34626

Preliminary results of the "on-demand" vortex-generator experiments

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1. Motivation and background

This is a report on the continuation of our experimental investigations (Saddoughi 1994) of "on-demand" vortex generators. Conventional vortex generators as found on aircraft wings are mainly for suppression of separation during the off-design conditions. In cruise they perform no useful function and exert a significant drag penalty. Therefore, replacement of fixed rectangular or delta-wing generators by devices that could be activated when needed would be of interest.

Also in our previous report, we described one example of an "on-demand" device, which was developed by Jacobson & Reynolds (1995) at Stanford University, suitable for manufacture by micro-electro-mechanical technology. This device consists of a surface cavity elongated in the stream direction and covered with a lid cantilevered at the upstream end. The lid, which is a metal sheet with a sheet of piezoelectric ceramic bonded to it, lies flush with the boundary. On application of a voltage the ceramic expands or contracts; however, adequate amplitude can be obtained only by running at the cantilever resonance frequency and applying amplitude modulation: for 2.5 mm × 20 mm cantilevered lids, they obtained maximum tip displacements of the order of 100 μm. Thus fluid is expelled from the cavity through the gap around the lid on the downstroke. They used an asymmetrical gap configuration and found that periodic emerging jets on the narrow side induced periodic longitudinal vorticity into the boundary layer. Their device was used to modify the inner layer of the boundary layer for skin-friction reduction.

Also in our previous report, we proposed that the same method could be implemented for the replacement of the conventional vortex generators; however, to promote mixing and suppress separation we needed to deposit longitudinal vortices into the outer layer of the boundary layer, which required a larger vortex generator than the device built by Jacobson & Reynolds. Our vortex generator was built with a mechanically-driven cantilevered lid with an adjustable frequency. The device was made about ten times the size of Jacobson & Reynolds', the shape or size of the cavity and lid (28 mm × 250 mm) could be easily changed. The cavity depth, the cantilever-tip displacement, and the maximum lid frequency were 20 mm, 10 mm, and 60 Hz respectively. Our vortex generator was mounted on a turntable so that its yaw angle could be changed. Finally, tests over a range of ratios of vortex-generator size to boundary-layer thickness could be carried out simply by changing the streamwise location of the device.

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Our vortex generator was mounted on the top wall of the 76 cm × 76 cm flow-visualization wind tunnel in the Mechanical Engineering Department at Stanford University. We conducted extensive flow-visualization experiments at different free-stream velocities for the vortex generator set at different orientations to the flow direction. Smoke was sucked into the flow by the boundary-layer fluid, through a slot located upstream of the vortex generator. A laser-light sheet was used to visualize the motion in cross-stream planes.

For the first time, we were able to see the vortices that the "on-demand" vortex generator deposited into the boundary layer. Also, we obtained a more efficient vortex generation for the case where the vortex generator was pointed in the upstream direction. However, in all of our experiments we observed that the stronger jet emerged from the wide-gap side rather than the narrow side. This was contrary to the finding of Jacobson & Reynolds.

2. Accomplishments

2.1 Continuation of the flow-visualization experiments

To explain the differences in flow behaviors between our case and the experiment of Jacobson & Reynolds, we investigated the effect of Stokes' parameter, $St \equiv \sqrt{2\pi f d^2/\nu}$, where f is the frequency, d is the diameter of the circular hole for the wall-jet actuators, and ν is the kinematic viscosity. Based on dimensional analysis, Rathnasingham *et al.* (1994) proposed that for this kind of actuator, $St > 1$ is required to prevent the blockage of the exit flow due to the viscous effects.

For the present type of actuator, one may assume d to represent the gap-width size. In our investigations, for the narrow gap at the highest lid-frequency, $St < 1$. Therefore, it appeared that for our narrow gap the exit flow was viscous dominated. However, for the narrow gap of Jacobson & Reynolds' case, $St > 1$ since their experiments were conducted in water, and also in their case the lid frequency was larger than the present studies.

In order to match the Stokes' parameters for our case with those of Jacobson & Reynolds' experiments, we repeated all of our flow-visualization experiments in a water tunnel at Stanford University. In this case dye was introduced inside the cavity when the actuator was off. Photographs were taken after the vortex generator was switched on.

An example of these pictures is presented in Fig. 1. In this case the top view is shown, where the flow is from left to right and the vortex generator is pointing in the downstream direction. In this picture the wide-gap side is located on top of the actuator plate. In this case for both the narrow and wide gaps $St > 1$; however, it can be seen clearly that all the dye is ejected out only from the wide gap. Thus it appears that $St > 1$ is not a sufficient condition to prevent the blockage of the exit flow through a gap.

It does appear that Direct Numerical Simulation (DNS) results are needed to explain the differences between the present case and the experiment by Jacobson & Reynolds. These DNS are being conducted presently by Koumoutsakos (see related report in this volume).

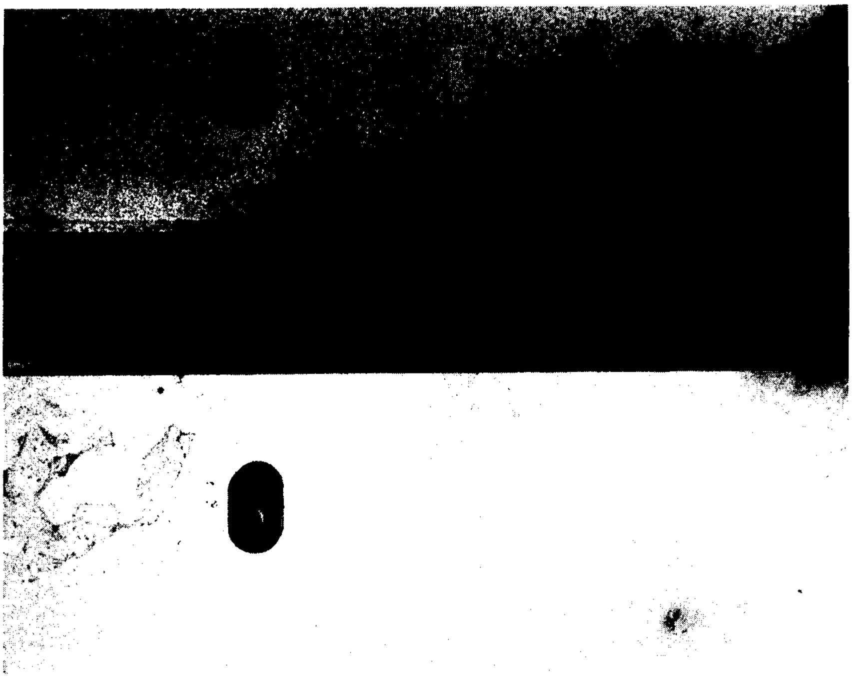

FIGURE 1. Top view of flow-visualization experiment in water tunnel. Flow is from left to right. Vortex generator is pointing in the downstream direction and ejecting the dye only from the wide-gap side.

2.2 Quantitative identification of longitudinal vortices

Vortex generators delay flow separation by increasing the overall skin friction. The presence of longitudinal vortices in a boundary layer can be detected by spanwise skin-friction (C_{fz}) measurements. The C_{fz} values will be high at places where the normal-to-the-wall component of mean velocity near the surface will be negative, bringing high-speed fluid down from above, and low when the flow is away from the surface (for detailed measurements and discussion see Shabaka, Mehta & Bradshaw 1985).

We took spanwise skin-friction measurements in the smoke tunnel by means of Preston tubes. These measurements were conducted at a fixed longitudinal location, which corresponded to a distance of $4W$ downstream of the end of the vortex generator, where W is the width of the actuator plate. The spanwise extent of the data was approximately $10W$. Measurements were conducted for three different vortex generator operating conditions: (1) switched off, (2) switched on, pointing downstream, and (3) switched on, pointing upstream. All the data were normalized by the mean value of the skin-friction coefficient for the vortex-generator switched-off condition, $C_{fz-mean(off)}$. In Figs. 2 and 3 the normalized C_{fz} values for condition (1) are compared with the data for conditions (2) and (3) respectively.

Two well-defined peaks in the spanwise distribution of skin friction for condition (2) can be seen in Fig. 2. This indicates that when the vortex generator points

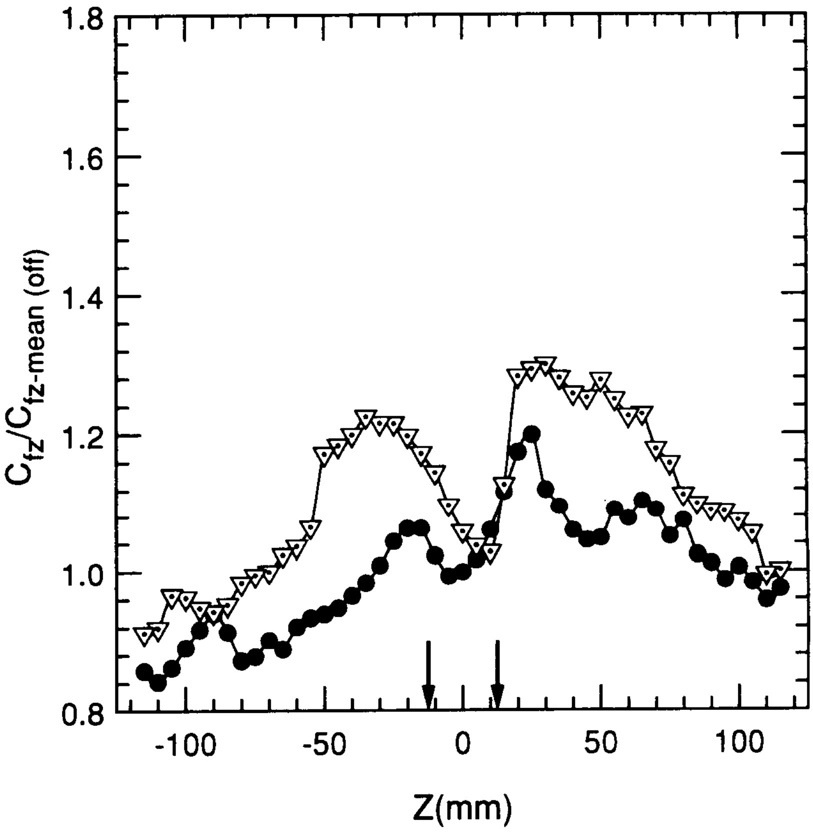

FIGURE 2. Comparison between the distributions of normalized spanwise skin-friction coefficients for vortex generator switched-off (•) and switched-on (pointing downstream) (▽) conditions. Distance between arrows shows the width of the actuator plate.

downstream, two counter-rotating vortices with common flow away from the surface are created. However, in Fig. 3 we can observe that when the actuator points in the upstream direction, a single strong vortex is generated. This is consistent with our wind-tunnel flow-visualization experiments. However, it is important to note that in this respect a definite conclusion cannot be reached, because for the reference-flow condition (i.e. the case where the vortex generator was switched off) the spanwise variation of C_{f_z} is fairly large (more than ±10%). Therefore, it is not clear whether the vortex generator would have increased the skin-friction coefficients by such large amounts, if these pre-existing variations were not present in the boundary layer.

3. Future plans

This project will be continued at McGill University. We plan to install the vortex generator in a canonical boundary layer and repeat all the spanwise measurements of skin friction. To obtain a measure of the mean longitudinal vorticity, hot-wire measurements will be conducted. Also, our on-demand vortex generators will be

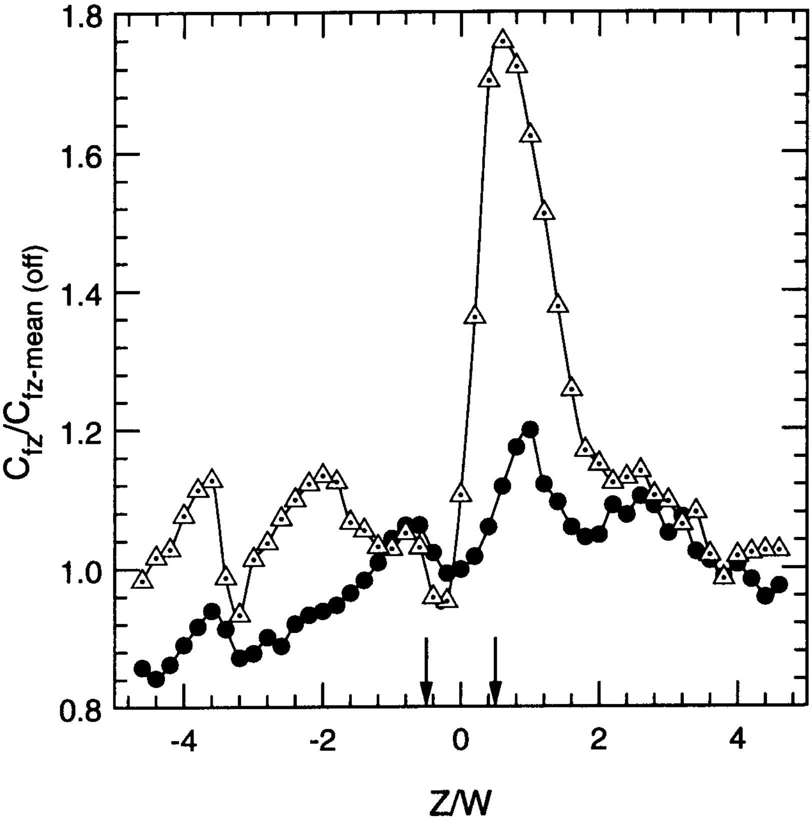

FIGURE 3. Comparison between the distributions of normalized spanwise skin-friction coefficients for vortex generator switched-off (●) and switched-on (pointing upstream) (△) conditions. Distance between arrows shows the width of the actuator plate.

used in laboratory adverse-pressure-gradient boundary layers to suppress separation.

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