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14. ABSTRACT
An experimental study of the pressure fluctuations generated by zero-pressure-gradient turbulent boundary layers at high Reynolds numbers over rough walls has been performed. The work, which extends the study of Meyers et al. (J Fluid Mech., vol. 268, pp. 261-293, 2015), has been specifically directed at examining the scaling behavior of the pressure fluctuations. Measurements have been made on boundary layers formed over a series of deterministic rough surfaces selected to define, in combination with those of Meyers et al., systematic variations in roughness size, density, shape and distribution as well as surfaces formed from combinations of shape and size. Major findings of this work include include: the apparent universality of the high frequency viscous scaling proposed by Meyers et al, and that the associated scaling velocity (the shear friction velocity) is a unique function of roughness Reynolds number and density; the fact that low-frequency pressure fluctuations scale most accurately on defect velocities (either the convection or boundary layer averaged defect velocity); that the mid-frequency behavior of the pressure spectrum cannot in general be scaled since pressure fluctuations in this range are highly dependent on the local topology of the surface. Significant findings also include new insights into the relationship between wall pressure fluctuations and the velocity fluctuations that produce them, as well as direct measurements

15. SUBJECT TERMS
Turbulence, boundary layers, roughness, pressure fluctuations

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Establishing universal scaling laws for pressure fluctuations in high Reynolds number rough wall turbulent boundary layers

Final Technical Report to the Office of Naval Research
(Technical Monitors: Joseph Gorski and Thomas Fu)

Grant N00014-15-1-2247

William J. Devenport, Liselle Joseph and Russell Repasky
September 2018

Introduction

This final technical report summarizes work conducted for the above grant during the period April 1, 2015 until June 30, 2018. This project is concerned with revealing the scaling and physical mechanisms behind the surface pressure fluctuations produced by rough wall turbulent boundary layers. The experiments of Meyers *et al.* (J Fluid Mech., vol. 268, pp. 261-293, 2015), performed by our group at Virginia Tech published during the first phase of this project, for the first time provided views of the wall pressure spectrum of rough wall turbulent boundary layers at carefully-controlled conditions representative of large scale practical applications. These conditions produce substantial separation between the viscous, the roughness, and the boundary layer scales. Consequently, Meyers *et al.* were able to identify three distinct scaling regions in the wall-pressure spectrum, including the so-called classical low frequency scaling on boundary layer thickness and friction velocity, a mid- frequency scaling on the Strouhal number of the roughness elements (of the type proposed by Blake, J. Fluid Mech., vol. 44, pp. 637-660, 1970) and a new high-frequency viscous scaling based on the substrate friction velocity U_ν. They found that U_ν could be quite accurately predicted from estimates of the roughness element drag coefficient. Although Meyers *et al.*'s experiments were limited to hemispherical roughness fetches of the same sparseness ratio, it appears plausible that their findings, and the physics they imply, are quite fundamental and apply to a large range of high Reynolds number rough wall boundary layers. The purpose of this project was to test this hypothesis: to study high Reynolds number turbulent boundary layers generated by deterministic rough surfaces of much more varied geometry and to use these measurements to generate additional fundamental understanding of the boundary layer dynamics at different scales, as reflected in their wall pressure signatures. Our strategy has been in part to examine, extend, improve on or revise the scaling behavior established by Meyers *et al.*, focusing separately on frequency regimes controlled by boundary layer, roughness, and viscous scales.

Specific questions that were a focus for the research were:

1. How universal is the new high-frequency viscous scaling on U_ν and the mid-frequency Strouhal number scaling? Specifically, how far do they persist as we increase the roughness density and what happens when the roughness is dense so that the substrate friction velocity ceases to be a significant controlling parameter of the flow?
2. What happens when we systematically vary the roughness element shape and density? Can we continue to predict U_ν based upon reasonable estimates of the roughness element drag coefficient? Does the Blake scaling continue to describe the mid-frequency behavior, and does the -4/3 region seen here persist?

3. What happens at low frequencies? Is the scaling on wall shear stress and boundary layer thickness robust?
4. Is there an identifiable relationship between the low-frequency scaling and the scaling of low-frequency velocity fluctuations at different locations within the boundary layer?
5. What happens for multi-scale or multi-shape surfaces? Do such surfaces in any sense produce flows that are linear combinations of the flows over the single shape or size components of the surface
6. Depending on the answers to the above questions, can we formulate an interpolation function for the pressure spectrum of rough wall flows that is sufficiently universal to be of practical use to engineers and scientists?
7. Are there lessons to be learned concerning the measurement of wall pressure fluctuations in turbulent flow?

Major Activities

Major activities in the project were centered on two sequences of wind tunnel tests, conducted in August 2015 and September/October 2016. These intensive experiments, each involving detailed turbulence and wall pressure measurements on sequences of large scale surfaces, necessarily were preceded by extended periods of preparation, and followed by much work reducing, analyzing and interpreting the results obtained. Additional experiments in an auxiliary facility were also a focus of instrumentation studies in 2017 and 2018.

Preparations for the main experiments included developing scientific strategies for surface selection, surface design and fabrication, as well as instrumentation selection, preparation and calibration. Each rough surface needed to be 24-feet long and 6-feet wide in order to generate the high Reynolds numbers desired and to precisely accommodate the microphone instrumentation needed for measurement of surface pressure spectra and space time correlations. Each surface needed to have accurately defined geometry based on repeated patterns of between 50,000 and 500,000 roughness elements. Surface design and fabrication was conducted by vertically integrated student teams bringing together high-school students, undergraduates, MS and PhD graduate students and research staff. Assembling and testing these surfaces in the test section of the Virginia Tech Stability Wind Tunnel similarly required collaboration amongst a diverse team of researchers. Indeed, a significant stretch of the 2016 wind tunnel entry was co-located with a senior-level required undergraduate course for aerospace and ocean engineering BS students. Thus, in addition to the graduate students, undergraduate researchers, and faculty explicitly involved in the research, this experimental test sequence provided research training to some 160 undergraduate students, many of whom graduated in May 2017. Student activities on the project were led by Liselle Joseph, who graduated with her PhD on this work in August 2017. In total 5 new surfaces were developed and studied as part of this project in addition to the smooth surface control case and the three surfaces that had been fabricated previously for the Meyer's *et al.* study. The resulting 9 surfaces produced a strategically designed set (Fig. 1 in the attached PDF).

The focus of the 2015 wind tunnel entry was the boundary layers generated by rough surfaces of hemispherical elements of different density, but otherwise identical geometry. Specifically, the two new roughness fetches formed from square arrays of hemispheres of sparseness ratio 0.13 and 0.33 (Fig. 1, cases 5 and 6), compared with a sparseness ratio of 0.052 for the similar surface of Meyers *et al.* (case 3) were investigated. Boundary layer flows over the new rough surfaces, studied for a range of free-stream velocities produced momentum thickness Reynolds numbers in excess of 100,000, roughness Reynolds numbers from 300 to 800 and boundary layer thickness to roughness size ratios of about 85. Three-component mean velocity and turbulence stress profiles were measured in these boundary layers using sub-miniature four-sensor anemometer probes. Fluctuating pressure on the wall was measured using an array of seven Bruel & Kjaer (B&K) 4138-A-015 1/8-in microphones were fitted with pinhole caps to reduce their sensing area and thereby reduce the effect of spatial averaging.

The focus of the 2016 wind tunnel entry was three further cases in which roughness element shape was varied (introducing sharp-edged cylindrical elements, case 7), and in which multi-shape and multiscale surfaces were studied formed by linear combination of previously studied cylindrical and hemispherical element surfaces (case 8) and hemispherical elements of different sizes (case 9). Again, detailed turbulence and pressure fluctuation surveys were conducted. In addition, two surfaces tested previously in 2015 (cases 5 and 6) were re-mounted and re-tested. The purpose of this repetition was to improve the accuracy of Reynolds stress profiles measured in these boundary layers.

The focus of the 2017 and 2018 auxiliary wind tunnel experiments (carried out in the VT Anechoic Wall Jet Wind Tunnel) was diagnosis and understanding of the response of wall mounted pinhole microphones to the wall shear stress generated by an over-riding boundary layer. These experiments involved MS student Russell Repasky and PhD student Agastya Balantrapu in experiments studying the dynamic response characteristics of the B&K 1/8-in microphones as a function of mean wall shear stress generated by the over-riding wall jet, as well as microphone pinhole geometry.

Specific Objectives

The specific objectives of this study have been to:

1) Broaden the understanding of the flow structure of a turbulent boundary layer over rough surfaces of varying geometries. Specifically we have sought to
   a) Infer the presence of organized motions near rough elements based on the pressure field measured at different locations relative to the elements
   b) Reveal the effect of rough surfaces of different element shape and spacing on the turbulence statistics and typical boundary layer parameters
   c) Identify characteristic flow features from the pressure spectrum of rough surfaces of different geometries
   d) Detail the relationship between the pressure spectrum of single-scale rough surfaces with that of two-scale rough surfaces (which are combinations of the single- scale surfaces)

2) Identify the scaling laws that govern the time-spectrum of wall pressure fluctuations in various frequency ranges. More specifically,
   a) Determine whether the high frequency shear friction velocity (U_ν) scaling of Meyers et al (2015) is universal to rough surfaces of different shape and roughness density
   b) Determine whether estimates of the roughness drag coefficient can be used to usefully predict the shear friction velocity for rough surfaces of different shape and density
   c) Shed light on the nature of the shear friction velocity
   d) Identify the parameters that govern the pressure spectrum at low frequencies, and thus the associated source of these pressure fluctuations
   e) Identify and explain similarities in low-frequency pressure scalings and the scaling of turbulent velocity fluctuations throughout the boundary layer.

f) Assess the effectiveness of the presently proposed mid-frequency roughness scalings, as it relates to rough surfaces of different shape and density
g) Evaluate the mid-frequency region as an `overlap' region where the low- frequency and high-frequency scaling both apply
h) Determine the extent to which the location of the pressure measurement within the depth of a rough surfaces influences the pressure measured and its scaling
i) Explore the effectiveness of scalings laws which govern single-scale roughness when applied to two-scale rough surfaces

3) Uncover the effect of rough surfaces of different geometries on the space-time correlation of the wall-pressure fluctuations. Specifically,
   a) Infer, from streamwise and spanwise spatial separations, the persistence of turbulent eddies in the boundary layer over various kinds of rough surfaces
   b) Explore the role that roughness geometry plays on the convection velocity of turbulent eddies in the boundary layer

4) Explore the development of an interpolation function for the pressure spectrum of rough wall flows which is sufficiently universal to be of practical use.

5) Determine and quantitatively assess the effects of mean shear on turbulent pressure fluctuations measured using pinhole microphones at a wall.

Major findings

Detailed results were obtained, analyzed and interpreted in the areas of all the above objectives. Full presentation and discussion of these is contained in the PhD dissertation of Liselle Joseph ("Pressure Fluctuations in a High-Reynolds-Number Turbulent Boundary Layer over Rough Surfaces of Different Configurations", Virginia Tech, 2017). A selection of principal findings are summarized below.

1. The high frequency scaling of Meyers et al., based on the shear friction velocity U_ν, is robust and applies to the pressure spectra measured on all the surfaces, regardless of roughness shape, density, size and combinations of them (Fig. 2).
2. Roughness element pressure drag coefficients C_{dp}, estimated from U_ν, are a unique function of roughness element density (represented by the sparseness ratio lambda) and roughness Reynolds number k_g^+ but independent of roughness shape details. A simple curve fit that correlates all C_{dp} measurements has been developed (Fig. 3)
3. The so-called classical low-frequency scaling does not scale the surface pressure spectrum of rough wall boundary layers particularly well. Many alternative low-frequency scalings based on suggestions from the literature, such as from the work of Blake, deGraff and Eaton and Klewicki were attempted, with no better success.
4. Instead, the scaling of the pressure spectrum at low frequencies is found to be accurately scaled using variables based on the convection velocity of the largest turbulent eddies in the boundary layer (Fig. 4) U_c. Specifically, U_c and the boundary layer thickness are found to scale the frequency of the pressure fluctuations, and $U_e - U_c$ and the density are found to scale the intensity of the pressure fluctuations.

5. Alternatively, at low frequencies, the pressure spectrum can be accurately scaled using the spatial average of the mean velocity in the boundary layer and the boundary layer thickness itself (Fig. 5). This scaling, when applied to the mean velocity defect profile is known as the Zagarola Smits scaling ("A New Mean Velocity Scaling for Turbulent Boundary Layers". ASME FEDSM'98, 1998). In that context it is known to provide correlation between the outer velocity distributions of boundary layers tolerant of surface condition, initial condition and mild pressure gradient effects, consistent with the robustness we observed here
6. The convection velocity defect and Zagarola Smits scalings also perform well in relating the intensity of wall-normal velocity fluctuations measured throughout the boundary layers formed above different rough surfaces. These scalings, however, do not do well in relating these velocity fluctuations to those measured in the smooth wall boundary layer. It is as though the rough wall boundary layer turbulence is a more efficient producer of pressure fluctuations (for a given turbulence level) than a smooth wall boundary layer. This observation that suggests that the scattering of pressure fluctuations from roughness elements (as in roughness noise generation) may provide an additional source when the wall is not flat.
7. The mid-frequency Strouhal number scaling of Blake for rough surfaces performs poorly in relating pressure spectra measured at the substrate level of surfaces with difference sparseness ratio. This happens because the mid-frequency regions of spectra measured at the substrate level of a high density rough surface roll off at much lower frequency than those measured over less dense surfaces, and do not display a -4/3 slope, or any consistent slope, in this region (Fig. 6). As a result no simple scaling can be formed in this region.
8. In contrast pressure spectra measured at the roughness tops of the high density rough surface display a form qualitatively very like that of pressure spectra measured under a smooth wall boundary layer. The difference appears to be a consequence of the evanescent decay of pressure fluctuations between the roughness tops and substrate. Analytical predictions of this decay appear to agree well with measurements, suggesting that the form of the wall pressure spectrum may be predictable in these terms.
9. At mid frequencies, the slope of the pressure fluctuation spectrum is also a function of the proximity of the measurement to roughness elements and thus there appears to be little prospect for any universal mid-frequency scaling.
10. The establishment of a low frequency scaling, the apparent universality of the Meyers *et al.* high frequency scaling and the simple functional dependence of its parameters on roughness density and Reynolds number, have been shown to form a sufficient basis for the development of an interpolation function for the rough wall pressure spectrum. Without referencing local flow behavior, blending between the better understood low and high frequency scaling regions may be sufficient to define the functional dependence of the mid-frequency spectrum.
11. It is clear that the response of pinhole microphones used for wall pressure fluctuation measurement is a significant function of the wall shear stress of the over-riding flow. In accordance with previous researchers studying the response of resonators in the context of liners and silencers, the pinhole microphone reactance reduces with increase in wall shear. At variance with those studies, the pinhole microphone resistance was

found to first reduce with wall shear before reaching a minimum. These effects must be accounted for *a priori* or *a posteriori* if accurate wall pressure measurements are desired.

Research Training

A major purpose of this project is the research training of students over a range of levels. The project is the entire focus of Liselle Joseph's dissertation. Liselle successfully completed her PhD in August 2017, as well as current preparation and submission of her research findings to the Journal of Fluid Mechanics. Liselle also attended the 22nd AIAA/CEAS Aeroacoustics Conference in Lyon France in June of 2016 where she presented her findings on the project at that time. This work has also been the entire subject of Russell Repasky's MS research (graduation anticipated May 2019).

Others who have benefitted through the training and professional development provided by the project include Nicholas Molinaro, who was responsible for all the flow measurements made. Nicholas graduated with his thesis MS in May 2017 on the topic of two-point space time correlations in plane turbulent wakes, relevant to a parallel effort carried out under ONR sponsorshi. Nevertheless, Nicolas gained the research training needed to contribute to that work through his efforts on this project. This project is also providing training opportunities for Agastya Balantrapu, a new PhD student, in planning and executing large wind tunnel tests as well as in the dynamic calibration of microphone wall pressure sensors in the presence of shear. Research training was also provided by Tim Meyers in the role of consulting research engineer on this effort.

A major challenge for this project was how to manufacture accurate rough deterministic surfaces with up to half a million roughness elements. This problem was tackled by teams including high school, undergraduate, and graduate student researchers. This project involved 4 high school students from the Southwest Virginia Governor's School Program in 2015, and 3 in 2016, working with 3 undergraduates (Michael Colazza, Cayla Schnebele and Paul Stellato) under the mentorship of PhD student Liselle Joseph, working on fabrication strategies for complex surfaces and element geometries. In Fall 2016 experiments on the turbulence structure of rough-wall boundary layers over multi-scale and multi-shape surfaces were integrated into AOE 4154 Aerospace Engineering Laboratory, a required course for some 140 aerospace engineering seniors. The research test matrix was subdivided into some 78 test conditions, each group of students taking hot-wire profiles or surface pressure fluctuation measurements over a small portion of the test matrix. Students were required to analyze, plot and discuss their results in particular to consider elements of their results (such as the slopes of logarithmically plotted pressure spectra) that were fundamental to the project.

Publications

Degrees

1. Joseph, Liselle A.. *Pressure Fluctuations in a High-Reynolds-Number Turbulent Boundary Layer over Rough Surfaces of Different Congurations*. Ph.D. (2017). Virginia Tech.
2. Repasky, Russell J., *The Large Scale Structures of a High Reynolds Number Turbulent Boundary Layer over Rough Surfaces* M.S. (anticipated May 2019). Virginia Tech.

Journal Papers

3. Meyers, T., J. B. Forest and W. J. Devenport (2015). The wall-pressure spectrum of high-Reynolds-number turbulent boundary-layer flows over rough surfaces. *Journal of Fluid Mechanics*. 768 261. DOI: 10.1017/jfm.2014.743

Textbook

4. Glegg, S., and Devenport, W., *Aeroacoustics of Low Mach Number Flows: Fundamentals, Analysis, and Measurement*: Elsevier Science, 2017.

Conference Papers

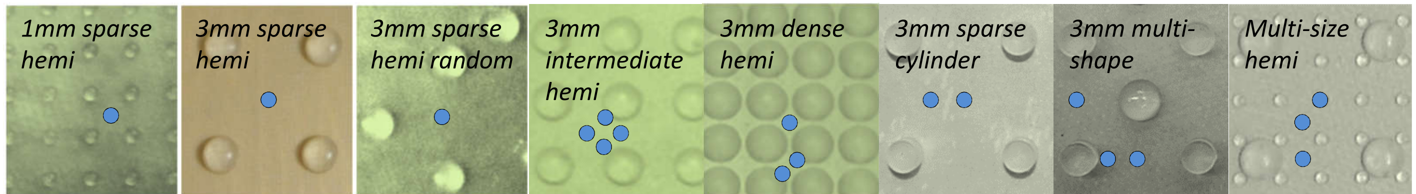
5. Joseph, Liselle A. Meyers, Timothy W. Molinaro, Nicholas J. Devenport, William J. (2016). Pressure Fluctuations in a High- Reynolds-Number Turbulent Boundary Layer Flow over Rough Surfaces of Different Element Spacing. 22nd AIAA/CEAS Aeroacoustics Conference (peer reviewed abstract).
6. Repasky, R., L. A. Joseph, N. J. Molinaro and W. Devenport (2018). The Large Scale Structures of a High Reynolds Number Turbulent Boundary Layer over Rough Surfaces. <u>24th AIAA/CEAS Aeroacoustics Conference</u>. Atlanta, GA.
7. Balantrapu, A. N., R. Rapasky, L. A. Joseph and W. Devenport (2018). The Dynamic Response of a Pinhole Microphone under Flows of Varying Shear Stress. <u>24th AIAA/CEAS Aeroacoustics Conference</u>. Atlanta, GA.

Impact

The fundamental insight into turbulent boundary layers generated by this project has had, and will have, a direct impact on both the community understanding of the physics that governs these near-universal flows, the ability of engineers and scientists to predict these flows and their effects, and on the understanding of turbulent shear flows in general. This work impacts on the many engineering applications, from vehicles to wind turbines, where high Reynolds number boundary layers occur and determine the performance characteristics and environmental acceptability of these devices.

The impact of this work on related disciplines is particularly significant. Wall pressure fluctuations are the source terms used by aero/hydro acousticians for computing roughness noise and trailing edge noise. They are also the source terms for hydro/aero-elastic calculations of structure borne noise and vibration. The scaling properties being revealed in this work directly impact the scaling of these practically important phenomena, and thus provide new insight into their behavior at vehicle or system scales.

As detailed above, the project has had a significant impact on the research training of high-school and college students. As such this work is helping to train the next generation of engineers/scientists in an area of broad technical relevance. This project has also be instrumental in demonstrating a new model for how to integrate large numbers of undergraduate students in research, through the collocation of research testing with educational laboratory classes.



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
	Smooth	*1mm sparse hemi*	*3mm sparse hemi*	*3mm sparse hemi random*	*3mm intermediate hemi*	*3mm dense hemi*	*3mm sparse cylinder*	*3mm multi-shape*	*Multi-size hemi*
k_g	0	1mm	3mm	3mm	3mm	3mm	3mm	3mm	3/1mm
Shape		hemi	hemi	hemi	hemi	hemi	cylinder	hemi/cyl	hemi
Spacing		5.5mm	16.5mm	random	10.4mm	6.5mm	16.5mm	11.7mm	16.5/5.5mm
$\lambda/\Delta y$ (mm)	0/0	0.052/0.069	0.052/0.21	0.052/0.21	0.13/0.52	0.33/1.34	0.052/0.24	0.104/0.45	0.104/0.28
Re_θ	27000 - 92000	29000 - 72000	31000 - 83000	33000 - 83000	50000 - 129000	50000 - 127000	47480 - 103700	50100 - 125300	44900 - 92900
δ	230mm	211mm	220mm	220mm	260mm	255mm	239mm	222mm	233mm
δ/k_g		~211	~74	~74	~87	~85	~80	~74	~78/234
k_g^+		62 - 172	205 - 507	177 - 492	299 - 770	312 - 800	254 - 547	235 – 551	236 – 521 79 - 174

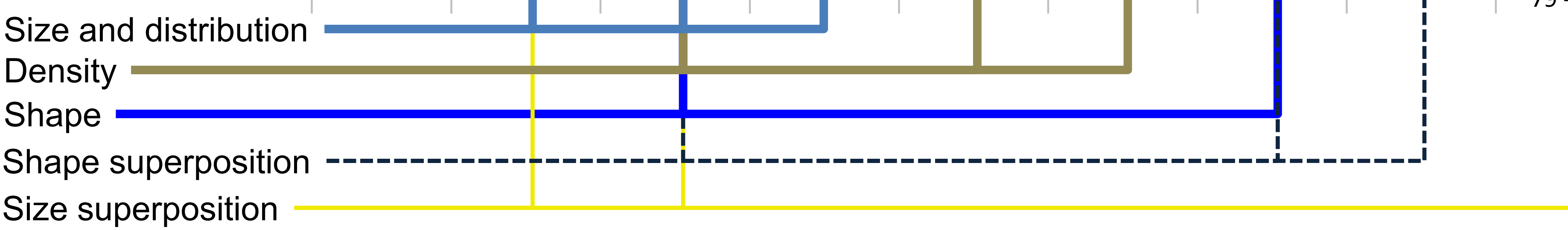


Figure 1. Flows studied during the project compared with the smooth and rough surface boundary layers investigated by Meyers *et al.*(2015) (first 4 columns). Boundary layer characteristics of the flows generated by these surfaces are also given. Graphic at the bottom of the figure shows independent effects revealed by different combinations of these flows.

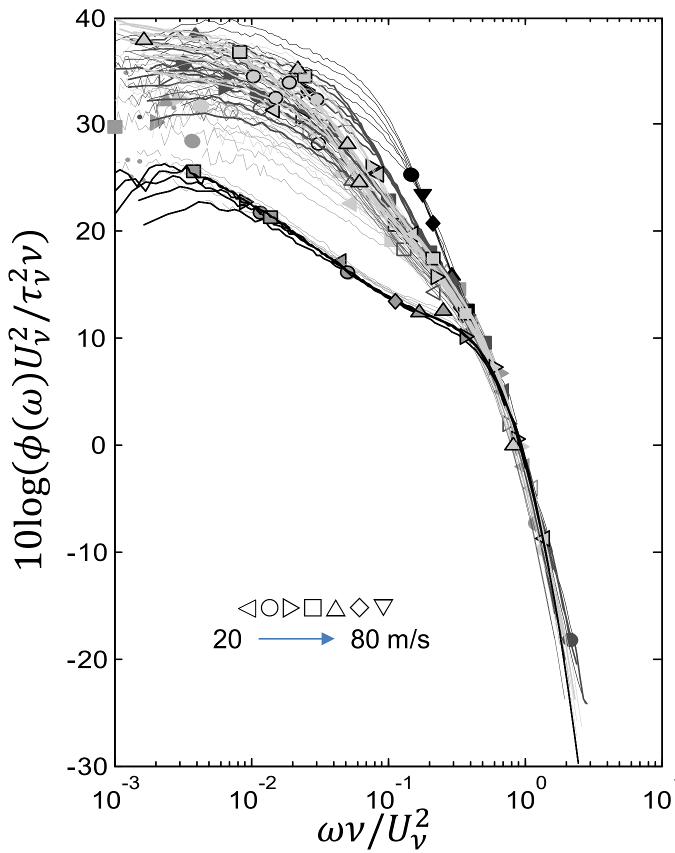


Figure 2. Scaling of the pressure spectra of all smooth and rough wall flows (some 60 cases) represented in Figure 1 using the high frequency scaling of Meyers *et al.*(2015) based on the shear friction velocity U_ν.

$$C_{D_p} = \frac{2}{\lambda}\left(\frac{U_\tau^2}{U_e^2} - \frac{U_\nu^2}{U_e^2}\right)$$

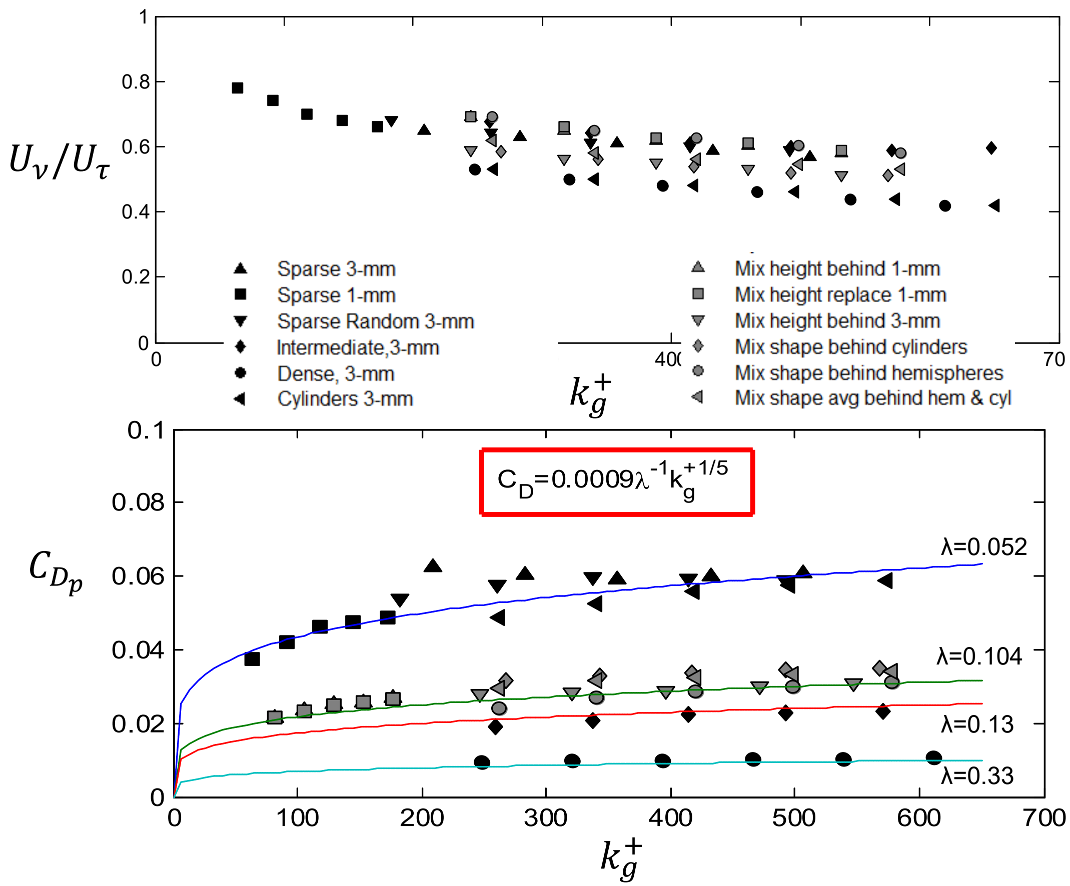


Figure 3. Shear friction velocities (top) and implied roughness element pressure drag coefficients (bottom) inferred from the high-frequency spectral collapse shown in Figure 2. Bottom figure includes the curve fit of roughness element drag coefficient as a function of sparseness ratio and roughness Reynolds number

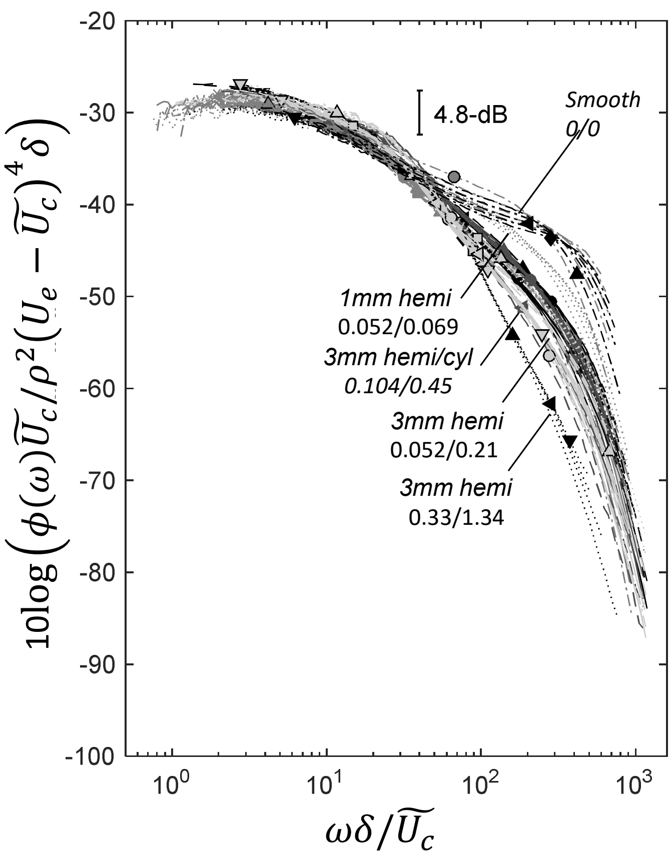


Figure 4. Scaling of the pressure spectra of all smooth and rough wall flows (some 60 cases) represented in Figure 1 using the large scale asymptote of the convection velocity of pressure fluctuations, $\widetilde{U_c}$ determined from two-point pressure measurements..

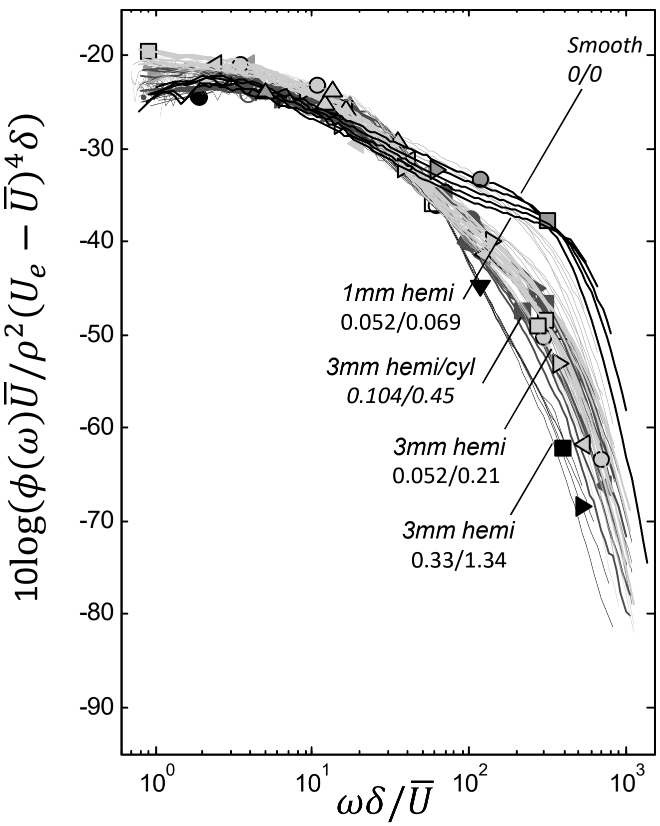


Figure 5. Scaling of the pressure spectra of all smooth and rough wall flows (some 60 cases) represented in Figure 1 using the new spatially averaged boundary layer mean velocity defect for pressure, and the mean velocity and boundary layer thickness for frequency. Note that the spatially averaged mean velocity $\overline{U} = U_e(1-\delta^*/\delta)$ where δ^* is the boundary layer displacement thickness.

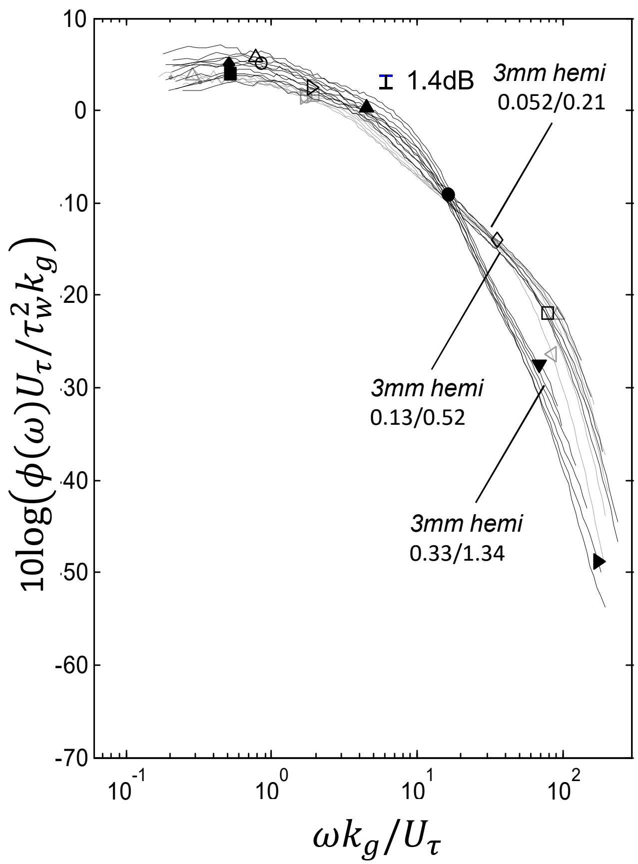


Figure 6. Scaling of the pressure spectra of hemispherical rough surfaces of different density using the mid-frequency Strouhal number scaling of Blake