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HIGH LIFT APPLICATIONS OF SPANWISE BLOWING

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ABSTRACT

A method for increasing the lift of a wing or other aerodynamic lifting surface is described. The method employs a jet of air blown spanwise along the upper surface of the wing at approximately the quarter-chord line. The jet of air, due to its entrainment, acts like a line sink and carries away the flow which has separated from the leading edge of the wing and causes the flow to reattach to the after portion of the wing downstream of the jet. A strong vortex forms around the jet which effectively increases the aerodynamic camber of the wing/jet combination. The increased camber and the reattached flow allow increased lift coefficients to be developed on the wing.

INTRODUCTION

The objective of the vortex studies discussed in this paper is to gain a better understanding of the vortex phenomenon and find means of controlling the vortex to produce high lift or to control drag. Of basic interest are those discrete vortices external to the geometric lifting body but linked close to the body by a vortex sheet, physically affecting the forces on the body. Many examples of such phenomena have been investigated for several years. An early typical example is the Föppl Vortex Pair which is observed in the initial stages of flow around a circular cylinder at very low Reynolds numbers. In this case, two symmetrical vortices of equal strength are formed and stabilized on the downstream side of the cylinder.(1) A similar observation is found for delta wings at high angles of attack where the vorticity from leading edge separation rolls up into leading edge vortices.

In both of these cases, the vortices which are formed downstream of the separation point do not shed periodically into the wake. Instead, vorticity passes into the wake in a smooth continuous manner. In the case of the Föppl pair, sufficient vorticity is shed from around the periphery of the attached vortices that they never grow large enough to be shed. As the Reynolds number is increased, the vorticity entering the vortices from the upstream boundary layers is more than can be shed by the vortex causing it to grow to the critical size and then shed into the wake. In the case of highly swept wings at high angles of attack, the vorticity which enters the vortices attached to the leading edge flows along the core in a direction parallel to the leading edges and passes into the wake. If the sweep angle is great enough, this flow can be sufficient to prevent the vortices from being shed.

Another example of non-shedding vortex flow can be found at the upstream side of discrete protuberance as shown in Figure 1. There is no periodic shedding since a sufficient amount of vorticity is carried downstream in the trailing vortices. On the other hand, Ringleb(2) has shown that the stagnation vortex upstream of a two-dimensional step will periodically shed over the step and thence downstream since the vorticity within the core cannot escape by other means.

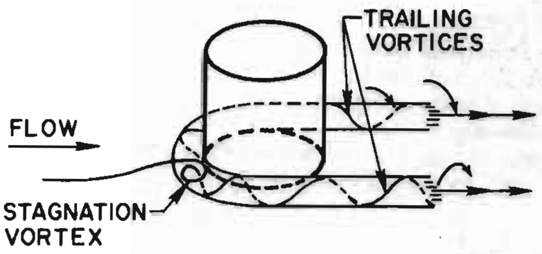

Figure 1. Stagnation Vortex in Front of a Vertical Cylinder

For the above concepts the vortices may be considered as being linked to the geometric body by a vortex sheet at the separation point. This sheet continually feeds vorticity into the discrete vortex, and in the case of a circular cylinder with its axis normal to the flow, the vortices grow until instability occurs. At this point the well-known Von Karman vortex street is formed with its alternate shedding vortices.

The strength and frequency of the vortices shedding from lifting bodies have been the subject of study by many well-known investigators. It has been found that the closer vortex shedding is to being periodic, the larger the vortices and unsteady lift forces. Roshko(3) and others have also shown that periodicity is not only a low Reynolds number phenomenon but occurs at the very high operating Reynolds numbers of large aircraft and space vehicles. Means have been sought by several investigators to control the vortex shedding or "lock" the vortex onto the lifting body and preserve its lift inducing effect. Among works putting considerable effort into this concept are those of Ringleb.(2) His theoretical efforts can apply readily to the effects of spanwise blowing.

The concept of the use of spanwise blowing as a means to increase lift came from a series of fundamental studies of jets and vortex flows conducted at the Lockheed-Georgia Research Laboratories beginning in 1965. At that time the research was primarily concerned with the properties of the axial flow which exist in the core of vortices. To aid in these studies, a smoke tunnel was designed for operation in the subcritical Reynolds number regime which was virtually turbulence-free. With the aid of smoke injection the flow was made visible. In this way the behavior of the vortex system was mapped as various conditions and constraints were applied.

DISCUSSION

Investigations have verified conclusively that the periodic shedding of vortices behind a two-dimensional circular cylinder is not a two-dimensional phenomenon. Separated flow has been observed to leave a cylinder in a manner which varies along the span as shown in Figure 2.

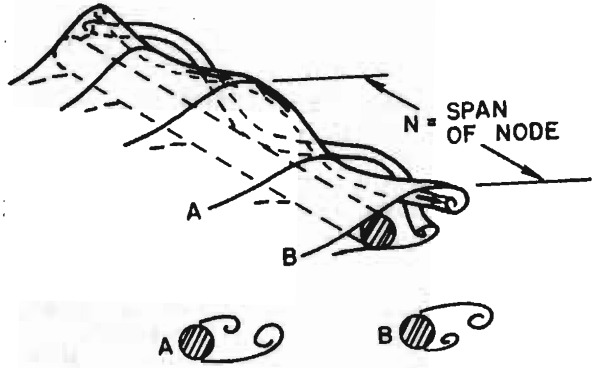

Figure 2. Three-Dimensional Flow around a Two-Dimensional Cylinder

Thus the flow at point A is a semi-node apart from that at point B (180 degrees out of phase). In the next instant, the situation is reversed with pattern A taking on the form previously at B as the large vortices are shed from the cylinder.

It has also been observed that there exists a spanwise flow within the cores of the vortices which is periodic at half the frequency of the shed vortices. This spanwise flow moves into the large vortex nodes causing them to grow at an even greater rate than would occur if all of the flow entered from the immediately upstream boundary layer. Conversely, this periodic spanwise flow extracts flow from the mid-node portions of the vortices and delays their shedding. When the large vortices do shed downstream, the spanwise flow reverses its direction and feeds the mid-node vortex points from which flow had previously been extracted. The phenomenon has been described in greater detail by Theisen.(4) This three-dimensional flow was probably first discussed by Nisi(5) who examined the flow behind a low aspect ratio circular cylinder at Reynolds number = 15.

In an attempt to suppress the vortex shedding, plates were mounted on the cylinder parallel to the main flow but perpendicular to the axis, as shown in Figure 3.

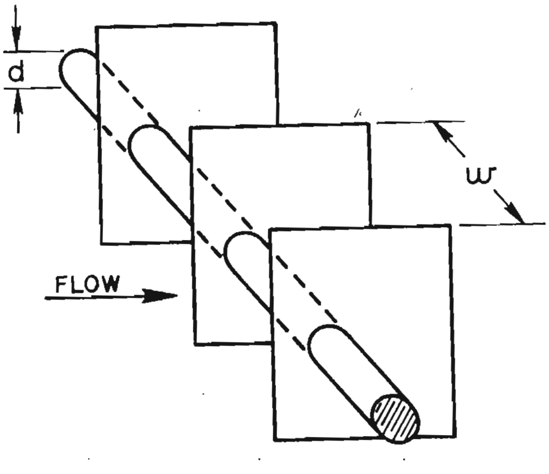

Figure 3. Circular Cylinder with Plates along the Span

It was found that when the plates were spaced four cylinder diameters apart or less ($w/d \leq 4$), the shed vortices were suppressed. As the plates were moved to a ratio of $w/d = 6$, the vortex shedding again occurred and was virtually unaffected at $w/d = 10$. Figure 4 shows the flow behavior behind a cylinder without plates (top view) and with plates spaced at $w/d = 4$ (bottom).

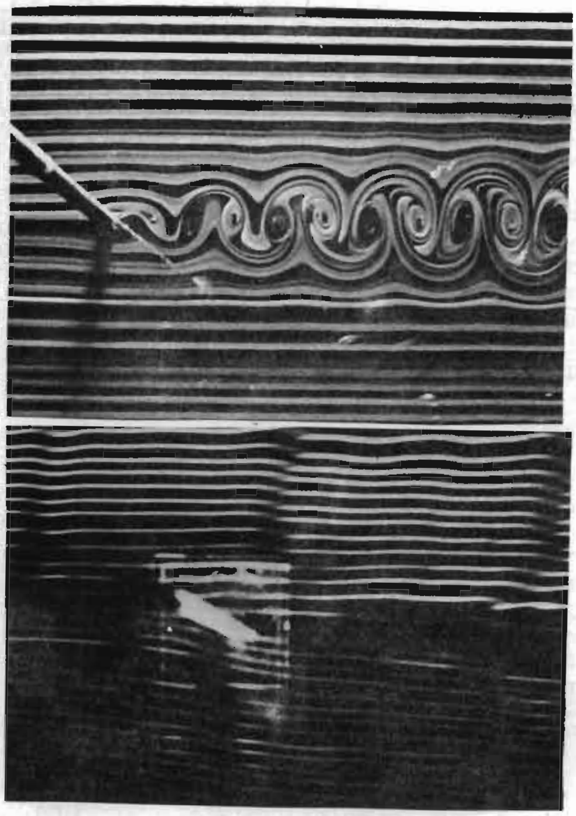

Figure 4. (Top) Vortex Street, Unsuppressed. (Bottom) Vortex Shedding Suppressed with Plates at $w/d = 4$.

It was found that the mechanism which prevented the periodic shedding of vortices was similar to that of the stagnation vortex ahead of a protuberance In the present case, the vortex which would normally have been shed periodically into the wake of the cylinder was instead not shed due to the effect of the trailing vortices which formed at the intersections of the plates and the cylinder. As the plates were moved further and further apart, their effect on carrying away the incoming vorticity was diminished with the result that the vortex again began to be shed periodically into the wake.

These studies clearly indicated that the vortex downstream of a separation point could be fixed and caused not to shed if sufficient vorticity could be removed from its core. To further test and exploit this phenomenon, an airfoil was constructed which has a cylindrical cut-out at the wing/flap junction. As shown in Figure 5, a perforated cylinder was mounted co-axially in the cylindrical cut-out and suction was applied in order to remove the flow from the core of the vortex which was formed there. By this means, as shown in Figure 6, the flow was prevented from separating and instead remained attached to the upper surface.

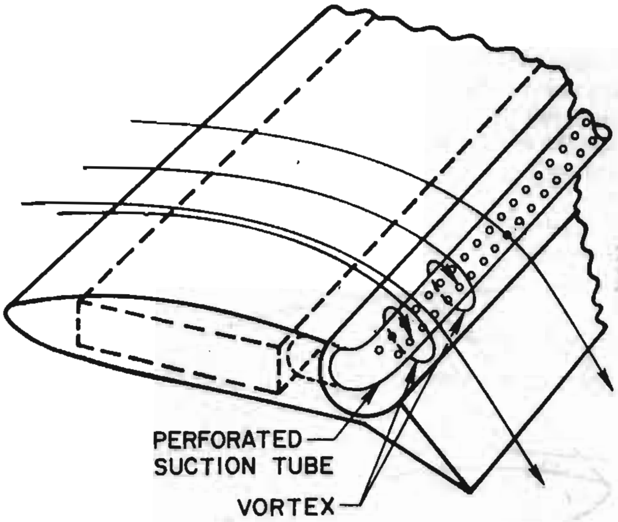

Figure 5. Wing Model with Perforated Tube at Flap Junction

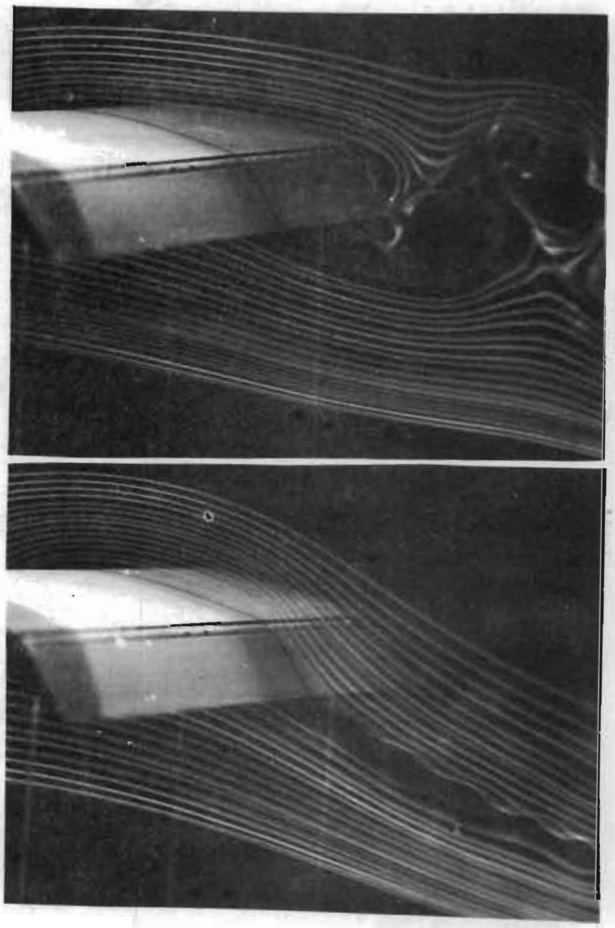

Figure 6. 4415 Airfoil with Perforated Tube; Suction-Off (Top), and Suction-On (Bottom)

Subsequent studies were conducted in which the suction was not distributed uniformly along the span but instead was applied at discrete "ports" spaced at intervals along the wing as shown in Figure 7.

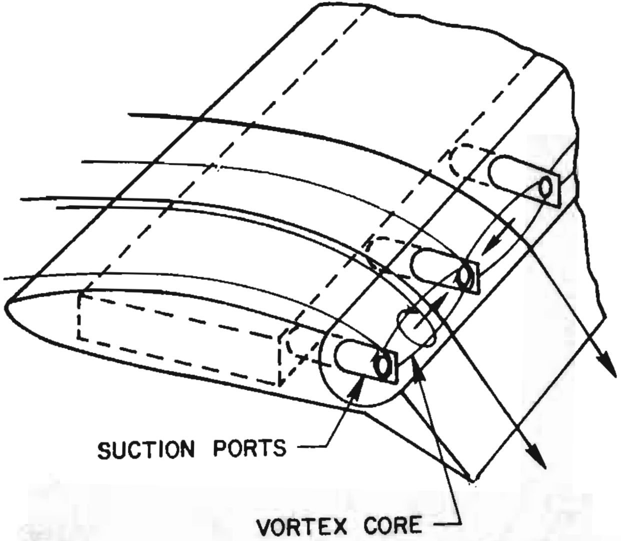

Figure 7. Wing Model with Suction Ports Along S

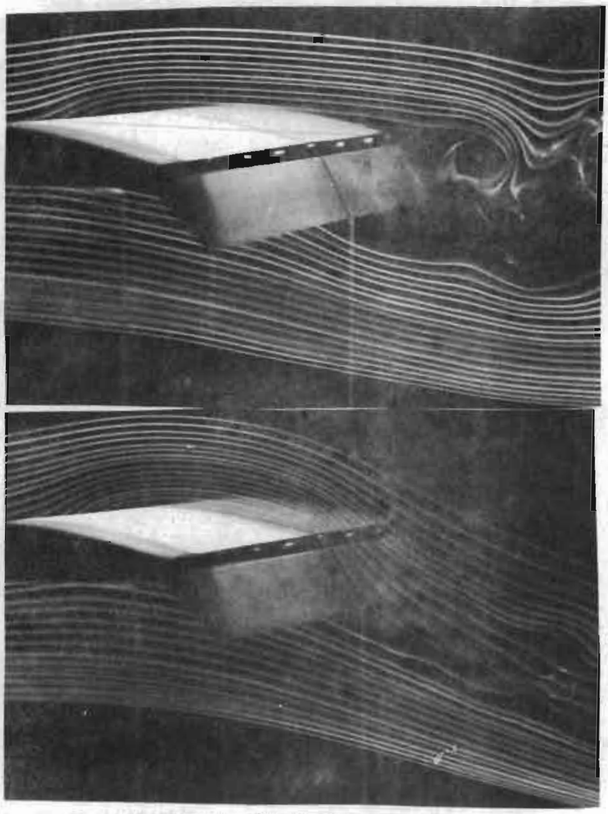

Figure 8. 4415 Wing with Suction Ports Shows Separated Flow Without Suction (Top) and Attached Flow with Suction (Bottom).

The concept here was that the suction from each port would have spanwise influence on the vortex in much the same manner as that shown in the experiments with the circular cylinder with the plates mounted perpendicular to its axis. It was found that, with suction applied, the spanwise influence extended about the thickness of the airfoil on either side of any suction port. This suction removed enough of the vorticity from the core of the vortex that it remained fixed or "locked" in the circular cut-out at the flap junction. Under these circumstances, the main flow did not separate from the wing but remained attached to the wing and the flap as shown in Figure 8.

Having demonstrated the principle of delaying flow separation by this method, the principle was next applied to a full-scale flight vehicle. A wing "glove" with a 6-foot span was prepared and installed on a glider at Mississippi State University. The "glove" contained the suction ports, flap cusp, plenum chamber, and a power supply (suction fan). The geometric configuration is shown in Figure 9.

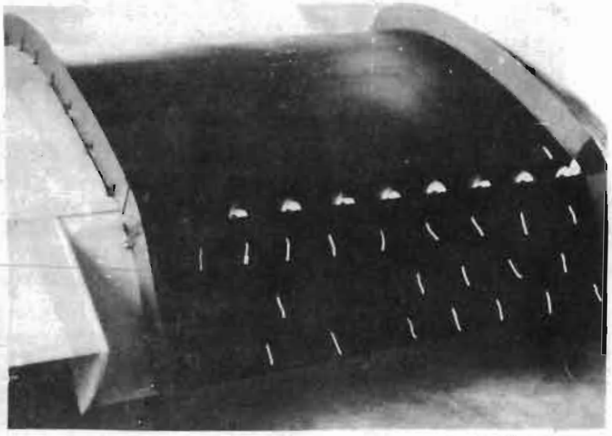

Figure 9. Vortex Locking Mechanism Installed on an MSU Glider

Instrumentation was installed for measuring pressure distribution, suction quantities, freestream conditions, and power requirements. Preliminary results indicated that the stall speed of the glider was reduced by about 5 mph during "suction-on" conditions, indicating that the vortex was being stabilized in the flap "cusp" and that lift augmentation was achieved.

Following the flight test, additional flow visualization tests were conducted in the wind tunnel for the purpose of optimizing the suction quantities. One test examined the redistribution of the suction ports to correspond to the half-node spanwise position corresponding to the maximum diameter of the vortex core. The intent here was to minimize the suction power required for a given suction flow quantity.

Drag Reduction

In addition to its lift augmentation potential, the locked vortex can also be used to reduce drag. One application of this technique is illustrated in Figure 10 where a half-body model with a bluff trailing edge is shown with a horseshoe vortex locked in place by suction at the places indicated.

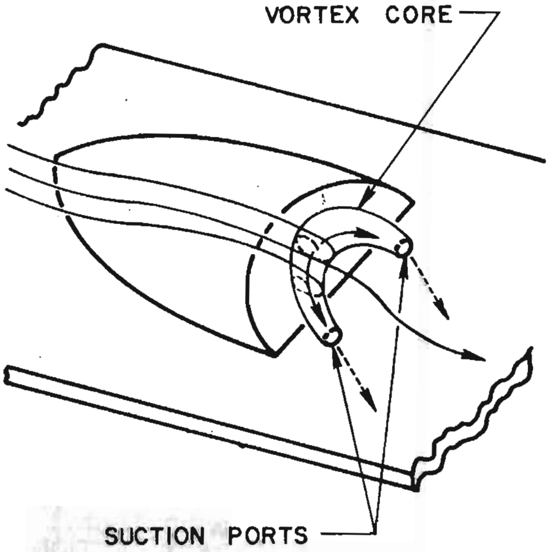

Figure 10. Half-Body Model with Bluff Trailing Edge

The principle of flow reattachment here is the same as that of the other locked vortex systems, namely, low energy boundary layer air enters the vortex core and is subsequently removed by suction at the orifices in the plate. This action causes the flow to reattach to the base of the bluff body, thus eliminating the separation.

Smoke tunnel tests with a half-body such as described were conducted and the results are illustrated by Figure 11, where the top portion shows the body without suction and the bottom photo depicts flow behavior behind the body with suction on.

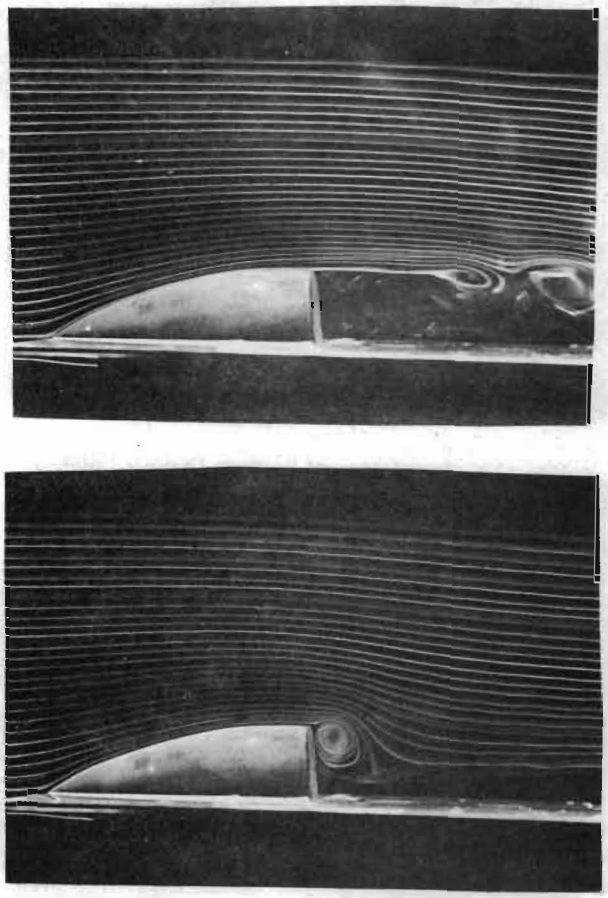

Figure 11. Half-Body of Revolution Without Suction (Top) and with Suction (Bottom).

Observations of the vortices shed from the bluff body of Figure 10 proved to be quite interesting. It was determined that the frequency of vortex shedding could be correlated with the suction quantity as shown in Figure 12. The term f_o represents the frequency of shedding with no suction and S_o represents the suction quantity required to completely eliminate vortex shedding. Since the vorticity is concentrated in the boundary layer, it is reasonable that if more boundary layer is removed less vorticity is shed and more time is required to build the discrete vortex to a strength and size required for it to shed.

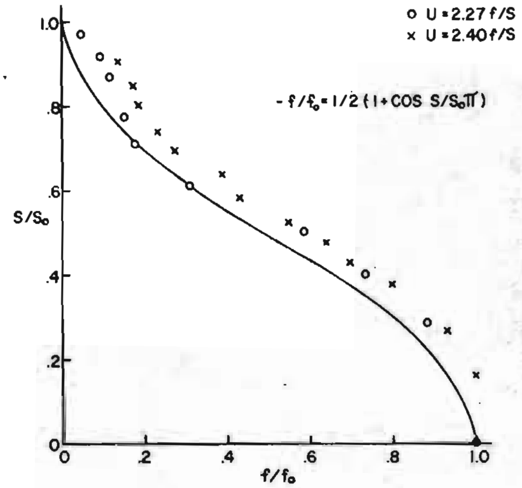

Figure 12. Correlation of Suction Quantity and Frequency of Vortex Shedding from Bluff Body.

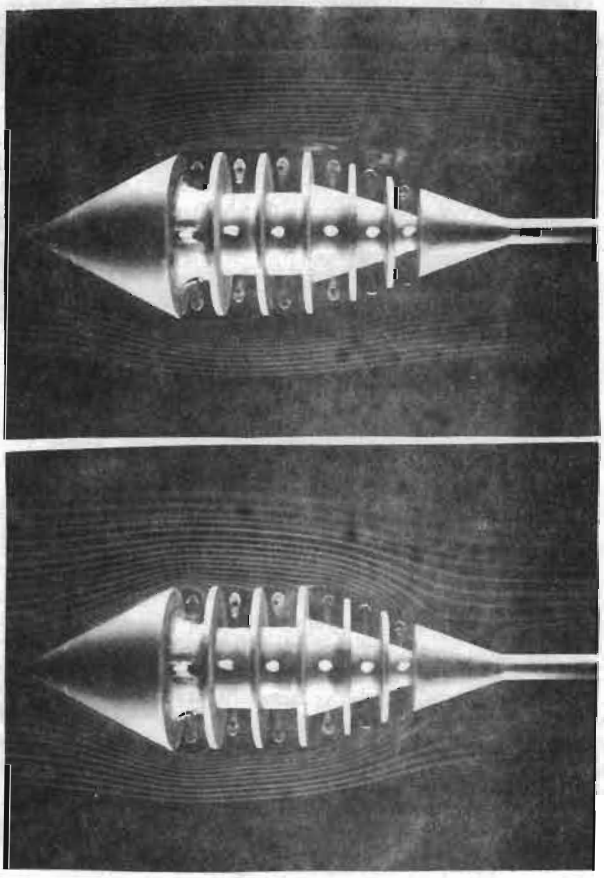

Figure 13. Irregular Body of Revolution Without Suction (Top) and With Suction (Bottom).

The application of the locked vortex is very broad in that the principle is amenable to very complex bodies. This is illustrated by Figure 13, which shows the flow over a highly irregular body of revolution. Rings were cut out of the body and suction ports installed circumferentially within each ring. Figure 13 (top) shows the separated flow pattern over the body of revolution, without suction, and Figure 13 (bottom) shows ring vortices being formed in each cut-out as suction is applied with the end result being the reattachment of the flow at the trailing edge.

Spanwise Blowing Concept

The previous studies of the effects of suction applied at the core of a vortex led to the concept of spanwise blowing as a means of vortex control. It was determined that a high speed jet could provide the necessary suction by means of its entrainment. By blowing a high velocity jet of air down the core of a vortex, the low velocity, high vorticity flow there can be removed by entrainment and the jet, in effect, acts like a spanwise line sink. In the case of a semi-span wing model, for example, the jet would be exhausted from an orifice at the wing root, pass along the wing, and leave at the wing tip as shown in Figure 14.

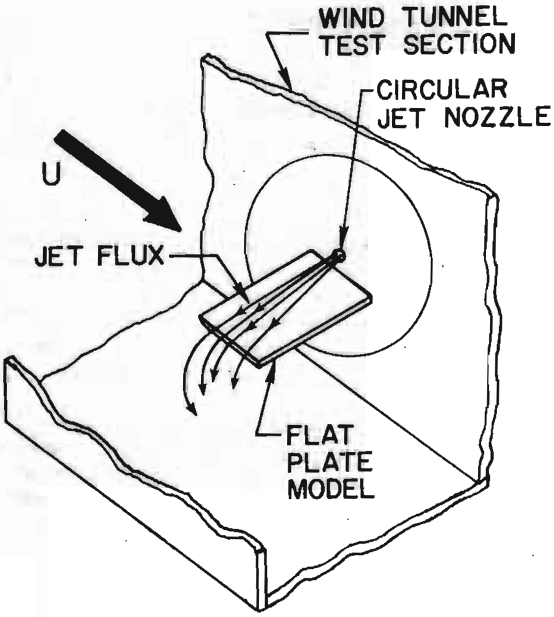

Figure 14. Rectangular Flat Plate, Spanwise Blowing Wind Tunnel Model

Photographs made in our 18 by 18 inch smoke tunnel clearly show how the flow which separates from the sharp leading edge of the model is made to reattach to the plate as shown in Figure 15.

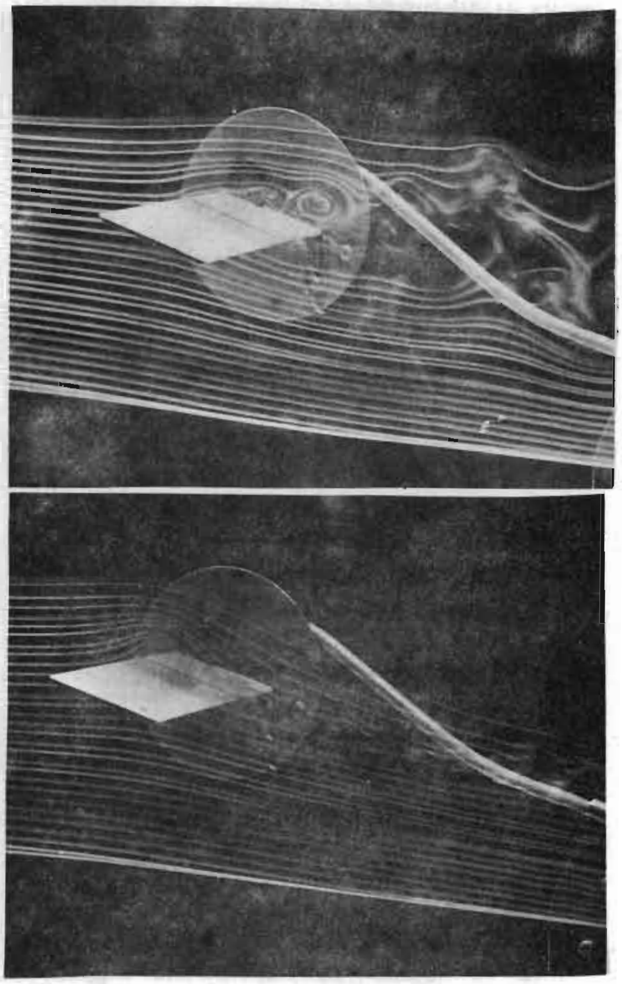

Figure 15. Spanwise Blowing over Flat Plate Without Blowing (Top) and With Blowing (Bottom).

Later, more detailed smoke tunnel tests demonstrated that with the nozzle at positions behind the 15 or 20 percent root chord, two phenomena occurred. Not only does the flow from the core get entrained into the jet thus controlling the vortex, but also a secondary vortex may develop ahead of the jet whose strength is a function of the vorticity shed at the sharp leading edge.

To establish an order of magnitude for the lift increase possible with spanwise blowing and to find the optimum jet size and position, simple wind tunnel tests were conducted. Details of these tests are discussed in Reference 6 and are briefly reviewed here. The model tested consisted of a simple flat plate mounted on the side wall turntable of the 43 by 30 inch test section of the Lockheed-Georgia Research Laboratory Wind Tunnel. The jet is a circular nozzle flush mounted to the turntable and can be adjusted to vary its position relative to the wing.

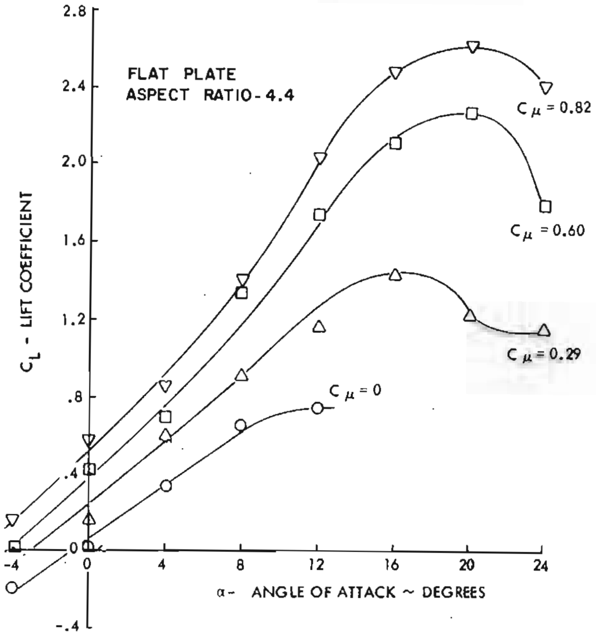

Figure 16. Lift Due to Spanwise Blowing.

The term C_μ represents the momentum coefficient of the jet.

Spanwise Blowing over Flaps

Another application of spanwise blowing is that of blowing spanwise over trailing edge flaps or control surfaces. The result is lift control by means of a very simple mechanical system that can be implemented on either thin or thick wings with a minimum of ducting requirement. To determine the potential of this concept, the flat plate model previously discussed was modified to include a 25% chord trailing edge flap and a 7.5% chord leading edge flap. The model mounted on the side wall of the wind tunnel is shown in Figure 17.

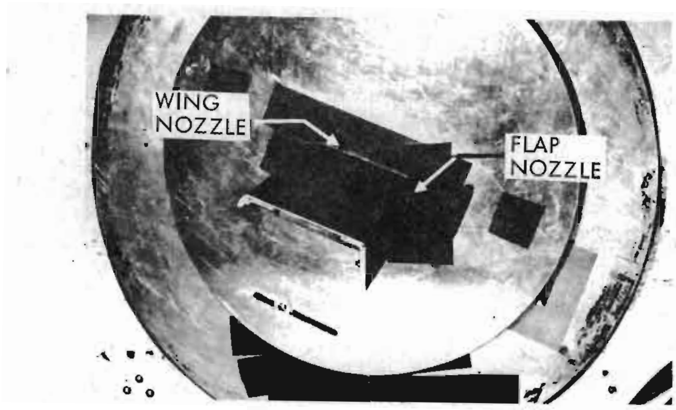

Figure 17. Basic Wing Plus Leading and Trailing Edge Flap.

The model has spanwise blowing nozzles at 17% of the flap chord and at 20% of the wing chord. A small level of blowing on the wing was held constant to delay flow separation at the knee of the leading edge flap while the quantity of blowing at the trailing edge flap was varied.

Figure 18 shows the results of flap spanwise blowing on the lift curves. It is noted that a large increase in lift occurs with a small amount of blowing and thereafter the effect of blowing is small. This is also typical of boundary layer control by chordwise blowing at the knee of the trailing edge flaps.

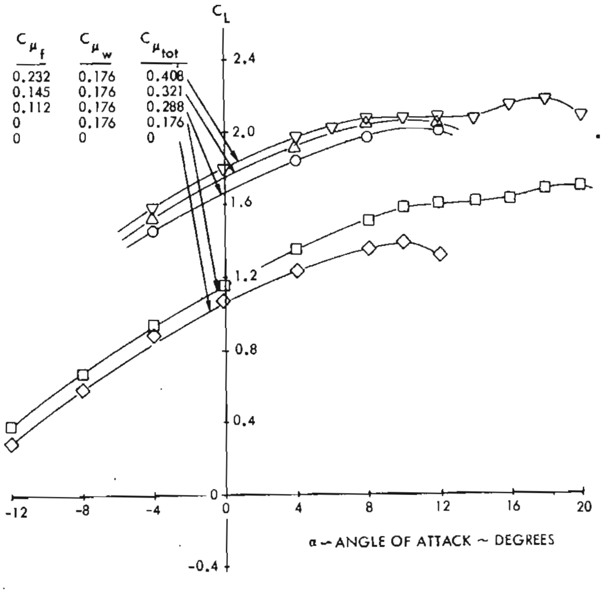

Figure 18. Flap Blowing Effectiveness

It can be recognized from this plot that a favorable characteristic results from the use of spanwise blowing over the flap. This shows the possibility of changing the lift without changing either the angle of attack or the flap deflection angle. This ability to directly alter the lift by changing the jet velocity has considerable potential in STOL aircraft where flight path control is ordinarily accomplished by quick acting flaps or modulation of the thrust.

Further smoke tunnel results of spanwise blowing over the flaps and wing of another model are illustrated in Figure 19.

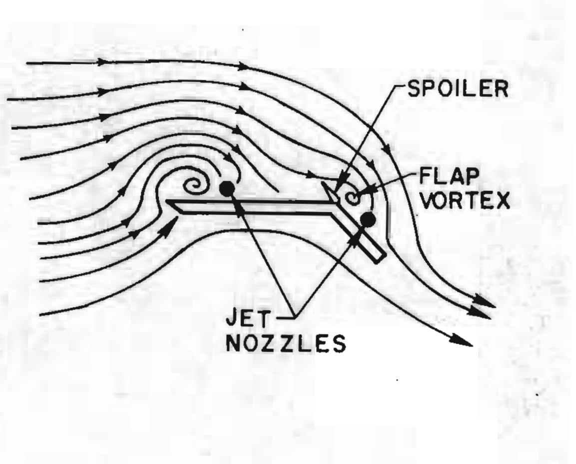

Figure 19. Vortex Locked at Flap Knee and Wing Leading Edge by Spanwise Blowing

Actual smoke tunnel photographs are shown in Figure 20 with and without flap blowing. The wing is a flat plate with sharp leading edge and spanwise blowing at the quarter-chord. The flap is a flat plate, attached to the wing at 70 degrees deflection. A spoiler projecting from the flap knee into the flow is shown also. This spoiler serves to create vorticity that is rolled up ahead of the flap blowing jet. The resulting vortex appears to increase circulation in the same manner as the wing leading edge vortex. Without the spoiler little vorticity is concentrated ahead of the flap jet and the smoke filaments in the flow field show considerably less downwash aft of the model.

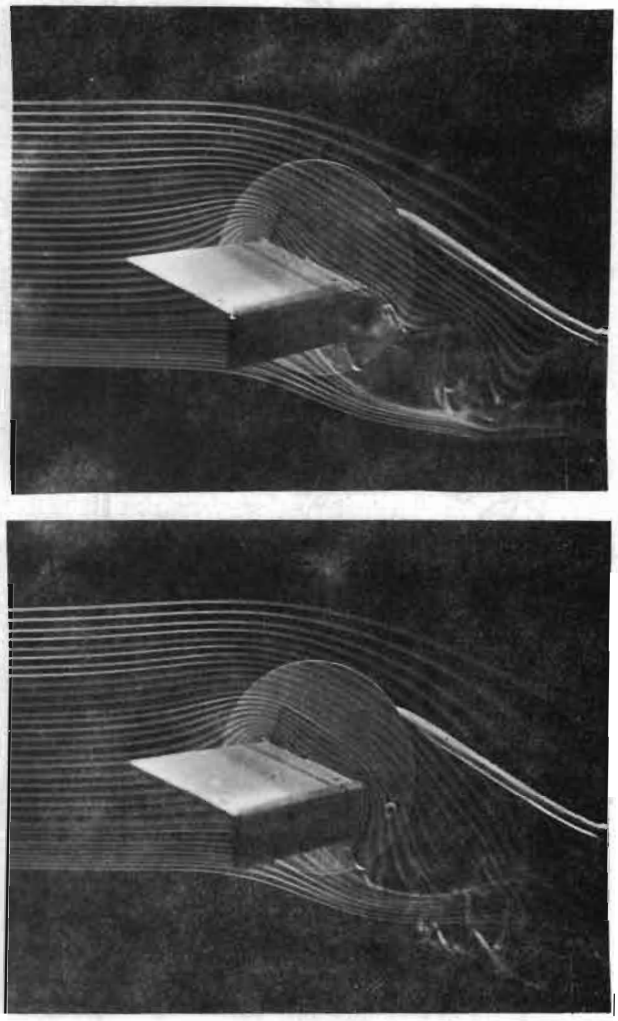

Figure 20. Spanwise Blowing Over Wing and Flaps Without Flap Blowing (Top) With Flap Blowing and Spoiler Blowing (Bottom).

Model Force Tests

The Lockheed-Georgia Research Laboratory has designed and fabricated a finite span model to test the spanwise blowing concept and obtain lift, drag, and pitching moment data as well as stabilizer effectiveness. The model shown in Figure 21 is sting mounted in the 43 by 30-inch test section of the Research Laboratory Wind Tunnel. Three wings are available, all of the same aspect ratio as the original half-span pressure model but with different sweep angles of the quarter chord. Sweep angles of 0, 20, and 40 degrees are available. Variable incidence tail and variable jet nozzle positions are provided.

Figure 21. Spanwise Blowing Force Model.

Some tests of the straight wing model of Figure 21 have been conducted. Although data reduction has not been completed, preliminary results show good agreement with the data of Figure 16.

The straight wing has also been modified to provide a 25 percent chord trailing edge flap but test results on this configuration are not yet available.

Future Investigations

In addition to the concepts and techniques displayed, there are several additional areas of potential application which will be the subjects of future investigations. The first of these is the use of spanwise blowing over the control surfaces such as ailerons, rudders, and elevators in order to increase the forces developed there. A jet located at the root of a rudder for example could be arranged to blow parallel to the hinge axis and augment the rudder control at high deflections where the flow would otherwise have separated, as shown in Figure 22.

It is conceivable that a single jet could be employed in this case. The jet would operate only when the rudder deflection was "hard over" and additional control was required. Similar arrangements could be installed on ailerons and elevators for additional control forces. It is anticipated that the effects of these arrangements will be similar to that obtained by spanwise blowing at the wing/flap juncture in which case a large augmentation resulted.

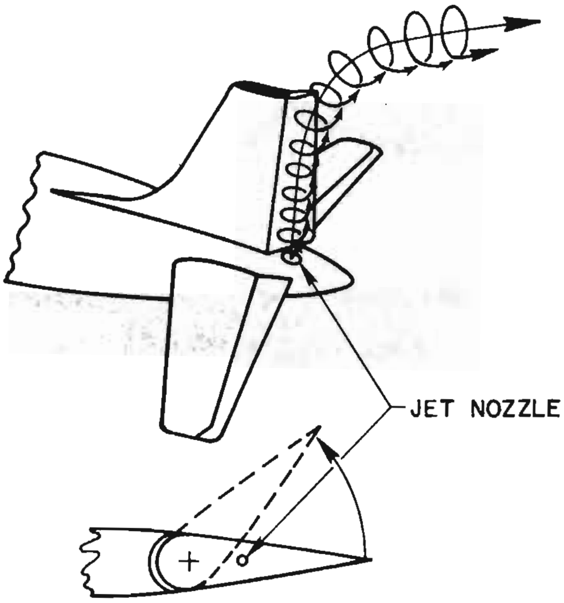

Figure 22. Rudder Control Augmentation By Spanwise Blowing.

A second area which is to be studied further is the influence of the jet passing off of the wing tip. Smoke tunnel studies have indicated that when a vortex is "locked" to the upper surface of a wing behind the leading edge, the vorticity which is concentrated there becomes a major part of the trailing vortices which leave the wing tips. When the jet velocity is great enough, these trailing vortices are moved outward and the effective aspect ratio of the wing is increased as shown schematically by Figure 23.

The effect of this increased effective span is twofold, first, the loading on the outboard portions of the wing is increased and, second, the induced drag is reduced. The incremental changes in these effects must of course be weighed against the power required for the blowing of the spanwise jet.

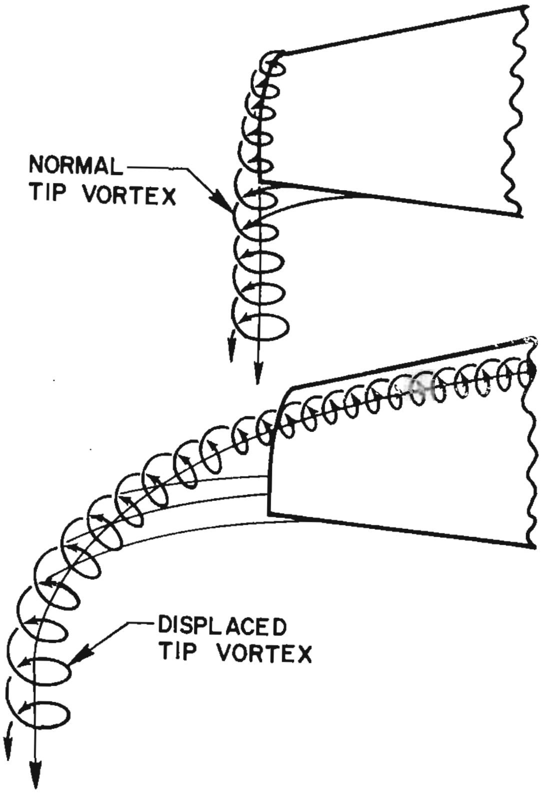

Figure 23. Wing-Tip Vortex Displaced Off of Wing by Spanwise Blowing

In summary, the concepts of vortex control by removing flow from the core has been shown to be practically achievable. Furthermore, the technique of providing this control by the simple means of a spanwise jet has been demonstrated, and potential future applications have been suggested.

ACKNOWLEDGMENT

The author gratefully acknowledges the efforts of Mr. Billy Passinos and Mr. C. J. Dixon in both the preparation of this paper and the gathering of much of the experimental data.

NOMENCLATURE

AR	Aspect Ratio
d	Cylinder Diameter
f	Vortex Shedding Frequency
f_o	Natural Vortex Shedding Frequency (no suction)
N	Vortex Core Axial Node
S	Suction Quantity
S_o	Suction Quantity Required to Stop Vortex Shedding
U	Free Stream velocity
α	Angle of Attack
ω	Spacing of Perpendicular Plates on a Cylinder
C_L	Total Lift Coefficient
$C_{L_{MAX}}$	Maximum Lift Coefficient
C_μ	Momentum Coefficient
$C_{\mu f}$	Flap Blowing Momentum Coefficient
$C_{\mu w}$	Wing Blowing Momentum Coefficient
$C_{\mu tot}$	Total Wing and Flap Momentum Coefficient

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