Compressible Turbulent Skin Friction on Rough and Rough/Wavy Walls

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Nomenclature

C_f = skin-friction coefficient, $\tau_w/\frac{1}{2}\rho_\infty U_\infty{}^2$
C_{f_o} = smooth-wall skin-friction coefficient
k = roughness dimension, peak-to-valley
M = Mach number
Po, To = stagnation pressure, temperature
Re/ft = unit Reynolds number, $\rho_\infty U_\infty/\mu_\infty$
Re_k = roughness Reynolds number, kU_τ/ν_w
U = velocity
U_τ = friction velocity, $(\tau_w/\rho_w)^{1/2}$
U^+ = law-of-wall coordinate, (U/U_τ)
y = vertical coordinate, from $(k/2)$
y^+ = law-of-wall coordinate, (yU_τ/ν_w)
δ = boundary-layer thickness
$\varepsilon_{sw}, \varepsilon_{lw}$ = short, long waveform amplitude
$\lambda_{sw}, \lambda_{lw}$ = short, long waveform wavelength
μ, ν = viscosity, kinematic viscosity
ρ = density
τ = shear stress

Subscripts

∞ = local freestream condition
w = at wall, or based on wall properties

Theme

THE objective of this research was to investigate experimentally effects of roughness and roughness superimposed on single and multiple, shallow, periodic waveforms on turbulent boundary-layer skin friction and velocity profile in compressible, adiabatic flow. Results were generated in support of the Trident missile development program, which required information on effects of fiberglass-wound motor case (i.e., random rough/wavy) surface conditions on missile range performance.

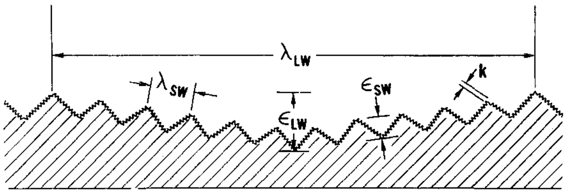

Fig. 1 Model surface schematic.

Contents

Surface contour traces taken from an actual motor case showed the existence of three dominant features: 1) a roughness scale; 2) a short wavelength scale; and 3) a long wavelength scale. In an attempt to simulate these features, several rough/wavy patterns were created. Figure 1 schematically shows the most complex simulation, wherein roughness was superimposed on a short wavelength waveform, both of which were superimposed on a long wavelength waveform. All machined waveforms were periodic and shallow, with slopes less than two degrees. Table 1 summarizes the physical scales of all surfaces tested, including basic sand grain roughened surfaces and a full-scale planar mold of the motor case roughness (#9).

Table 1 Summary of surfaces tested[a]

Model	Type	k	ε_{SW}	ε_{LW}	λ_{SW}	λ_{LW}	(ε/λ) SW	(ε/λ) LW
smooth	machined	0	0	0	0	0	...	...
24 grit	sand grain	0.027	...	...	...	...	...	...
36 grit		0.019	...	...	...	...	...	...
50 grit		0.012	...	...	...	...	...	...
80 grit	↓	0.006	...	...	...	...	...	...
#6	machined	0.002	...	...	...	...	...	...
#7		0.002	0.004	...	0.45	...	0.009	...
#8	↓	0.002	...	0.013	...	2.55	...	0.005
#9	molded	0.0013	0.004	0.010	0.30	1.70	0.013	0.006
#10	machined	0.0013	0.003	0.009	0.30	1.80	0.010	0.005
#11		0.002	0.004	0.013	0.45	2.55	0.009	0.005
#12	↓	0.003	0.012	0.026	0.79	5.40	0.015	0.005

[a] All dimensions in inches.

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Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Supersonic and Hypersonic Flow.

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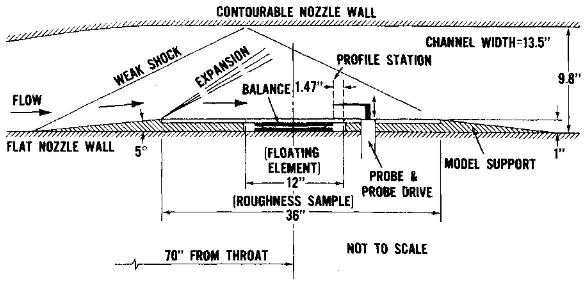

Fig. 2 Test setup schematic.

All tests were run in the NOL Boundary Layer Channel, a vertical, asymmetric, variable Mach number facility; a schematic of the test setup is shown in Fig. 2. Test conditions were $M_\infty = 2.9$, $Po_\infty = 1.0$–4.0 atm., and $To_\infty = 582$–592°R, which yielded Re_∞/ft values of 2.0–8.0×10^6; all data were obtained under adiabatic flow conditions. Details concerning the balance and its calibration, probes, test procedures, etc., are given in Ref. 1. Smooth wall δ varied from 1.0–0.8 in., and sublayer thickness, based on measured surface shear, varied from 7.0–2.0 mils over the stated Re/ft range.

Present skin friction results are summarized in Fig. 3 in comparison with the bounds of Goddard's[2] compressible sand grain results and the V-groove roughness data of Young,[3] Mann,[4] and Wade.[5] Several points concerning this figure should be made. First, present sand grain results resubstantiate Goddard's correlation and the conclusion emanating from it, that roughness effects are localized deep within the boundary layer and are independent of the external flow, i.e., no M_∞ dependence. Second, a similar functional dependence between (C_f/C_{f_o}) and Re_k has also been demonstrated for V-groove roughnesses as superimposed on both flat and single periodic waveform surfaces (for these surfaces, equivalent sand grain roughnesses were found not to differ substantially from actual values). Third, superposition of roughness on surfaces which simultaneously possessed both short and long periodic waveforms (#10, 11, 12) resulted in a narrow, self-consistent band of data, but one which failed to fall within the bounds of Goddard's correlation. Rather, these results (plotted using k as the scale in Re_k) departed from the smooth wall limit at Re_k values near 4–5 and, thereafter, exhibited a functional dependence on Re_k similar to that of the original correlation. Such behavior is indicative of the amplification in surface shear caused by this type rough/multiple waveform surface (superimposed roughness was not sufficient, by itself, to cause such increases, i.e., at departure from smooth wall behavior k was always less than one-half the corresponding smooth wall sublayer thickness). Finally, motor case data, plotted using its ascribed k value, did not correlate with any of the other results. A horizontal shift applied to these data via a replacement of the k scale with ε_{sw} (ascribed short-wave amplitude) brought them within bounds, but the weaker functional dependence on Re_k remained, of course, unchanged (equivalent sand grain roughnesses were found to be of the order of four to eight times the ascribed k value, the factor being Reynolds number dependent).

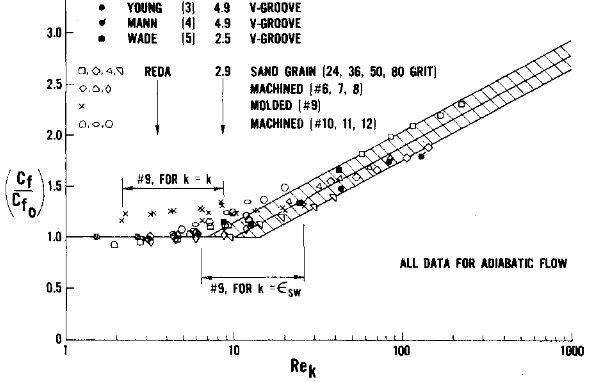

Fig. 3 Skin-friction correlation.

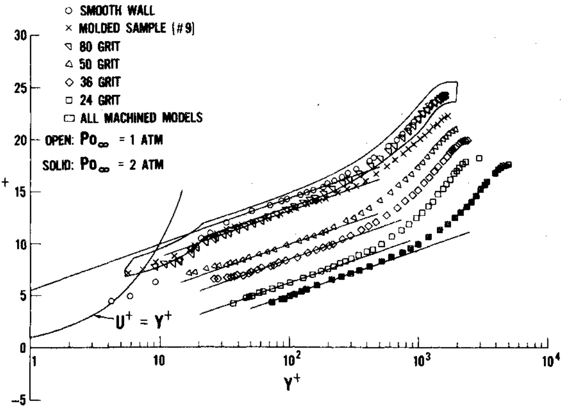

Fig. 4 Law-of-the-wall correlation.

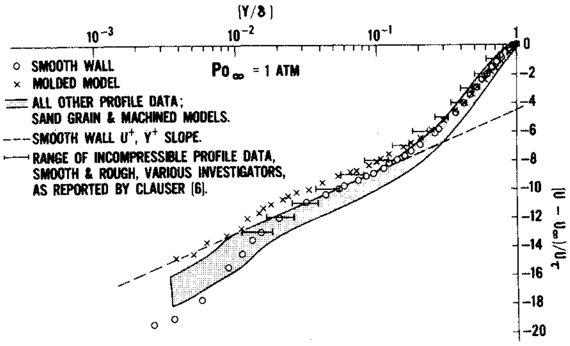

Fig. 5 Velocity defect correlation.

Profile data are summarized in Figs. 4 and 5. Two important conclusions were derived. First, velocity profiles measured over all rough/wavy surfaces were found to possess a logarithmic region wherein the law-of-the-wall correlation was valid. Second, when plotted in terms of velocity defect coordinates, present smooth, rough, and rough/wavy profile data collapsed to a near universal curve in the outer portions of the layer, in agreement with previously published results,[6] verifying again that, even for the complex surface contours considered here, roughness effects are localized to the immediate vicinity of the surface, independent of the external flow.

References

[1] Reda, D. C., "Compressible Turbulent Skin Friction on Rough and Rough/Wavy Walls in Adiabatic Flow," NOLTR 74-34, Feb. 1974, Naval Ordnance Lab, Silver Spring, Md.

[2] Goddard, F. E., Jr., "Effect of Uniformly Distributed Roughness on Turbulent Skin-Friction Drag at Supersonic Speeds," *Journal of the Aerospace Sciences*, Vol. 26, Jan. 1959, pp. 1–15, 24.

[3] Young, F. L., "Experimental Investigation of the Effects of Surface Roughness on Compressible Turbulent Boundary-Layer Skin Friction and Heat Transfer," Rept. DRL-532, May 1965, Defense Research Lab., Univ. of Texas at Austin, Austin, Tex.

[4] Mann, H. W., "Experimental Study of the Compressible Turbulent Boundary-Layer Skin Friction and Heat Transfer in the Fully Rough Regime," Rept. DRL-554, Aug. 1967, Defense Research Lab., Univ. of Texas at Austin, Austin, Tex.

[5] Wade, J. H. T., "An Experimental Investigation of the Effect of Surface Roughness on the Drag of a Cone-Cylinder Model at a Mach Number of 2.48," Rept. 34, Sept. 1955, Institute for Aerophysics, Univ. of Toronto, Toronto, Canada.

[6] Clauser, F. H., "The Turbulent Boundary Layer," *Advances in Applied Mechanics*, Vol. IV, 1956, pp. 1–51.