Skin-Friction Measurements in the Transitionally Rough Regime

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Abstract
An important unresolved issue in fluid mechanics is accurately predicting the drag on a generic rough surface. Currently, hydrodynamic tests are required to determine an equivalent roughness height (k_s) for a given roughness geometry. The equivalent height takes into account the surface texture and roughness density. This technique is employed in the widely used Moody [1] diagram which is based on the results of Nikuradse [2] and Colebrook [3]. Using this diagram, a friction factor as a function of Reynolds number can be determined for a narrow range of surfaces whose equivalent roughness heights are listed. Slightly altering the roughness texture or density could result in a significantly different equivalent roughness scale. Additionally, if the specific roughness is not on the list, a hydrodynamic test needs to be performed. While the Moody diagram is accurate in the fully rough regime for a given equivalent roughness, some studies [4, 5] have shown discrepancies in the transitionally rough regime. Therefore, the diagram may only capture the asymptotic behavior of the skin friction in the hydraulically smooth and fully rough flow regimes. This indicates that a mapping of the transitionally rough regime for a wide range of roughness geometries, coupled with detailed measurements of roughness scales, is needed to accurately predict frictional drag in the transitionally rough regime.

The overall goal of this research is to determine the roughness scales that can be used to accurately predict frictional drag based solely on surface measurements. Previous work by the present authors has related frictional losses to surface parameters and moments of the surface probability distribution function (*pdf*). Tests in the fully rough regime [6] indicated that the important predictive scales are the *rms* roughness height (k_{rms}), a statistic based on the entire range of roughness heights, and the skewness (S_k) of the *pdf*, a measure of whether the surface has more peaks or troughs. The best gauge of departure from hydraulically smooth was the peak-to-trough roughness height (k_t), indicating that the largest roughness scales have the greatest influence the onset of roughness effects [7]. The current paper highlights work to map out the entire transitionally rough regime, thus determining the onset of roughness effects, the shape of the roughness function in the transitionally rough regime and the start of fully rough behavior. This is accomplished by taking very accurate pressure drop measurements in a fully developed channel flow facility. Results from the hydrodynamic test are used to relate roughness functions to appropriate scales based on surface statistics obtained from detailed surface profilometry.

A fully developed channel flow facility has been constructed in which measurements of the streamwise pressure gradient allow the wall stress to be determined within ±1% to accurately map the skin friction coefficient and the roughness function throughout the transitionally rough regime (figure 1). The channel has a height of 2.5 cm, a width of 20.3 cm, and a length of 3.25 m, producing fully developed channel flow. The Reynolds number range is 12,000 – 320,000 (based on the channel height, H, and the bulk mean velocity, U_m). The facility has ten static pressure taps in the fully developed region of the flow. The small scale of the facility make it ideal for testing a wide range of surfaces. A smooth surface and three grades of sandpaper were tested. A sample surface topographical map for 320 grit sandpaper is shown in figure 2. The surfaces were profiled with a Veeco WycoNT9100 optical profilometer utilizing white light interferometry with sub-micron vertical accuracy. Surface statistics for all three sandpapers are given in table 1.

The skin-friction is determined from the pressure drop in the fully developed regime between locations 90H and 110H downstream of the trip at the inlet to the channel. The skin friction coefficient, C_f, is shown as a function of Reynolds number, Re_m in figure 3. Also shown for comparison are the experimental results of Monty [8] and the recent empirical correlation of Zanoun, *et al.* [9]. The agreement between the present results and those of Monty is within ±1% over the common range. The agreement with the empirical correlation proposed by Zanoun *et al.* is also within ±2.5% for $Re_m \leq 150{,}000$. The rough wall skin friction coefficients indicate that the facility can be used to discern small differences in surface roughness. Results indicate that the departure from hydraulically smooth behavior occurs at progressively higher Reynolds numbers for finer grade sandpapers. The facility is also able to capture the entire transitionally rough regime, with profiles showing fully rough behavior with a constant C_f for a wide range of Re_m.

An alternative presentation of the frictional drag is the roughness function (ΔU^+) as a function of roughness Reynolds number $k_s^+=U_\tau k_s/\nu$ (figure 4), where U_τ and ν are the friction velocity and kinematic viscosity, respectively. The roughness function is defined as the downward shift in the mean flow profiles in the log-law region. The results in figure 4 indicate that all three sandpaper surfaces display uniform roughness functions with the experimental uncertainty. It should also be noted that these results match the previously obtained roughness function of Ligrani & Moffat [10] based on the uniform sand grain results of Nikuradse [2]. For all the present sandpaper surfaces, the onset of roughness effects occurs at k_s^+ = 5.5 with transition to fully rough behavior at k_s^+ = 50. The corresponding Nikuradse uniform sand limits were k_s^+ = 5 and 70. Tests are planned in the facility for a range of surfaces of engineering interest including ship bottom paints. These results will be discussed in the final paper and the conference presentation.

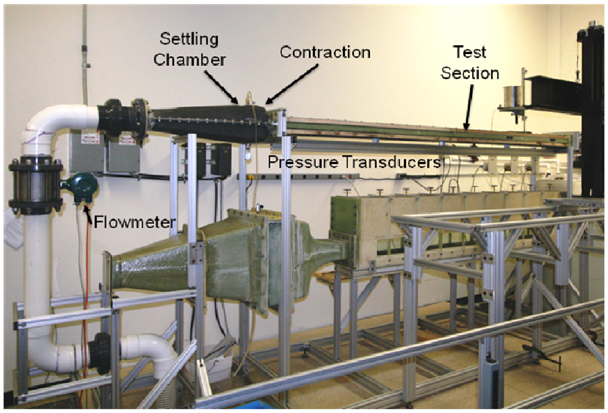

Figure 1. Fully developed channel flow facility.

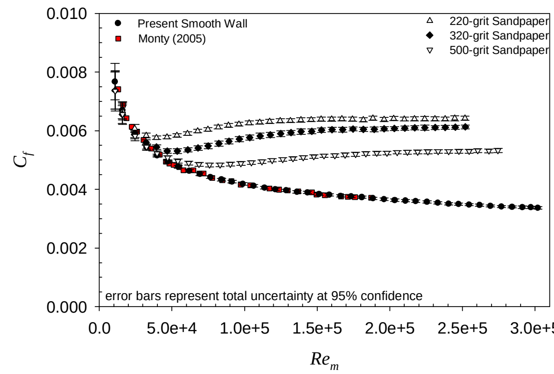

Figure 3. Skin friction coefficients.

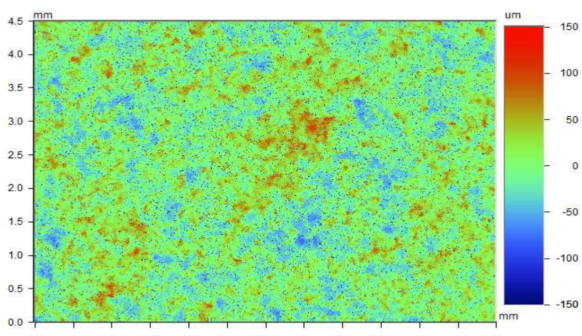

Figure 2. Surface topographical map of 320 grit sandpaper.

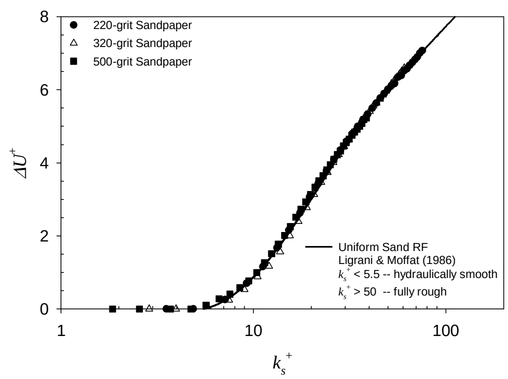

Figure 4. Roughness functions for sandpaper roughness.

Table 1. Surface statistics.

	k_{rms} (μm)	k_t (μm)	S_k	K_u
220 grit	28.2	309	0.47	3.58
320 grit	24.8	216	0.34	3.22
500 grit	21.0	178	-0.12	2.72

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