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The Roughness Induced Drag-Penalty of an Operational Tanker Ship

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1. Introduction

Bio-fouling, the growth of organisms on submerged objects, is widely known to negatively impact ship performance; significantly increasing hydrodynamic resistance (WHOI, 1968) and increasing emissions. Based on existing empirical models it can be shown that for a 100-metre-long fouled vessel the skin-friction drag can double due to the presence of hard fouling (Kempf, 1937; Schultz, 2007). With the upsurge in world-wide shipping over the last decades, the environmental and economic impact of ship hull roughness is more relevant than ever. This has led to increased regulation of the industry, with the International Maritime Organisation (IMO) setting the stringent goal for a 20% reduction of greenhouse gas emissions by 2030. However, due to lack of effective full-scale predictive correlations linking hull-state to fuel efficiency, ship operators struggle to see the benefit in expensive and often time-consuming dry-docking or in-water cleaning. The principle aim of this work is to address these issues, using field and laboratory experiments to (i) improve empirical relationships for the estimation of the equivalent sand-grain roughness height (k_s) for realistic ship hull roughness, and (ii) validate the efficacy of full-scale ship drag predictions.

2. Methodology & Results

To this end, the hull-state (roughness) and skin frictional drag of an operational vessel have been monitored during regular operation since it was sand-blasted and fully re-coated in March 2022. A schematic depiction of this ship, the chemical tanker Sinar Morotai operated by Samudera Indonesia, is shown in figure 1(a). The hull condition in dry-dock was obtained using vinylpolysiloxane imprints, which capture the as applied coating condition. In water, the hull state is monitored using dive-inspections and an in-house developed under-water photogrammetry system called *AQUAMARS* (Advanced Quality Underwater Mapping and Analysis for Rough Surfaces). During dry-docking, a window was installed in the flat bottom of the hull, 69 m downstream of the forward perpendicular allowing optical access to the turbulent boundary layer (TBL) on the outer surface of the hull. An outward facing Laser-Doppler Velocimetry (LDV) set-up mounted to a hull-normal traverse within the vessel (accommodated in the cavity between the double hulls), permits measurements of the streamwise (u) and spanwise velocity (v) components as a function of the hull-normal distance (z); see figure 1(b). We account for the refractive index of the ocean/air interface as well as for variations in density (ρ) and kinematic viscosity (ν) due to temperature and salinity.

Four measurement campaigns have been conducted, figure 1(c) shows the routes and the GPS-velocity of the ship during the LDV measurement intervals. It is evident that the cruising speed is not constant in time and has been observed to vary between 4 and 6 m/s depending on currents, sea condition, and wind direction. To account for the drift in the free-stream velocity U_∞, the boundary layer traverse is frequently interrupted (every 5th measurement) to traverse the LDA to the freestream to monitor U_∞. A lab-validated linear correction was applied to the mean profile recovering canonical flat-plate TBL behaviour. However, due to the varying speed of the ship it is still not trivial to determine the TBL-thickness (δ_{99}) or friction velocity (U_τ) directly from the mean-profile. Therefore, using the assumption of outer-layer similarity (Townsend, 1956) at large friction Reynolds numbers ($Re_\tau = U_\tau \delta_{99}/\nu$), we first determine δ_{99} by collapsing the already dimensionless skewness of u to a flat-plate laboratory TBL skewness profile of Squire *et al.* (2016), thus obtaining a skewness-based estimate of δ_{99}. To obtain U_τ, the variance ($\overline{u'^2}/U_\tau^2$) vs z/δ_{99} is again fitted to reference data (Squire *et al.*, 2016). With U_τ determined, the inner-scaled mean velocity profiles ($U^+ = U/u_\tau$ vs $z^+ = zu_\tau/\nu$) can be plotted, as shown in figure 1(d), indicating that the roughness function $\Delta U^+ = 4.15 \pm 0.5$. Assuming a Colebrook type

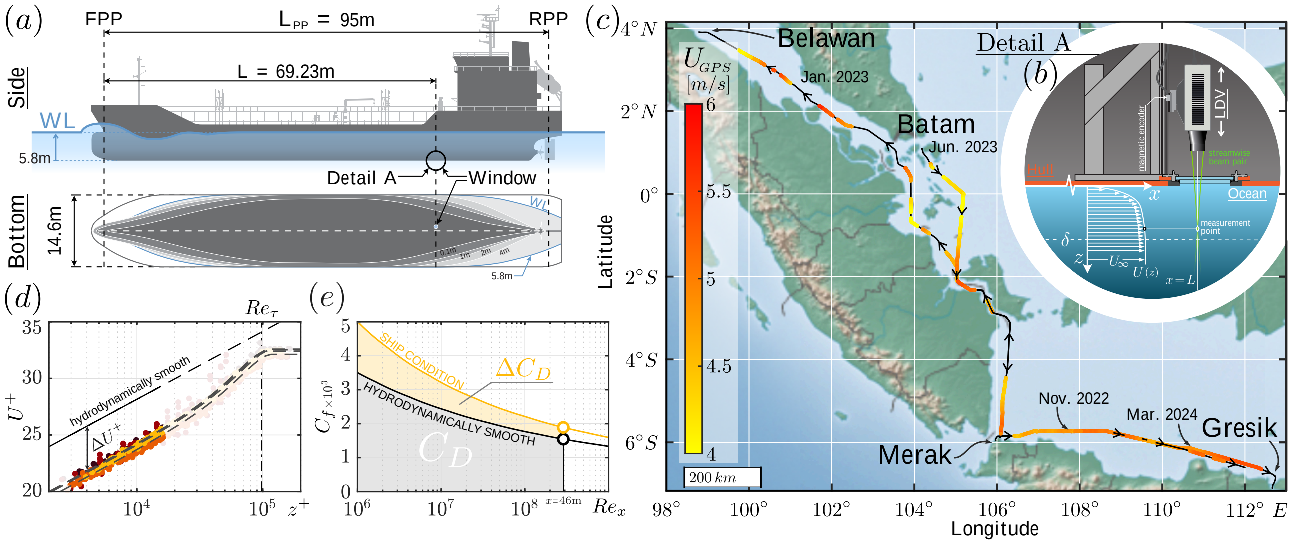

Figure 1. (a) Schematic side and bottom views of the Sinar Morotai, showing the measurment location, where the LDV setup, shown in (b) (detail A), is located. (c) Map of western Indonesia showing the routes travelled during the four campaigns. The trail colour indicates GPS-velocity of the vessel during a measurement. (d) Inner-scaled mean velocity profiles for the four measurement campaigns. (e) Ship operational point, comparison between hydrodynamically smooth (black) and the most recent ship state (yellow).

behaviour for $\Delta U^+(k_s^+)$ with an exponent $p = 1$ (Pullin *et al.*, 2016) (appropriate based on laboratory tests), we find $k_s^+ = 21 \pm 4$, i.e. the flow is in the transitionally rough regime and $k_s = 110 \pm 20\mu$m. We further find that the measured mean profiles all match well to results obtained from an integral BL evolution code (Monty *et al.*, 2016) with a flat-plate equivalent development length of x =46m, a wake-strength of $\Pi = 0.56$, and the aforementioned k_s determined from the measurements, indicated by the dashed lines in figure 1(d).

3. Conclusion & Outlook

Based on the four campaigns, the skin friction drag has not significantly increased since 2022, this is corroborated by the dive-inspections and surface scans carried out over this period which show no build-up of fouling. Surprisingly, the total frictional drag penalty of the vessel, ΔC_D shown in figure 1(e) as the yellow-shaded area, straight out of dry-dock is 26 ± 4% compared to an ideal hydrodynamically smooth surface. Based on surface scans and laboratory measurements we suspect this increase is the result of the cumulative effect of the roughness due to 1) paint application, 2) docking-blocks (areas not cleaned during dry-docking), and 3) weld-seams, with the former responsible for the majority of the measured penalty. We are currently working on determining the proportion of each contribution in order to prioritise proposed mitigation strategies to reduce fuel consumption and emissions.

References

Woods Hole Oceanographic Institution [WHOI] 1968, Marine Fouling and its Prevention, *United States Naval Institute: Annapolis*, MD, USA.

Kempf, G. 1937, On the Effect of Roughness on the Resistance of Ships *Trans INA*, **79**:109-119.

Schultz, M.P. 2007, Effects of Coating Roughness and Biofouling on Ship Resistance and Powering *Biofouling*, **23:5**, 331-341.

Townsend, A. A. 1956, The properties of equilibrium boundary layers. *J. Fluid Mech.*, **1**(6), 561-573.

Squire, D. T., Morrill-Winter, C., Hutchins, N., Schultz, M. P., Klewicki, J. C., & Marusic, I. 2016, Comparison of turbulent boundary layers over smooth and rough surfaces up to high Reynolds numbers *J. Fluid Mech.*, **795**, 210-240.

Pullin, D. I., Hutchins, N., & Chung, D 2017, Turbulent flow over a long flat plate with uniform roughness *Phys. Rev. Fluids*, **2**(8), 082601.

Monty, J. P., Dogan, E., Hanson, R., Scardino, A. J., Ganapathisubramani, B., & Hutchins, N. 2016,. An assessment of the ship drag penalty arising from light calcareous tubeworm fouling. *Biofouling*, **32**(4), 451-464.