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Measurements of skin-friction of systematically generated surface roughness

Julio M. Barros*[,a], Michael P. Schultz[b], Karen A. Flack[c]

[a] Fluid Mechanics Unit, Okinawa Institute of Science and Technology, 1919-1 Tancha, Onna-son, Okinawa 904-0945, Japan
[b] Department of Naval Architecture and Ocean Engineering, United States Naval Academy, Annapolis, MD 21402, USA
[c] Department of Mechanical Engineering, United States Naval Academy, Annapolis, MD 21402, USA

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ABSTRACT

The flow conditions at which a given surface will begin to show the effects of roughness in the form of increased wall shear stress above that of the hydraulically-smooth wall and the behavior of frictional drag in the transitionally-rough regime are still poorly understood. From a practical standpoint, the engineering correlations to predict this behavior should be based on information that can be obtained solely from the surface topography, thus excluding any information that requires hydrodynamic testing. The goal of this work is to take a systematic approach when generating surface roughness where the roughness parameters can be controlled. Three surfaces with fixed amplitude and varying power-law spectral slope ($E(\kappa) \sim \kappa^P$; $P = -0.5, -1.0, -1.5$) were generated and replicated using high-resolution 3D printing. Results show that the surface with the shallower spectral slope, $P = -0.5$, produces the highest drag, whereas the surface with the steeper spectral slope, $P = -1.5$ produces the least drag. This highlights that some roughness scales do not contribute significantly to the drag. In fact, the effective slopes, ES of the investigated surfaces were less than 0.35, which indicates that the surfaces are in the so-called "wavy" regime (Schultz and Flack, 2009). A high-pass filter of 1 mm (corresponding to ~ 10 times of the roughness height) was applied. By removing the long-wavelength roughness scales, the correlation between the filtered roughness amplitude and the frictional drag showed the correct trend.

1. Introduction

Surface roughness is encountered in a multitude of practical and industrial applications, such as flow inside pipelines or over turbine blades (which may degrade with deployment time), and flow over complex geometries and/or topographies, such as urban and environmental flows. It is widely known that roughness increases frictional drag, which may lead to higher thermal loads and degradation of performance. Recently tested roughness was seen to cause additional undesirable effects in certain conditions, such as secondary flow (Barros and Christensen, 2014; Kevin et al., 2017; Anderson et al., 2015; Nugroho et al., 2013), which may lead to lateral drag (Willingham et al., 2014). Given the complexity of rough-wall flows, it is often desired to develop simple predictive models for frictional drag that can provide a good degree of accuracy in practical engineering applications. Such a model can be derived purely from the surface topography (i.e., roughness statistics, such as, root-mean-square, *r.m.s.*, skewness, *Sk*, kurtosis, *Ku*, etc.). Therefore, it is crucial to understand the relationship between surface's topography and its impact on the hydraulic resistance. One example would be the characterization of drag penalties due to different biofouling conditions on ship hulls. A particular advantage for having a simple drag predictive model based upon the roughness statistics would be the optimization between drag penalties (and thus a reduction in ship's performance and cruising speeds) and fuel/cleaning costs.

Many important studies have been conducted on simplified, sparse arrays of roughness elements, such as cubes and transverse square bars, which often have a single roughness scale, in order to develop correlations between drag penalties (more specifically, the roughness function, ΔU^+) and some roughness parameters. These parameters range from simple ones, such as roughness spacing parameter, λ = pitch/height (Bettermann, 1965) and the density parameter, λ_d = total surface area/total roughness area (Dvorak, 1969), to more complex ones, such as the combined density and shape parameter, $\Lambda = (d/k)(A_f/A_s)^{-4/3}$, where d is average element spacing, k is the roughness height, A_f is the frontal area of a single roughness element, and A_s is the windward wetted surface area of a single roughness element (Dirling et al., 1973). Macdonald et al. (1998) introduced an analytical model to predict drag, in the form of surface roughness height, z_0 (similar to the equivalent sand-grain roughness height, k_s), for staggered and square arrays of cubes. This model agrees very well with experimental data for a wide range of planform densities,

* Corresponding author.
E-mail addresses: juliomanuel.barrosjunior@oist.jp (J.M. Barros), mschultz@usna.edu (M.P. Schultz), flack@usna.edu (K.A. Flack).

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$\lambda_p = A_p/A_d$, where A_p is the total plan area and A_d it the total area covered by the roughness elements. Recently, Yang et al. (2016) proposed a new analytical model for cubes (staggered and square arrays), where an exponential mean velocity profiles is assumed in the roughness sublayer, as evidenced in LES results presented in their work. Additionally, this model takes into account volumetric sheltering effects due to the momentum deficit in the wake of the roughness elements, which is accounted for in the drag on adjacent elements. Good agreement was found between their LES results and the Macdonald et al. (1998) analytical model.

As was previously mentioned, many practical roughness topographies embody a multitude of roughness scales, and therefore cannot be easily characterized by the parameters described above. In addition, these practical, realistic roughness types usually cover the entire surface, which, again, limit the use of parameters based on element to element spacing. Therefore, it seems that any predictive model for the frictional drag on these realistic surfaces should rely upon surface statistics. Flack and Schultz (2010), using a multitude of roughness geometries ranging from sandpaper with various grit scales to pyramids and packed spheres, developed a predictive model for k_s that is solely based upon the roughness root-mean-square height, k_{rms}, and the skewness of the probability density function, Sk, in the form of,

$$k_{s,\ \mathrm{predicted}} = A\, k_{rms}(1 + Sk)^b \tag{1}$$

where A and b are determined from a least square fit. It should be noted that this model is only applicable in the fully-rough regime. If fact, developing a model that covers all regimes - that is, hydraulically-smooth to transitionally-rough and fully-rough regimes, has proven to be challenging. Flack et al. (2016) generated 15 surfaces via grit-blasting, with various media sizes and combinations of thereof, and the skin friction was measured for a wide range of Reynolds numbers, covering all roughness regimes. They showed that the roughness function, ΔU^+ remains largely invariant with surface texture. One possible reason why these surfaces did not display significant differences in the transitionally-rough regime could be linked to Sk, which for all the tested surfaces were inherently negative. Additionally, the authors verified that k_s correlated quite well with k_{rms} and Sk.

Based upon the work from Flack et al. (2016), the current work takes a more systematic approach, which consists of mathematically generating surfaces roughness where the roughness statistical parameters can be controlled. Three surface were created where the amplitude of the roughness was nominally kept constant coupled with a systematic variation in the power-spectral density. The reproduction of these surfaces was done via high-resolution 3D printing, and subsequent hydrodynamics tests were performed in a channel flow facility where the skin-friction was measured.

2. Experimental facilities and methods

The present experiments were conducted in the high Reynolds number turbulent channel flow facility at the United States Naval Academy. The test section is 25 mm in height (H), 200 mm in width (W), and 3.1 m in length (L). The channel flow facility has a reservoir tank containing 4000 L of water. The water temperature is held constant to within ± 0.25 °C using a thermostat-controlled chiller. The water is deaerated and filtered to remove particulate material larger than 2 µm. The flow is driven by two 7.5 kW pumps operated in parallel. The pumps are operated by separate, variable frequency drive units which are computer-controlled. The flow rate is measured using a Yokogawa ADMAG AXF magnetic flow-meter that has an accuracy of 0.2% of the reading. The bulk mean velocity in the test section ranges from 0.4–11.0 m/s, resulting in a Reynolds number based on the channel height and bulk mean velocity (Re_m) range from 10,000–300,000. Further details of the facility including flow management devices, tripping, and flow quality are given in Schultz and Flack (2013).

Nine static pressure taps are located in the test section of the channel. They are 0.75 mm holes and are placed along the centerline of the side wall of the channel and are spaced 6.8H apart. The streamwise pressure gradient (dp/dx) is determined with a GE-Druck LPM 9000 series differential pressure transducer with a 100 mbar range, and have an accuracy of ± 0.1% of full scale. Pressure taps 5–8 are used to measure the streamwise pressure gradient in the channel, located ~ 90H–110H downstream of the trip at the inlet to the channel. The linearity in the measured pressure gradient using these four taps was quite good with a coefficient of determination (R^2) of the regression generally greater than 0.995.

The wall shear stress, τ_w, is determined via measurement of the streamwise pressure gradient given as follows:

$$\tau_w = -\frac{H}{2}\frac{dp}{dx} \tag{2}$$

or expressed as the skin-friction coefficient, C_f

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U^2} = 2\left(\frac{u_\tau}{U}\right)^2 \tag{3}$$

where H = channel height, p = static pressure, x = streamwise distance, ρ = fluid density, U = bulk mean velocity, and u_τ = friction velocity. A similarity-law procedure of Granville (1987) for fully-developed internal flows was employed to determine the roughness function, ΔU^+. Granville's method states that the roughness function can be obtained by:

$$\Delta U^+ = U_s^+ - U_r^+ = \sqrt{\frac{2}{C_{f_S}}} - \sqrt{\frac{2}{C_{f_R}}} \tag{4}$$

where the subscripts S and R represents smooth and rough surfaces, respectively, evaluated at the same $Re_m(C_f)^{\frac{1}{2}}$ or Re_τ.

The flow develops over smooth walls for a distance of 60H in the upstream portion of the channel. The roughness-covered plates (~ 1.5 m) form the top and bottom walls for the remainder of the test section. This results in a roughness fetch of 30H before the first tap used in the determination of dp/dx. In a previous work Flack et al. (2016), fully-developed flow was confirmed with velocity profiles located 90H and 110H downstream of the trip. Details of the velocity measurements are outlined in Schultz and Flack (2013).

The rough surfaces investigated in this work were created mathematically with the desire to achieve full control of the surface parameters. That is, surface statistics, such as *r.m.s, peak-to-trough height, skewness* and *kurtosis*, can be systematically changed and controlled. This methodology opens the possibility to better identify the roughness scales that contribute the most to frictional drag, as well as the onset to the transitionally- and fully-rough regimes. The surfaces were generated in MATLAB using a circular Fast Fourier Transform (FFT) with a random set of independent phase angles, distributed between 0 and 2π, with a power-law slope transfer function, $H = \kappa^P$, where κ is the wavenumber and P the slope of the power-law. This approach is similar to the one used by Anderson and Meneveau (2011). Therefore, the roughness generated by this method contains a multitude of scales that obeys the imposed power-law slope power spectrum ($E(\kappa) \sim \kappa^P$), and the surface elevation possesses a Gaussian probability-density-function (*p.d.f*). For the surface roughness tested in this work, the slope of the power law was systematically changed while holding the amplitude constant. Table 1 summarizes the surface statistics of the three tested surfaces, $P = -0.5, -1.0$ and -1.5, which includes the roughness *r.m.s*, k_{rms}, peak-to-trough height, k_t, mean elevation, k_a, skweness, Sk, kurtosis, Ku, effective slope, ES (Napoli et al., 2008), and the equivalent sang-grain roughness height, k_s. The generated surfaces were then reproduced using a high-resolution 3D printer (Projet 3500 HDMax, with lateral resolution 34 µm, elevation resolution 16 µm). Due to the complexity of these rough surfaces and limitations of the printer's software,