Engineering Notes

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Control of Turbulent Separated Flow Over a Rearward-Facing Ramp Using Longitudinal Grooves

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Introduction

THE loss of momentum or energy due to flow separation is detrimental to airfoil and diffuser performance and increases body drag. For excessive separation, stalling may occur which can lead to catastrophic results. Effective control of separated flow regions can result in an increase in system performance with consequent energy conservation, as well as weight and space savings. Thus, flow separation and its control is an important issue in fluids engineering.

A common flow-separation-control technique is to add momentum to the near-wall flow by redirection of higher momentum flow from the far-wall region. Vortex generators have long been known to increase mixing between external streams and boundary layers.[1] Another alternative in redirecting the outer flow momentum is the three-dimensionalization of a two-dimensional flow through longitudinal grooves.[2-5] References 2 and 3 indicate that large longitudinal V-grooves in the shoulder of a bluff body can produce up to 33% drag reduction. These references suggest that the pumping action of the *attached* groove flow decreases the size of the flow-separation region. It should be noted that this is also an example of locally mitigating the imposed adverse pressure gradient through the technique of partial "boattailing" for separation control. In the present Note, the longitudinal groove approach is extended to the low-speed two-dimensional case.

Apparatus and Tests

The experiments were conducted in the NASA Langley 20×28-Inch Shear-Flow Control Tunnel. This is a low-turbulence, subsonic, open-circuit wind tunnel. In the current study, all experiments were conducted at a freestream velocity of 132 ft/s. Flow separation was established on a backward-facing curved ramp located approximately 76 in. from the test-section entrance (see Fig. 1 for the test configuration). A suction slot at the test-section entrance was used to remove the converging section boundary layer to eliminate any influence of upstream history on the test boundary layer. The new laminar boundary layer that developed downstream of the suction device was artificially tripped with a 2-in.-wide strip of sandpaper (36 grit). The ceiling height of the test section was adjusted to obtain zero pressure gradient upstream of the ramp. The bondary layer just ahead of the separation ramp was fully turbulent. At this location, the boundary-layer thickness δ was approximately 1.3 in., the spanwise momentum thickness θ variation across the test plate was within $\pm 2.5\%$, and the momentum-thickness Reynolds number R_θ was approximately 9000.

The baseline (or reference) separation model was a two-dimensional 25-deg ramp with an 8-in. shoulder radius as shown in Fig. 1. The width of the model was 28 in., which covers the entire test section in the spanwise direction. This model produced reasonably two-dimensional flow separation at approximately the midpoint of the ramp or about 2δ downstream of the horizontal (or first) tangent point.

The longitudinal grooves investigated in the present study consisted of "short" V-groove, "long" V-groove, and sine-wave groove configurations. The geometry of these longitudinal grooves is summarized in Fig. 2. All grooves were located on the shoulder of the ramp model itself. The "short" V-groove configuration consisted of a constant slope (19.4 deg) groove from just upstream of the horizontal tangent point to the base of the ramp. The "long" V-groove and sine-wave groove configurations, on the other hand, consisted of a 1/2-in.-deep groove parallel to the ramp surface from 2.5δ upstream of the horizontal tangent point to the base of the ramp. Each longitudinal groove was cut in a 2-in.-wide spanwise section of the ramp model. The spanwise groove spacing λ could

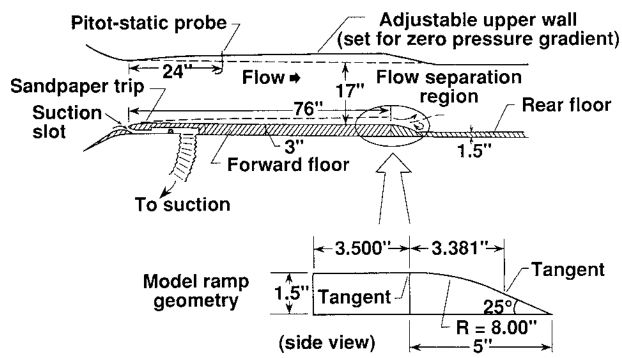

Fig. 1 Test configuration in tunnel.

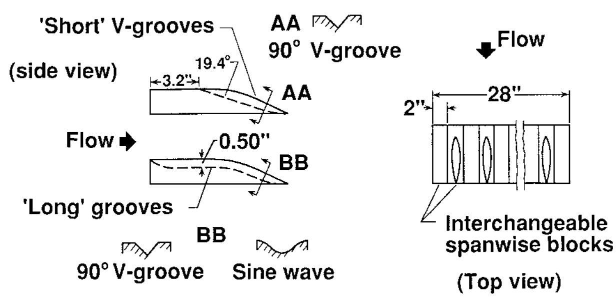

Fig. 2 Geometry of longitudinal grooves.

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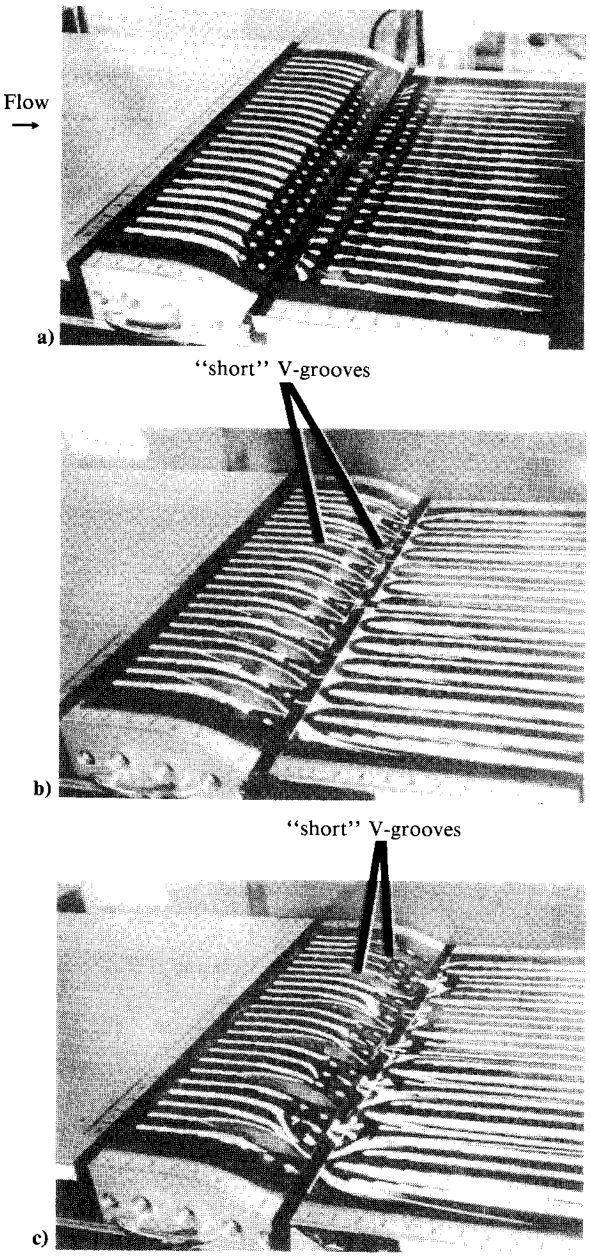

Fig. 3 Oil flow visualization for "short" longitudinal V-grooves: a) baseline case; b) groove spacing ~ 1.5δ; and c) groove spacing ~ 3δ.

be changed by adding or removing one of the aforementioned spanwise sections. The volume removed for a single groove is 0.75 in.^{3} for the "short" V-groove, 1.5 in.^{3} for the "long" V-groove, and 2.6 in.^{3} for the sine-wave groove.

Static pressure orifices were located on the centerline of both the reference separation ramp and the floor downstream of the ramp. The pressure tubes for the orifices were connected to a motor-driven valve which sequentially connected each orifice to a single differential pressure gage. All surface static pressure measurements were referenced to the freestream static pressure measurement located near the entrance of the test section. These pressure differences were normalized by the freestream dynamic pressure to obtain pressure coefficients C_p. Because of physical constraints, the closely packed longitudinal groove ($\lambda \sim 1.5\delta$ or 2 in.) models did not have pressure orifices installed on the separation ramp. However, for these closely packed cases, pressure measurements were made on the floor downstream of the separation ramp to study reattachment and pressure recovery.

The method of "oil dot" flow visualization using a mixture of titanium dioxide and 10-cS silicone oil was utilized to determine the surface flow patterns. Figure 3a indicates that this method worked quite well in identifying the separation line for the reference model. Oil dots were placed approximately 1 in. apart, both spanwise and in the flow direction, to obtain an overall flow pattern.

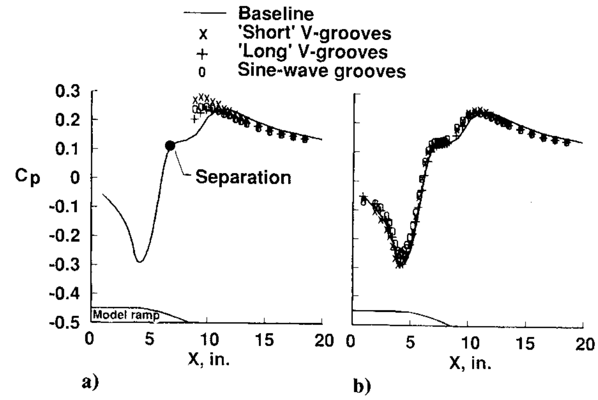

Fig. 4 Pressure distributions for longitudinal grooves: a) groove spacing ~1.5δ; and b) groove spacing ~3δ.

Results and Discussion

Figures 3b and 3c show the flow-visualization comparison between the "short" longitudinal V-grooves with a groove spacing of 1.5δ (11 grooves total) and the same groove with a groove spacing of 3δ (6 grooves total), respectively. The results indicate that the V-grooves spaced 1.5δ apart significantly reduced the distance to reattachment, whereas the V-grooves spaced 3δ apart provided only a partial improvement in the same region (compare with Fig. 3a). Figure 3 also shows a separation delay of 0.5δ on the smooth surfaces of the ramp (between the grooves) with the 1.5δ groove spacing, whereas the 3δ groove spacing shows no significant delay of separation in this same region with respect to the baseline model. Similar results were obtained for sine-wave grooves and "long" V-grooves. The downstream floor pressure distributions for all three longitudinal groove cases with the same 1.5δ groove spacing are shown in Fig. 4a. When examining the baseline pressure distribution, it should be pointed out that the flow around a corner (or a shoulder) first accelerates and then decelerates. Baseline separation occurred just before the sharply increasing C_p distribution began to level off and reattachment occurred near the region of maximum C_p. The reattachment distance, therefore, was defined as the distance between the trailing edge of the model ramp and the streamwise location where maximum C_p occurred. The closely packed "short" V-grooves provided the maximum pressure recovery on the downstream floor and Fig. 4a shows that this configuration reduced the reattachment distance by up to 66%. The pressure distributions for all three longitudinal groove cases with the same 3δ groove spacing are shown in Fig. 4b. The resulting pressure distributions are all very similar and just slightly above the baseline case. Notice that the "short" V-grooves are slightly better for separation control than the "long" V-grooves or the sine-wave grooves, while requiring only a fraction of the volume penalty (or loss) of these longer grooves. The volume penalty for the "short" V-grooves is 50% of that for the "long" V-grooves and 29% of that for the sine-wave grooves.

In summary, the present experimental study of turbulent flow-separation control over a backward-facing ramp indicates that closely packed, longitudinal grooves with $\lambda/\delta \sim 1.5$ can reduce the reattachment distance by up to 66%. A "short" longitudinal V-groove configuration with a constant groove slope performed slightly better than either a "long" longitudinal V-groove or a sine-wave groove configuration, while imposing a much smaller volume loss penalty.

References

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Effects of a Contoured Apex on Vortex Breakdown

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Introduction

STRONG streamwise vortices are a well-known feature of the flowfields above delta wings. The breakdown of these vortices at a high angle of attack is also commonly observed and results in a change in pressure distribution that affects the lift and, especially, the moment produced by the wing. It is probably not possible to avoid vortex breakdown entirely, but in any case the phenomenon should be delayed and controlled.

Although it is an oversimplification, it is useful for physical purposes to think of a vortex embedded in a pressure field generated by the delta wing. Vortex breakdown is sensitive to the exact nature of the vortex structure and to the flowfield (or pressure gradient) in which the vortex is embedded. Mathematical studies on the breakdown of symmetrical isolated vortices show that the vortex can be completely described by the radial profiles of total pressure and of streamwise vorticity. Reduced total pressure occurs in the core of the vortex because the fluid has undergone a history of frictional forces. Likewise, the process by which the vortex was formed must give the core fluid a vorticity profile.

The object of the research was to modify the total pressure or the vorticity distribution in the vortex and observe the effect on the location of the breakdown. The idea is that the core of the vortex is formed from fluid that passes near the leading edge. Adding friction at this point results in core fluid that has a lower total pressure than the main flow. On the other hand, additional vorticity is imparted to the vortex if the fluid crosses the leading edge at a higher angle of attack or, equivalently, a higher sweep. Contouring the planform in the region of the apex in principle alters the vorticity distribution in the vortex core.

It should be pointed out that in many cases a double delta produces two vortices: one from the apex and one from the intersection of the leading edges. These two vortices interact as has been documented in several studies. The concept employed here is distinctly different. The modifications to the delta are intended to be so slight that they alter the vorticity distribution in the main vortex, but do not produce a distinct second vortex.

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Background

The recent review by Escudier[1] shows that vortex breakdown is a very active research area. Vortex breakdown was first observed by Peckham and Atkinson[2] in 1957. Causal theories are still in a stage of development as evidenced by the articles of Leibovich[3] and Stuart.[4] In spite of this, much useful information is available. From the calculations of Grabowski and Berger,[5] it is known that bubble-like solutions of the Navier-Stokes equations exist. Sensitivity to pressure fields has been studied experimentally by Staufenbiel and Helming[6] and both experimentally and numerically by Délery et al.[7] This later work documents the insensitivity of numerical solutions of breakdown for vortex Reynolds numbers greater than 5×10^2. Aerodynamic researchers such as Earnshaw[8] have long noted the inviscid nature of vortex breakdown.

Test Program

The fluid in the core of a delta-wing vortex has previously passed the leading edge. There, the upper and lower flows merge at a slight angle to each other forming a sheet of vorticity. Fluid within the sheet comes from the boundary layers where viscous forces have reduced the total pressure. The rational for the present experiments is to modify the distribution of total pressure or vorticity that is introduced along the leading edge.

Extra friction was generated at the leading edge by wire protrusions extending into the flow so that more turbulence was introduced into the vortex sheet (Blowing at this location can introduce fluid with a higher total pressure than the freestream.) One wing had protrusions only at the apex, one for half span, and one for full span.

The freestream velocity can be decomposed into components along and normal to the leading edge. The angle of attack β of the normal component is

$$\tan\beta = \tan\alpha / \cos\Lambda$$

By changing Λ, the local effective angle of attack can be modified. Wings with different apex sweep angles that were set ahead of the basic delta by different distances were used to produce various vorticity distributions. A global measure of the effect of these modififcations of the vortex structure is the breakdown position as a function of the angle of attack. This was measured in a series of experiments.

Test Setup

A horizontal water channel with a cross section 40 cm wide and 18 cm deep was used for the tests. The channel had a free surface except in the vicinity of the model where an adjustable clear plastic plate was used to suppress waves. This was done primarily to improve the flow visualization; however, some opinion exists that surface waves can have minor effects on the test flowfield. Wings were pivoted 14 cm from the floor at roughly the midspan. At high angles of attack, wall interference effects were likely; therefore increments between configurations are more significant than absolute levels. Another reason to view the present results qualitatively is that Kegelman and Roos[9] have shown that breakdown position is somewhat sensitive to leading-edge shape.

For the current tests, the flow velocity was approximately 25 cm/s. This yields a test Reynolds number of 3.5×10^4. Although this is low from a wind tunnel or flight standpoint, it is generally agreed that the primary vortex and its bursting behavior are only slightly sensitive to Reynolds number. Wings were mounted in the water channel from the bottom. The support strut had a mechanism consisting of a worm gear and reducing gears driven by a wheel. A digital readout indicated the gear position to an equivalent of 280 counts/deg in angle of at-