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The concepts of flow vectoring have long been established through the use of mechanical moving surfaces such as ailerons, elevators, flaps, etc. to redirect the local flow on an aircraft in order to obtain high-lift control and thrust-vectoring. Only recently has aerodynamic flow vectoring been investigated whereby the flow may be redirected without any movable surfaces. The present study has addressed the open-loop control of a wake by means of trailing edge suction to enhance, or introduce, any asymmetry of the mean flow of the wake to produce aerodynamic flow vectoring.

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Aerodynamic Flow Vectoring of Wakes

Final Report to AFOSR Grant No. F49620-92-J-0377

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The concepts of flow vectoring have long been established through the use of mechanical moving surfaces such as ailerons, elevators, flaps, etc. to redirect the local flow on an aircraft in order to obtain high-lift control and thrust-vectoring. Only recently has aerodynamic flow vectoring been investigated whereby the flow may be redirected without any movable surfaces. The present study has addressed the open-loop control of a wake by means of trailing edge suction to enhance, or introduce, any asymmetry of the mean flow of the wake to produce aerodynamic flow vectoring.

The problem of interest in the current study consists of the formation of the wake downstream of a bluff splitter plate by the merging of two independent streams of flow having different ambient velocities (see Figure 1). Although the wake itself has an inherent asymmetry when the two streams of fluid have different velocities, the mean flow of the unsteady wake at a supercritical Reynolds number exhibits streamlined flow aligned with the streamwise axis of the bluff splitter plate. This flow regime is characterized by the Karman vortex street, which may be referred to as a global mode, due to its large streamwise extent far beyond the near-wake region. The application of suction at the trailing edge of the bluff body serves as the control mechanism for the wake in this study. When the global mode exists, it is only conceivable that the wake may be controlled if the control mechanism also extends far downstream of the bluff body. Therefore, the application of near-wake suction has very little influence on the direction of the wake flow when vortex shedding exists. However, once sufficient suction is applied, the global instability is suppressed and aerodynamic flow vectoring may be observed due to the preferred entrainment of the low speed stream over the high speed stream in the case of uniform suction.

The effectiveness of suction as a control mechanism in the flow vectoring problem relates to its ability to reduce the size of the absolute instability region which exists in the near wake of a spatially-developing flow. Although local flow conditions may imply absolute instability, the global flowfield is destabilized only when the region of local flow having absolute instability reaches a critical size. Base-bleed which also reduces the size of the absolute instability region is not very effective as a control mechanism for flow vectoring because base-bleed washes out the flow asymmetry whereas suction enhances the asymmetry required for the flow vectoring effect.

The degree of flow vectoring may be expressed in terms of a flow vectoring angle which is measured between the streamwise axis and the line which passes through the mid-point of the base and the near-wake saddle point. Once suction exceeds a critical value, there is a distinct increase in the flow vectoring angle associated with the deflection of the low speed flow towards the high speed flow. At a Reynolds number of 160, based on the base height and the average freestream velocity, the flow vectoring angle increased from 5° to 12° for the flow having velocity ratio of $r = 0.2$ once the uniform suction increased beyond a critical value. At a smaller velocity ratio of $r=0.1$, the increase in flow vectoring angle was found from 2° to 6°. Angles approaching 20° have been obtained for flows at a Reynolds number of 320 and $r=0.2$. The effect of flow vectoring may also be measured in terms of the normal force which the flow exerts on the body. The normal force coefficient, which is nondimensionalized by the dynamic pressure based on the average velocity of the two streams and the base height, is represented as C_N. Strong asymmetry in the flow produces favorable effects on the flow vectoring. The normal force coefficient has been found to decrease from a value near zero for the symmetric wake to C_N=-.65 at r=0.25 and Re=320 according to Figure 2a.

Although the inherent asymmetry of the flow prefers the aerodynamic flow vectoring of the low speed flow, it is also possible to vector the high speed flow by prescribing a non-uniform suction distribution at the trailing edge of the bluff splitter plate to entrain more of the high speed flow. The application of uniform suction over the half the base adjacent to the high speed flow accompanied by zero suction over half the base adjacent to the low speed flow has been found effective in flow vectoring the high speed flow. For the deflection of the high speed flow, strong asymmetry has also been found to enhance the flow vectoring effect. The normal force coefficient near 4.1 for the symmetric wake increases towards C_N=5.3 at r=0.25 and Re=320 as given by Figure 2b.

The distribution of suction at the trailing edge may be manipulated to enhance the aerodynamic flow vectoring of the high speed flow or the low speed flow beyond that of the case of uniform suction. When a linear suction distribution is applied over half of the base with the stronger suction applied adjacent to the flow of interest, improved flow vectoring is achieved. The normal force coefficient associated with the deflection of the high speed flow was found as C_N=7.1. Likewise, for the deflection of the low speed flow C_N=-1.9. A vector plot of the velocity field is shown in Figure 3 for the aerodynamic flow vectoring of the high speed flow. The relation of the normal force coefficient to the mass suction flow rate at the trailing edge boundary is presented in Figure 4ab. Beyond some transitional value of the mass suction flow rate, the flow vectoring effect is diminished by increased suction. Therefore, an optimization problem exists for each selected suction distribution to determine the minimum mass suction required to produce the strongest flow vectoring effect. These figures also illustrate that thinner boundary layers of the streams at the separation of the trailing edge leads to enhanced flow vectoring of the low speed flow and leads to inhibited flow vectoring of the high speed flow for this specific suction distribution.

The aerodynamic flow vectoring results of the present study may be summarized:

1. Suction is effective in suppressing the vortex shedding in wakes due to its effectiveness in reducing the size of the absolute instability region in the near wake.
2. The suppression of vortex shedding in the wake is required for the aerodynamic flow vectoring of wakes.
3. Either the high speed flow or the low speed flow may be redirected by choosing an appropriate suction distribution.
4. The asymmetry of the flow may be exploited to produce the maximum flow vectoring effect.
5. Asymmetry may be introduced to the flow by applying a non-uniform suction distribution at the trailing edge. A biased suction distribution may enhance the flow vectoring of one stream over another producing higher deflection angles and larger lateral forces.
6. Thinner boundary layers produce stronger flow vectoring of the low speed flow.
7. An optimization problem exists for each selected suction distribution to determine the least required suction to produce the greatest flow vectoring effect.

The results of this study can be extended to the thrust vectoring of co-flowing, two-dimensional jets. Preliminary work to date shows excellent promise for aerodynamic vectoring control of jets.

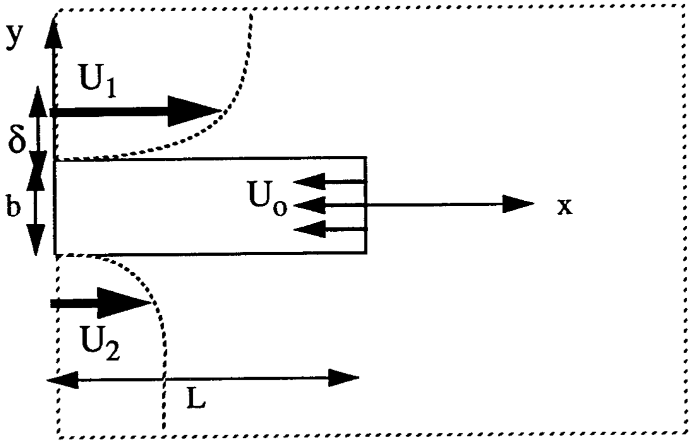

Figure 1. Schematic of Computational Problem

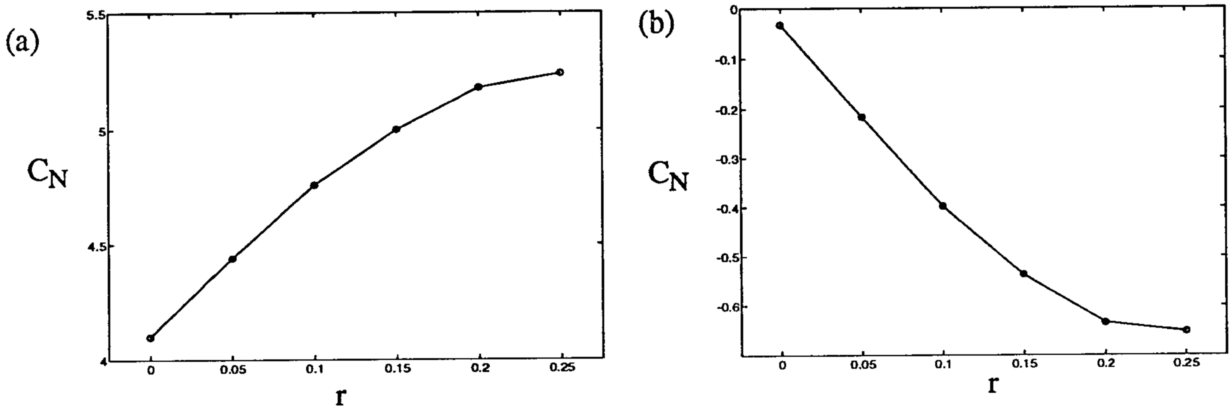

Figure 2. Effect of Shear on Normal Force Coefficient for a (a) High Speed Vectored Flow and a (b) Low Speed Vectored Flow Subject to Uniform Suction (Re=320, δ=1.2)

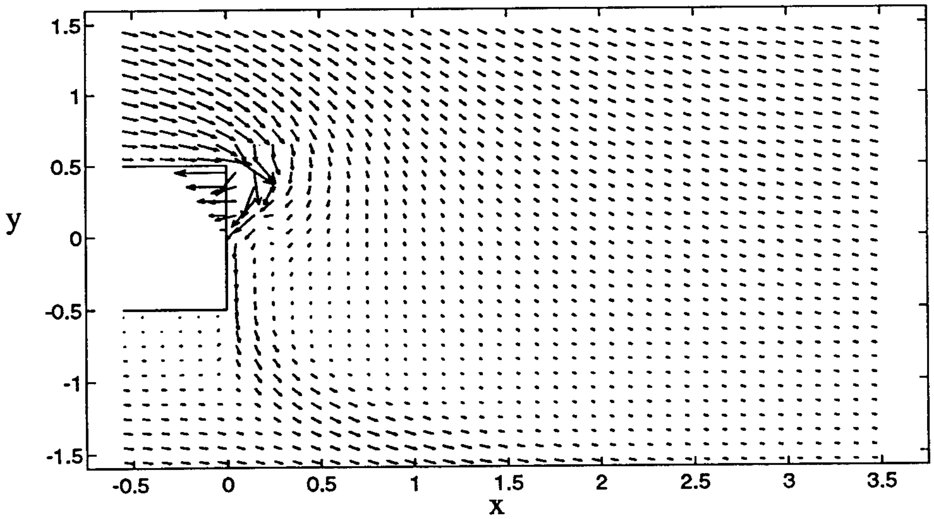

Figure 3. Vector Velocity Field of a High Speed Vectored Flow (Re=320, r=0.2, δ=1.2)

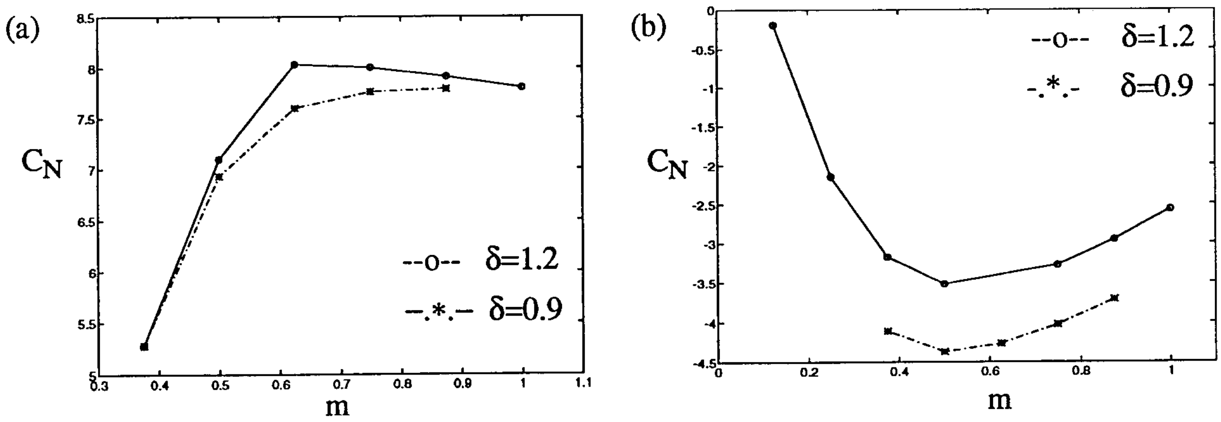

Figure 4. Effect of Mass Suction Flow Rate on Normal Force Coefficient of a (a) High Speed Vectored Flow and a (b) Low Speed Vectored Flow (Re=320, r=0.2)