TRANSITION AND WAVY WALLS: AN EXPERIMENTAL STUDY

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Abstract A wide body of research exists which explores the effects of surface roughness or patterned wall shapes on instability growth and transition. Building on those works as well as recent experiments demonstrating passive laminar flow control using arrays of discrete roughness [3, 8], a set of spanwise-wavy walls is designed with the goal of suppressing instability growth in two-dimensional boundary layers. In a numerical investigation of Tollmien–Schlichting (TS) wave growth in the presence of streamwise boundary-layer streaks, Cossu and Brandt [1] found that stabilization of TS waves results from spanwise shear in the mean flow, which forms a negative contribution to production in the perturbation kinetic energy equation. Whereas previous efforts have employed streamwise vorticity developing in roughness wakes to provide the requisite mean-flow deformation, in this work stabilization is achieved through modulation of the no-slip surface. Miniature vortex generators (MVGs) have proven an effective means of producing streamwise streaks for transition delay [8], though relatively large streak amplitudes are necessary to counter their eventual decay through viscous dissipation. The notion motivating this work is that spanwise-wavy walls extended in the streamwise direction can produce a similar effect while avoiding bypass transition resulting from large-amplitude streamwise streaks. Toward that end, six wavy walls are used in a modular test model. When TS waves are excited upstream of the wavy walls, substantial delays in the onset of transition are observed for certain spanwise wavelengths compared with the flat-plate reference case.

EXPERIMENTAL SETUP

The experiments are conducted in the Minimum Turbulence Level wind tunnel at KTH Royal Institute of Technology. A two-dimensional zero-pressure gradient boundary layer is used as the prototypical flow. Similarly, laminar-to-turbulent transition is forced by exciting planar waves at fixed frequencies. Instability growth in this scenario is well understood and forcing transition lessens the dependence of the results on the freestream turbulence signature of this particular facility. Disturbance excitation is accomplished with periodic wall-normal suction and blowing through a thin slot placed 160 mm from the plate leading edge, as illustrated in figure 1. An additional slot located 20 mm farther downstream is used to inject smoke for flow visualization. Aft of these slots, the modular plate includes removable sections which are replaced with wavy wall inserts whose streamwise and spanwise dimensions are 300 mm $\times$ 300 mm.

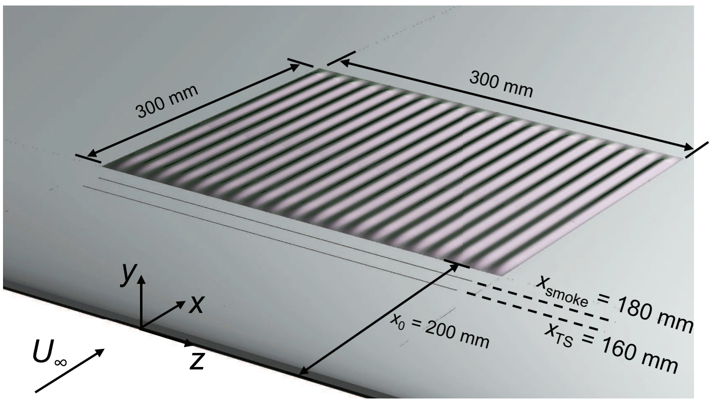

Figure 1. Drawing of the experimental setup showing the flat plate with wavy surface insert, and positions of the slots for smoke injection and TS-wave excitation.

Selection of the spanwise wavelength Λ and wall-normal height h follows a semi-empirical approach. Experiments with MVGs [7] indicated TS-wave attenuation is optimized when streak amplitude is around 30% of the freestream velocity, U_∞. Exploratory experiments were conducted with wavy surfaces whose amplitudes were chosen to produce mean-flow modulation of commensurate amplitude, and although initial assumptions underestimated the surface amplitudes sufficient for stabilization an effective value was determined: h is proportional to $x^{1/2}$ and reaches a maximum value of 1.98 mm. The spanwise waveforms are based on sine waves whose valleys are at the nominal plate surface ($y = 0$), with increased-width valleys in some cases. Casting the effective wavelengths in terms of dimensionless spanwise wavenumber $\beta = 2\pi\delta_0/\Lambda$, the tested surfaces have $0.14 \leq \beta \leq 0.47$ for a test speed of $U = 8$ m/s. The leading and trailing edges of the wavy surfaces are smoothly ramped to the plate surface to minimize wake effects and separation.

The qualitative similarity to riblets was also considered in constructing this experiment. It is now known that riblets can reduce skin friction drag in turbulent boundary layers [4], and their effect on instability growth and transition has also been considered. In a natural transition scenario, riblets appear to advance transition [6]. Similarly, when TS waves are excited in the presence of riblets, the waves experience higher growth rates relative to a flat plate reference case [5]. In these cases, however, the riblet wavelengths are relatively short, resulting in $\beta > 2$.

RESULTS AND DISCUSSION

Several combinations of freestream velocity, disturbance frequency, amplitude and wavy-wall shape have been tested, comprising more than 50 cases. The present results focus on the set of wavelengths described previously with flow conditions of $U_\infty = 8$ m/s and $F = 162$, where F is the dimensionless forcing frequency defined in the usual way: $2\pi\nu f \times 10^6/U_\infty^2$. The TS-wave amplitude is tuned to place the reference-case transition location near $x = 450$ mm, which is within the streamwise range of the wavy surfaces. Previous experiments with a similar surface configuration [2] showed initial amplification and subsequent attenuation of TS-wave amplitudes over a spanwise periodic surface, followed by delayed onset of transition at some conditions. As transition occurred in the wake of the surface pattern in those experiments, it could not be attributed directly to the modulated wall shape.

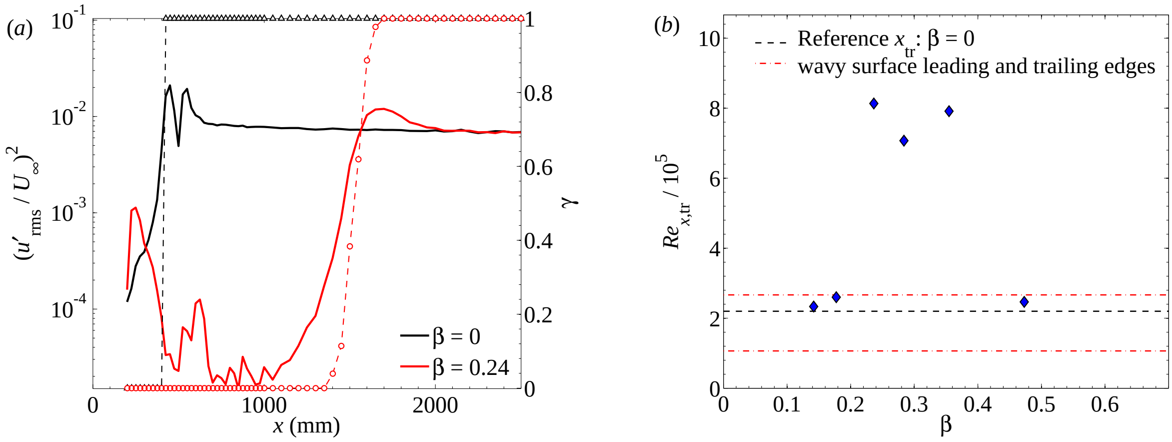

Figure 2. Transition measurements with $U_\infty = 8$ m/s, $F = 162$. (*a*) Streamwise energy evolution (solid lines) and intermittency (dashed lines) plotted for the flat plate reference case ($\triangle$) and for the wavy surface case ($\circ$) with $\beta = 0.24$. (*b*) Transition Reynolds numbers for a set of wavy surfaces.

Two transition measurements are presented in figure 2(*a*) via streamwise distributions of unsteady disturbance energy $(u_{\rm rms}/U_\infty)^2$ and intermittency γ. For a transition criterion of $\gamma = 0.5$, these data show $x_{\rm tr} \approx 410$ mm in the reference case, compared with 1520 mm when a wavy surface with $\beta = 0.24$ is installed. That is, transition on the wavy surface is avoided. A complete set of wavelengths is considered in figure 2(*b*), in which transition Reynolds numbers are plotted for each test case expressed in β values. When these results are compared with the reference case transition location denoted by the dashed black line, a range of optimal spanwise wavelengths for these conditions is clear: $0.24 \leq \beta \leq 0.35$. For long Λ, it seems that the mean-flow modulation is insufficient to produce a stabilizing effect. For the shortest wavelength tested, $\beta = 0.47$, the transition location observed in the absence of TS-wave excitation is large enough ($Re_{x,\rm tr} = 1.3 \times 10^6$) to suggest that the low value in figure 2(*b*) is a result of local disturbance amplification over the wavy wall.

References

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