughness, which is more or less homogeneous (barring local variability), by reproducing and testing it in a turbulent boundary layer (TBL) wind tunnel facility.

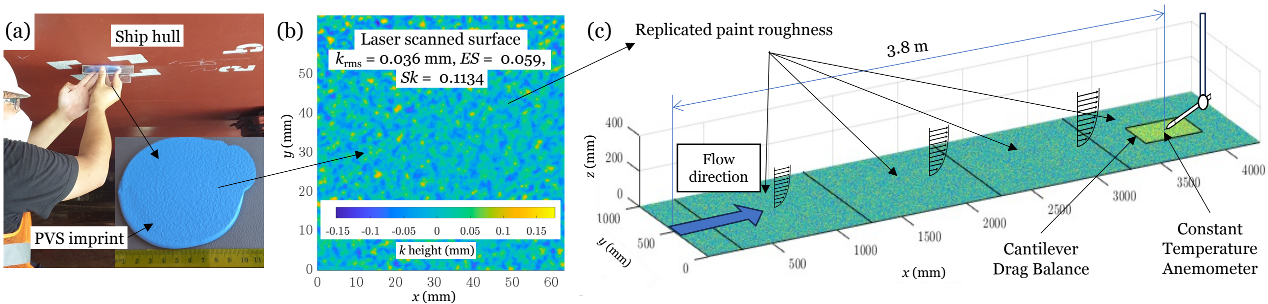

Figure 1. (a) Taking surface imprints. (b) Height map showing one of the processed imprints. (c) Laboratory experiment.

2 Methodology & Results

The surfaces being tested are reproductions from the chemical tanker Sinar Morotai, the same vessel that was used to measure the full-scale drag penalty (Will, *et al.*, 2023). During dry-docking, imprints of the hull were taken using polyvinylsiloxane (PVS) capturing the condition immediately after cleaning and re-coating, as shown in figure 1(a). These were subsequently scanned using a laser triangulation scanner and inverted. Figure 1(b) depicts a height map of one such location along with the key statistics of the surface. For wind-tunnel testing, to account for the difference in roughness Reynolds number ($k^+ = ku_\tau/\nu$) as compared to in-situ measurements on the ship, the surface was geometrically scaled by a factor of 5; resulting in $k_{\mathrm{rms}}^{\times 5} = 182\mu$m. The scanned area was then tessellated, and machined to cover the $4m \times 0.9m$ test surface of the wind-tunnel facility, with measurements being taken at $x_m = 3.8$m downstream of the trip, as shown in figure 1(c).

First of all, the skin friction coefficient $C_f = 2\tau_w/(\rho U_\infty^2)$ is measured directly as a function of $Re_x = U_\infty x/\nu$ using an in-house developed cantilever-type drag balance (Ramani *et al.*, 2024). The scatter in the results is shown by the blue dots in figure 2(a) and lies within $\pm 4\% C_f$ and the expected uncertainty of the balance. The mean of these results, indicated by the blue dashed line, is well described by an evolving TBL with $\Pi = 0.54$, $x_0 = 0.4$m, a Colebrook type roughness function with an exponent $p = 0.75$ (Cheng et al., 2020) and an equivalent sand-grain roughness height of $k_s = 135\mu$m as shown on the same figure by the circular symbols and solid blue line. The observed Colebrook-type behaviour may be related to the low effective slope (ES) of the surface. Based on this result we can also determine the ratio $c = k_s/k_{\mathrm{rms}} = 0.738$.

Secondly, the streamwise velocity component (u) is measured as a function of wall-normal distance (z) using constant temperature hot-wire anemometry (CTA) at 3 spanwise locations and 4 free-stream velocities. The profiles are made non-dimensional using the the friction velocity $U^+ = \bar{u}/u_\tau$ and the viscous length scale

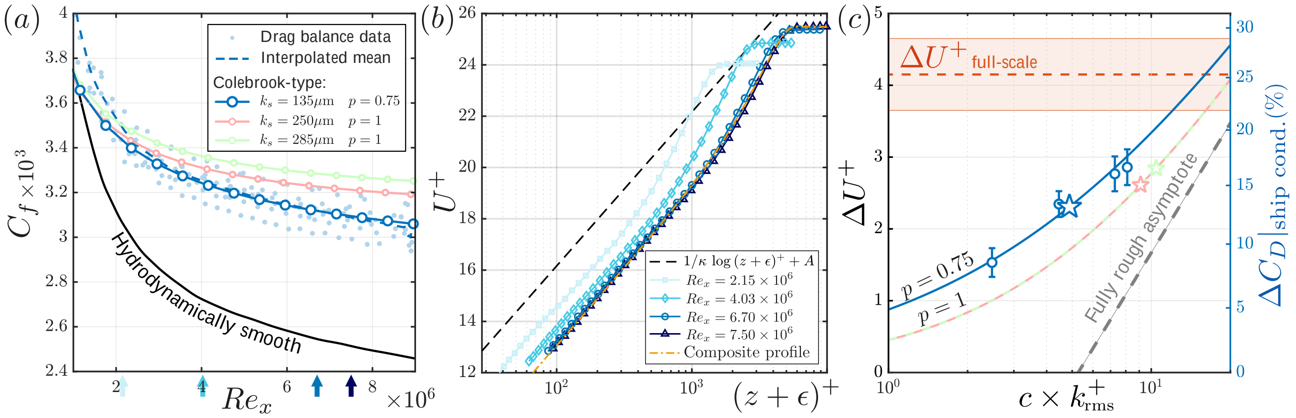

Figure 2. (a). Drag balance results (light blue dots) and interpolated mean (dashed blue line). TBL evolution matching DB data (solid blue line). Pink and green lines represent fits to experiments from different surface imprints. (b). Inner-scaled mean velocity hot-wire profiles. (c). Comparison of full-scale (ship) and laboratory (paint-roughness) drag penalties (ΔU^+ and ΔC_D).

$z^+ = z u_\tau/\nu$, where $u_\tau = U_\infty \sqrt{0.5C_f(Re_x)}$ where $C_f(Re_x)$ is obtained from the drag balance results. All profiles in the spanwise direction are averaged resulting in 4 mean-velocity profiles for varying Re_x shown in figure 2(b). From these, the roughness function ΔU^+ can be determined. Furthermore, by matching a composite profile to the measured mean profiles in figure 1(b) (shown by the dot-dashed yellow line) the wake strength parameter can be determined as $\Pi = 0.54$.

Finally, in figure 2(c) the blue circular markers show ΔU^+ obtained from the CTA results plotted versus $c \times /k^+_{\text{rms}}$, the error bars show the experimental standard deviation in ΔU^+. The important finding here is that ΔU^+ is observed to collapse well with the solid blue line, which is the Colebrook-type roughness function with $p = 0.75$ as fitted in figure 2(a). This suggests that drag behaviour is correctly described by the chosen roughness function. Having determined how ΔU^+ scales with $c \times k^+_{\text{rms}}$, or equivalently k_s^+, for this surface we can calculate what ΔU^+ and skin friction drag penalty (ΔC_D) the observed (non-scaled) roughness would have at ship operating conditions; $x = 46$m, $U_\infty = 5.17$m/s, and $\nu = 8.4 \times 10^{-7}$m^2/s, using the approach by Monty *et al.* (2016). The blue star shows this operating point, and we find $\Delta U^+ = 2.3$ and a ΔC_D of *only* 13%.

3 Conclusions & Outlook

Using wind-tunnel testing, it was found that the initial roughness resulting from the painting and cleaning process on the hull of the Sinar Morotai is *only* responsible for 13% out of the total measured full-scale drag penalty of 26%. One potential explanation for this discrepancy might be the heterogeneity of the hull-roughness. To investigate this, other surface imprints (taken at different locations on the ship hull) were also investigated using the drag-balance, shown by the pink and green lines in figure 2(a,c). However, these slightly different painted surface topographies still only result in a ΔC_D of 15.4% and 16.9%, respectively. Although these results require further validation with CTA experiments, they are broadly indicative of the level of variation one might expect due to heterogeneity. This result suggests that coating quality (on the Sinar Morotai) is responsible for about half of the out-of-dry-dock drag penalty, and an important way to reduce fuel consumption. It also implies that the other half is caused by alternate sources of roughness such as fouling and slime, weld seams, and docking blocks - with the latter most likely to result in the largest share of this discrepancy. In future work we aim to investigate the effect of each contribution to reduce the “out-of-dry-dock” drag penalty.

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