SKIN-FRICTION DRAG REDUCTION — NOW WITH REINFORCED PASSIVE CONTROL

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ABSTRACT

It is well known that the skin-friction coefficient can increase by an order of magnitude in a turbulent boundary layer compared to a laminar one for high enough Reynolds numbers, therefore, delaying transition to turbulence plays an important role in reducing the skin-friction drag on any aerodynamically smooth body. The conventional belief regarding the stability of wall bounded shear flows is that it highly correlates with the roughness of the surface in contact with the fluid, i.e. the smoother the surface is the longer it will remain laminar. However, recent investigations have shown that well designed *roughness elements,* if mounted on the surface in the boundary layer, can control the flow and delay the transition to turbulence by modulating the base flow in the spanwise direction. By mounting circular surface roughnesses on a flat plate for base flow modulations in the spanwise direction, Fransson et. al [1], [2] were able to damp the growth of Tollmein-Schlichting (TS) waves and to delay the transition to turbulence for artificially generated TS waves as disturbance source to the Blasius boundary layer by finite amplitude streaks. The behavior of the flow can be explained by the so called *lift-up* effect that pushes high momentum fluid towards the wall and elevates low momentum fluid away from the wall, which produces streamwise streaks of alternating high and low speed regions downstream of the roughness elements. Consequently, an additional turbulent energy production term $-\langle uw\rangle \partial U/\partial z$ appears, which turns out to be of negative contribution and together with the viscous dissipation they can overcome the wall-normal production term $-\langle uv\rangle \partial U/\partial y$ and hence stabilize the flow [3].

The damping effect of the modulated boundary layer is highly correlated to the amplitude of the streamwise streaks, which increases with the free stream velocity for a constant roughness height. As reported by Fransson and Talamelli [4], due to a vortex shedding type of instability on the circular roughness elements the streamwise streaks are breaking down to turbulence for high free stream velocities at a threshold streak amplitude of about 13% of the free stream velocity. To overcome this issue, they used vortex generators, conventionally used in boundary layers to delay separation, but in miniature geometries in order to produce robust and steady streamwise streaks of high amplitude in a flat plate boundary layer. They showed that streak amplitudes of up to 32% of the free stream velocity can be generated and still keep a stable streaky boundary layer further downstream.

Shahinfar et. al [5] tested the aforementioned miniature vortex generators (MVGs) to stabilize TS waves on a flat plate where the MVGs were mounted downstream of the disturbance source, in contrary to previous studies where the disturbances had been introduced in an already modulated boundary layer. As reported in their investigation, for the linear stability analysis, due to the complexity of the flow behind the blades of the MVG array, an initial growth in the TS wave amplitude is observed but it follows by an exponential decay of the TS wave amplitude. They show that the initial response and the damping effect scales with the height of the blades. Successful results for transition delay in the non-linear regime was also presented in their study where high forcing amplitudes of the TS waves were applied.

The idea of regenerating the spanwise modulated base flow by placing a second array of vortex generators on the flat plate was proposed by Fransson and Talamelli [4] where they showed experimentally that the streak amplitude can be reinforced by means of a second array. They report this as a potential approach towards further delaying the transition onset compared to having only one array of vortex generators.

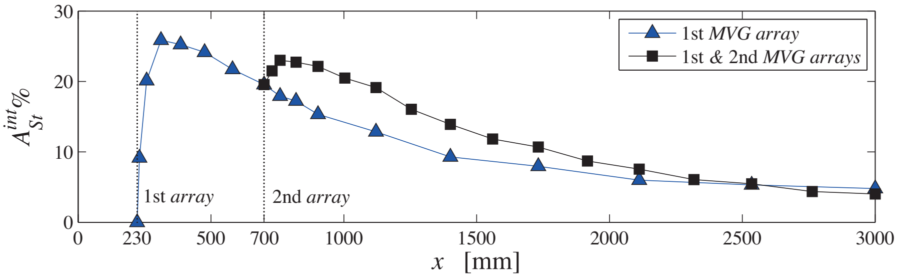

Figure 1. Streamwise evolution of the streak amplitudes in the linear TS-wave regime for the cases where one and two arrays of MVGs are mounted on the flat plate.

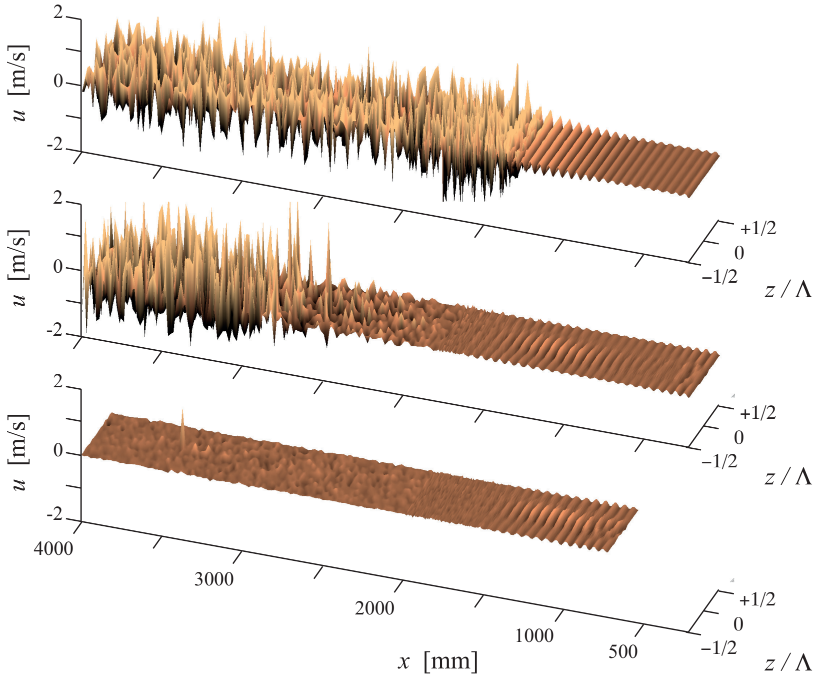

Figure 2. Streamwise fluctuating velocity distribution in a horizontal plane at $y/\delta_1 = 0.5$ above the plate for cases without MVGs (top), one array of MVGs (middle) and two arrays of MVGs (bottom). δ_1 is the displacement thickness and Λ the distance between MVG pairs.

In the present study, the transition delay result using one MVG array, reported in Shahinfar et. al [5], was repeated and successfully confirmed. In addition, by mounting a second set of MVGs downstream of the first array and reinforcing the streak amplitude, it is shown that the transition onset could successfully be pushed even further downstream. In figure 1, the streak amplitude evolution in the downstream direction including the second array is shown. After the second array the streak amplitude is increased with up to 6 percentage units compared to only applying a single array, which results in a reinforcement of the stabilizing effect. In figure 2, we show that it is possible to successively push the transition onset further downstream by adding another MVG array at an appropriate downstream distance from the first one. In this figure, where streamwise fluctuating velocity distribution is depicted, it is observed that the onset of transition is pushed downstream from the case in the top figure to the middle one by adding one set of vortex generators. Furthermore, for the case in the bottom figure, where two sets of MVGs are mounted, no onset of transition is captured within the measurement domain.

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