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Unsteady and Transitional Flows Behind Roughness Elements

F. Gökhan Ergin* and Edward B. White†
Case Western Reserve University, Cleveland, Ohio 44106

The role of surface roughness in boundary layers continues to be a topic of significant interest, especially with regard to how controlled roughness might be used to delay laminar-to-turbulent transition. Although it may be useful for control, large-amplitude roughness may itself lead to transition. In an effort to understand the breakdown mechanics associated with large-amplitude surface roughness, experiments are conducted to investigate the steady and unsteady disturbances generated by three-dimensional roughness elements whose amplitudes are close to the critical roughness-based Reynolds number Re_k for roughness-induced transition. Measurements are obtained in a flat-plate boundary layer downstream of a spanwise array of cylindrical roughness elements at both subcritical and supercritical values of Re_k. The steady disturbance field has strong shear in the wall-normal and spanwise directions, and the unsteady streamwise velocities in the roughness elements' wake show evidence of hairpin vortices. The locations of maximum fluctuation intensity correspond to the locations of inflection points in the steady flow streamwise velocity, and this suggests that the fluctuations may result from a Kelvin–Helmholtz-type instability. Temporal power spectra indicate an unstable band of frequencies from 300 to 800 Hz. The Strouhal number associated with the 650-Hz fluctuations that are often observed to be the strongest give $Sr = 0.15$, a value that is in good agreement with previous findings. At supercritical Re_k, rapid transition takes place when the unsteady disturbances reach nonlinear amplitudes. The disturbance growth rates indicate that in this situation transition can be understood as a competition between the unsteady disturbance growth and the rapid relaxation of the steady flow that tends to stabilize these disturbances.

Nomenclature

D	=	roughness diameter
E	=	steady disturbance energy
e_f	=	unsteady disturbance energy in a frequency band centered at f
f	=	frequency
H	=	shape factor, δ^*/θ
k	=	roughness height
N	=	number of samples
Re_k	=	roughness-based Reynolds number, $\bar{U}(k)k/\nu$
Re'	=	unit Reynolds number, U_∞/ν
Sr	=	Strouhal number of unsteady vortex shedding, $f\delta^*/U_\infty$
$\bar{U}$	=	spanwise-invariant streamwise basic state velocity
U'	=	steady streamwise disturbance velocity
U_∞	=	freestream velocity
u'	=	unsteady streamwise disturbance velocity
x, y, z	=	streamwise, wall-normal, and spanwise coordinates
x_k	=	streamwise location of the roughness array
α	=	spatial growth rate
δ	=	boundary-layer length scale, $[(x - x_{\text{vle}})/Re']^{1/2}$
δ^*	=	displacement thickness
λ_k	=	roughness spacing
η	=	Blasius coordinate, y/δ
θ	=	momentum thickness
ν	=	kinematic viscosity

Subscripts

c	=	centerline
crit	=	critical
rms	=	root-mean-square
s	=	shedding
samp	=	sampling
vle	=	virtual leading edge

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*Postdoctoral Research Associate, Department of Mechanical and Aerospace Engineering. Member AIAA.

†Assistant Professor, Department of Mechanical and Aerospace Engineering. Senior Member AIAA.

I. Introduction

THE study of laminar-to-turbulent transition on surfaces with significant roughness levels has had a long history motivated by the need to understand transition on realistic surfaces. Laboratory studies on low-speed flows have tended to treat three main classes of roughness: two-dimensional roughness strips; three-dimensional, isolated roughness elements or arrays of three-dimensional elements; and random distributed three-dimensional roughness fields. The distinctions among these arise from how each is accommodated as a disturbance source in stability theory and from practical considerations of what actually exists on aerodynamic surfaces.

In two-dimensional boundary layers, the role of two-dimensional roughness is well understood as a generator of two-dimensional Tollmien–Schlichting (TS) waves. Goldstein[1] uses a triple-deck analysis to show that the streamwise variations of the mean flow that are produced by two-dimensional roughness scatter acoustic waves into TS wavelengths and, thus, provide a receptivity mechanism for unstable TS waves. Additional details on the receptivity of TS waves are in the review by Saric et al.[2] Because the TS-wave amplitudes depend on the roughness amplitude, increasing the roughness amplitude should be expected to move gradually the transition location toward the two-dimensional roughness, and this is exactly what was observed in numerous transition experiments of the 1940s and 1950s.[3,4]

The role of isolated and distributed three-dimensional roughness in two-dimensional boundary layers has not been as well understood on a theoretical basis because the stationary, spanwise varying disturbances created by three-dimensional roughness are not unstable within the context of a normal-mode stability analysis.[5] Typically, transition in the wake of isolated three-dimensional roughness elements is predicted using correlations based on a critical roughness-based Reynolds number $Re_{k,\text{crit}}$, established in the 1950s.[4,6–10] Within the context of the correlation approach, if a roughness element exceeds Reynolds number $Re_{k,\text{crit}}$, then transition is expected to occur at or just aft of the roughness element, but if the critical value is not exceeded, then no effect is expected.

The correlation approach based on a critical Reynolds number Re_k is well established, but provides no guidance on the more subtle