Engineering Notes

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Turbulent Roughness Drag Due to Surface Waviness at Low Roughness Reynolds Numbers

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Nomenclature

A_f = projected frontal area of all waves
C_f = skin friction coefficient $2\tau_w/\rho U_\infty^2$
C_{Dm} = roughness drag coefficient $\Delta D/\bar{q}A_f$
d = diameter
h = total wave height (trough to crest)
h^+ = roughness Reynolds number $hU_\infty(C_f/2)^{0.5}/\nu$
M = Mach number
$\bar{q}$ = mean dynamic pressure over the wave height
U_∞ = freestream velocity
ΔD = drag increase due to surface waviness
δ = boundary layer thickness
λ = wavelength
ν = kinematic viscosity
ρ = density
τ_w = wall shear stress

Introduction

SURFACE waviness can be described as a repetitive change in surface contour that results in a sinusoidal type displacement of the local flow in the streamwise direction The multipanel manufacturing techniques that are used on aircraft and ships cause surface bulges or indentations that result in surface waviness Also in some applications, waviness may be employed to provide additional structural rigidity The amplitude of the surface waviness of aircraft may increase under the local stresses generated by flight loads; for example the pressurized fuselage of transport aircraft can undergo significant amounts of bulging at high cruise altitudes

In Ref 1 a Boeing 720 was flight tested to determine the effect of pressurization on surface waviness and the associated fuselage drag The measured drag increase due to pressurization was approximately 5% of the fuselage drag for the $h/\lambda = 0\ 00175$ surface waves The measured drag increase reported in Ref 1 was not separated into the drag due to leakage through the fuselage and drag due to skin bulging or increased surface waviness The roughness drag data obtained by Czarnecki and Monta[2] for a wavy cylindrical surface $[\delta/d \approx O(0\ 1)]$ having an ogive nose is the only subsonic wind tunnel data available for the roughness drag of continuous surface waves (axisymmetric body corrections for nose and base drag) Hoerner[3] generated a "curve" to estimate the roughness drag coefficient (C_{Dm}) due to surface waviness. However this variation is based on the experimental results of Hood[4] and Wieghardt[5] which are for single waves only Young and Patterson[6] questioned the small C_{Dm} values obtained for small h/λ surface waves They also noted a scarcity of experimental data for small h/λ and h^+ surface waves

The purpose of the current study is to provide data to better estimate the roughness drag for surface waviness at small h/λ and h^+ The data used for this study were obtained from a recent wavy wall investigation at NASA Langley Research Center[7] which was part of an overall program to reduce the skin friction of turbulent boundary layers in external flows [8]

Facilities and Models

The wavy wall investigation was conducted in the Langley 15 Inch Low Turbulence Wind Tunnel The velocity for the experiment was varied between 7 6 and 43 m/s As shown in Fig 1 the boundary layer which develops along the con traction is removed ahead of the test section by a suction slot; the new boundary layer developed downstream of the suction slot is artificially tripped with a strip of 40 grit sandpaper 25 4 cm in length The test surfaces (35 6 × 91 4 cm) were located 116 8 cm from the end of the sandpaper and were mounted on a free floating drag balance for force measurements (see Ref 7 for details of the drag balance) The mean test surface was positioned flush with the wind tunnel floor; the upper wall over this region of the test section was adjusted to minimize the longitudinal pressure gradient The ratio of the maximum freestream pressure gradient over the test surface to the dynamic pressure was less than 0 0002 cm^{-1} At the beginning of the test surface the boundary layer thickness (δ) was approximately 3 cm at $U_\infty = 22\ 9$ m/s The wavy wall models (sine waves) used in the current study were designed with wavelengths such that $\lambda/\delta \approx O(1)$ The wave height to wavelength ratios (h/λ) for these sinusoidal waves were 0 01, 0 02 0 03 and 0 04

Results and Discussion

The measured net drag data are plotted in Fig 2 in terms of the roughness drag coefficient (C_{Dm}) and h/λ where C_{Dm} is given by the following relationship:

$$C_{Dm} = \Delta D/\bar{q}A_f \tag{1}$$

where ΔD is the measured drag increase due to surface waviness, $\bar{q}$ the mean dynamic pressure over the wave height,

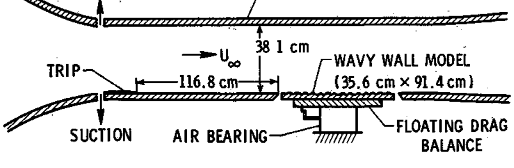

Fig 1 Schematic of experimental setup

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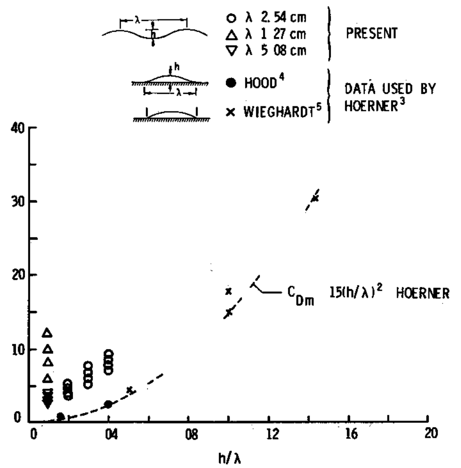

Fig 2 Roughness drag coefficient as a function of wave height to wavelength ratio

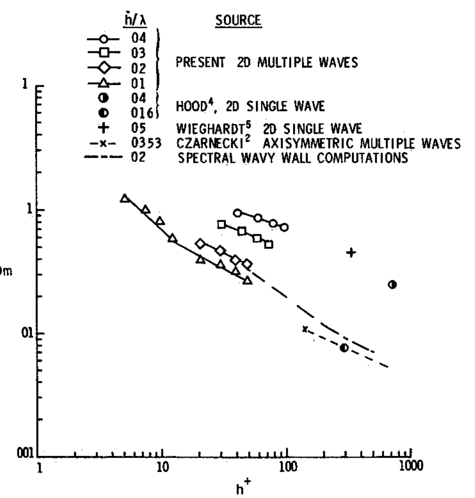

Fig 3 Roughness drag coefficient as a function of roughness Reynolds number

and A_f the projected frontal area of the waves Figure 2 shows the comparison between the current wavy wall roughness drag data and the correlation used in Ref. 3

$$C_{Dm} = 15(h/\lambda)^2 \tag{2}$$

As shown in Fig. 2, the drag values of the present data are at least a factor of three higher than the correlation curve of Ref 3 For geometrically similar waves (those having the same h/λ) Fig 2 indicates that the smaller waves cause a slightly larger increase in C_{Dm} for $h/\lambda = 0\,01$ sine waves This is expected because the smaller waves produce larger absolute pressure gradients The increase in C_{Dm} due to smaller λ was also found in Ref. 4 for single-wave geometries

The variation of C_{Dm} due to variation in U_∞ as shown in Fig 2 indicates that C_{Dm} is not just a function of h/λ but is probably also a function of the roughness Reynolds number h^+, where h^+ is defined as

$$h^+ = (hU_\infty/\nu)(C_f/2)^{0\,5} \tag{3}$$

Therefore, C_{Dm} of the present data was correlated against h^+ in Fig 3 The log log plot of Fig 3 shows that the roughness drag coefficient C_{Dm} for a constant h/λ decreases as the roughness Reynolds number h^+ increases The increase in h^+ at constant h/λ is obtained in the present tests by increasing U_∞ As h^+ is increased the pressure phase shift and the resulting pressure drag are reduced, giving smaller values of C_{Dm} As h/λ is increased the C_{Dm} curves shift to higher levels Notice the apparent break in slope of the $h/\lambda = 0\,01$ curve for $h^+ < 12$ This occurs in the region where the wave amplitude $(h/2)$ is on the order of the sublayer thickness Hood s roughness data[4] for single waves on a two dimensional airfoil at $M = 0\,3$ with $h/\lambda = 0\,04$ and 0 016 and Wieghardt's data[5] for the "rounded ledge' wave with $h/\lambda = 0\,05$ at $U_\infty = 25$ m/s are in reasonable agreement with extensions of the current data to higher h^+ (Fig 3) Czarnecki's roughness data[2] for an ogive wavy surface cylinder at $M = 0\,7$ $(140 \leq h^+ \leq 740)$ are also plotted in Fig 3 The apparent "misfit" in the $h/\lambda = 0.0353$ level is likely due to 1) the difference in model geometry (plane vs axisymmetric) and 2) the data "corrections" applied in Ref 2 to subtract out the nose and base drag contributions However the data of Ref 2 seem to have the same slope as the present lower h^+ $(12 < h^+ < 100)$ waves Finally the calculated results from a two dimensional Navier Stokes spectral code for turbulent flow over wavy walls[7] with $h/\lambda = 0\,02$ continuous sine waves at $50 \leq h^+ \leq 500$ are also in reasonable agreement with the trend and level of the present data

In summary the low-speed roughness drag of small amplitude sinusoidal wave trains having wavelengths the order of the boundary layer thickness is not just a function of h/λ, but is also a strong function of h^+ with C_{Dm} decreasing as h^+ increases

References

[1] Gyorgyfalvy D Effect of Pressurization on Airplane Fuselage Drag *Journal of Aircraft*, Vol 2 Nov Dec. 1965 pp 531 537

[2] Czarnecki K R and Monta W J Roughness Drag Due to Two Dimensional Fabrication Type Surface Roughness on an Ogive Cylinder from Force Tests at Transonic Speeds, NASA TN D 5004 1969

[3] Hoerner S F , Fluid Dynamic Drag Published by the Author 1965, pp 5 7 to 5 8.

[4] Hood M J The Effects of Surface Waviness and of Rib Stitching on Wing Drag NACA TN 724 1939

[5] Wieghardt K Increase of the Turbulent Frictional Resistance Caused by Surface Irregularities, ' Ministry of Aircraft Production MAP VG 129 Translation of ZWB, Berlin FB1563 June 1946

[6] Young, A D and Patterson J H Aircraft Excrescence Drag AGARD AG 264, 1981

[7] Lin J C Walsh M J Watson R D , and Balasubramanian, R Turbulent Drag Characteristics of Small Amplitude Rigid Surface Waves, AIAA Paper 83 0228 Reno Nev Jan 1983

[8] Bushnell, D M Turbulent Drag Reduction for External Flows AIAA Paper 83 0227 Reno Nev. Jan 1983