

## TOWARDS AN ADVANCED VORTEX FLAP SYSTEM - THE "CAVITY" FLAP

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## SUMMARY

An extension of the vortex flap concept was explored with the aim of providing high-alpha flight control capability coupled with maneuver drag reduction for highly swept wing configurations. A retractable lower surface flap mounted on a translating hinge is proposed, allowing chordwise extension as well as deflection, the two movements being independently controlled. The frontal cavity formed by the partially extended and deflected flap captures a vortex above a certain angle of attack. The cavity vortex downwash alleviates the effective incidence of the wing leading edge, thus modulating vortex lift; at the same time, the induced suction in the cavity generates thrust. These postulated aerodynamic features of the cavity flap were validated through low-speed tunnel pressure and visualization tests on a 65 deg swept oblique wing model, which also provided initial trends of the leading edge vortex alleviation and cavity suction with respect to flap extension, deflection and angle of attack. Force tests on a 60 deg delta model further showed the cavity flap L/D performance to compare favorably with the conventional vortex flap. A two-segment flap arrangement with independently controlled segments was envisaged for exploiting the vortex modulation capability of the cavity flap for pitch, roll and yaw control, in addition to drag reduction at high angles of attack.

## INTRODUCTION

The first wind tunnel demonstration of the vortex flap concept took place nearly seven years ago (ref. 1). The extensive experimental and theoretical research carried out since then (ref. 2) has concentrated on the application of vortex flap thrust recovery for drag reduction of highly swept wings at maneuver lift coefficients. Recent design studies related to advanced fighters have underlined the need to extend aerodynamic control effectiveness to increasingly high angles of attack. Accordingly there is considerable interest in evaluating vortex management ideas for improved high-alpha control.

Effective aerodynamic control of highly swept, slender vehicles at high angles of attack basically requires the ability to modify the onset, growth and shedding characteristics of large-scale vortices originating from forebody and wing leading-edge separation, and thereby to rapidly modulate the vortex lift and reposition its point of action relative to c.g. Although vortex lift modulation capability has been shown to be inherent to the vortex flap concept, its potential has not yet been explored in detail. This paper discusses an advanced vortex flap system, called the cavity flap, conceived for the purpose of obtaining high-alpha control as well as

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drag reduction from the same set of aerodynamic surfaces. Some results are presented of low-speed wind tunnel experiments undertaken to verify the aerodynamic basis of the cavity flap and to compare its drag reduction performance with that of a conventional vortex flap.

### CAVITY VORTEX FLAP

The conventional (or leading-edge) vortex flap aims to contain the vortex and its peak suction over the flap (fig. 1). Drag reduction then is a combined result of thrust recovery on the forward-sloping flap and reduced suction on the aft-sloping wing surface.

With increasing alpha the flap frontal projected area decreases and its direct contribution to drag reduction tends to zero. A 30-deg deflected flap on a 60-deg delta wing, for example, becomes essentially aligned with free-stream at 14 deg angle of attack (or  $C_L \approx 0.65$ ), beyond which it is the re-attached flow on the wing rather than the flap vortex force that yields a drag reduction.

If the flap hinge were to be moved some distance aft of the leading edge under the wing and a vortex trapped in the resulting cavity, the frontal area under vortex suction can be largely recovered. The leading-edge overlap now covers a large part of the flap plan area and therefore reduces its own vortex lift contribution. This cavity flap arrangement promises a substantial vortex lift modulation capability by independently varying the flap projection and deflection at a given angle of attack. In the limit, an optimum cavity vortex leading to a fully attached flow on the wing will essentially eliminate vortex lift. Additional cavity flap advantages envisioned are its applicability to sharp or blunt leading edges, plus a structurally superior attachment to the wing in comparison with the leading-edge hinged flap.

Figure 2 suggests a practical implementation of the cavity flap. The retracted flap is fully conformal to the wing lower surface contour. The flap hinge slides on internal tracks, the extension and deflection angle being actuated independently. Pure extension of the flap projects a sharp edge which can be used to augment vortex lift on blunt leading-edge wings (ref. 3). Partial extension plus deflection yields the cavity flap configuration. At the forward limit of extension the flap functions essentially as a conventional vortex flap. At a large deflection angle with the hinge at its aft limit, a vortex will form behind the flap, making it an effective drag brake.

### OBLIQUE WING TESTS

The key hypothesis underlying the cavity flap concept, namely the capture of a stable cavity vortex and its use to modulate vortex lift on the wing, was tested on a highly swept oblique wing model (fig. 3). The variable-sweep oblique wing was chosen to facilitate future study of the sweep-angle effect on the cavity vortex stability. In the initial tests reported here, however, the wing was set at the maximum sweep of 65 deg.

The wing section perpendicular to leading edge was a 12-percent thick, conventional subsonic type airfoil with a flat undersurface. Two chordwise pressure

stations were incorporated in the wing, one on the fore panel and one on the aft panel. At each station, taps were provided on the upper surface and over the first 15 percent chord on the lower surface.

A constant chord, flat plate flap was tested on the forward wing panel. Three deflection angles (10, 20 and 30 deg), and three hinge positions at each angle including the leading-edge position, were investigated. The tests were carried out in the North Carolina State Subsonic Tunnel at a free-stream velocity of 100 fps.

The vortex characteristics of oblique wings are not well known. Therefore, the oblique wing model was first tested with flap off in order to establish its suitability for evaluating the cavity flap. Figure 4 shows typical oil-flow and pressure distribution results. The oil pattern at  $\alpha = 16$  deg reveals independent leading-edge vortices on the fore and the aft wing panels. The upper surface pressures at four angles of attack (10, 12, 14 and 16 deg) show the evolution of the vortex suction peak. Comparison of the fore and aft pressure stations with increasing angle of attack shows the forward wing vortex to develop continuously, whereas on the aft wing the suction peak is gradually smeared out due to the locally thickened boundary layer (resulting from a spanwise outflow as on a swept-back wing). These tests showed that the fore panel of the oblique wing generated a leading-edge vortex flow representative of swept wings, thus providing a proper aerodynamic environment for validation of the cavity flap concept.

Typical flap effects on the forward wing pressures at an angle of attack 16 deg will now be discussed. Figure 5 shows the effect of moving the flap hinge forward with the flap angle held constant at 20 deg. The sketches on the right interpret the corresponding vortex patterns.

At the aft hinge position, the flap hardly affects the upper surface suction characteristics; on the lower surface, however, an increased suction suggests that a cavity vortex is already formed. No change in vortex lift due to flap deployment can be expected in this case although some drag reduction should be obtained.

Moving the flap hinge to the mid-position is seen to produce a marked reduction in the vortex suction on the wing upper surface. At the same time, the cavity suction is almost doubled. This position of the flap appears to come close to the postulated cavity vortex flow with attached flow on the wing. Substantial lift reduction can therefore be anticipated in this case, together with enhanced drag-reduction.

At the leading-edge position of the flap the vortex appears to be partly spilled onto the wing. Due to the fully exposed flap area in this case, lift reduction on the wing is likely to be largely compensated by the vortex lift on the flap. The drag reduction capability will be degraded due to the negligible frontal area projected by the flap.

The pressure results in figure 6 show the effect of increasing flap angle at a constant hinge position. A progressive decrease in the vortex suction on the wing upper surface is noted. There is little change in the cavity suction level with increasing flap angle; however, since the associated frontal area is increasing, the drag reduction should improve.

By integrating the upper surface pressures a local normal force coefficient is obtained. This upper surface normal force directly reflects the changes in the

vortex suction characteristics and is therefore useful for presenting the trends with respect to flap angle and hinge line position. It is seen in figure 7 that, at all three flap angles, a forward extension of cavity flap results in progressive and marked reduction in the wing normal force at angles of attack above 8 deg.

Typical cavity suction characteristics are shown in figure 8 for the mid-position of the flap hinge. Also shown for reference is the pressure at the same lower surface tap with the flap off. It is evident that with increasing flap angle, the onset of cavity vortex is delayed. At higher angles of attack, however, all three flap angles approach the same cavity suction levels.

#### 60-DEG DELTA FORCE TEST

Force measurements to evaluate the cavity flap were conducted on a 60-deg delta model (fig. 9) during a brief investigation in the NASA Langley 12-Foot Low-Speed Tunnel. The object of these initial tests was to compare the drag reduction capabilities of leading-edge flap and cavity flap at constant flap angles of 20 deg and 40 deg.

The leading-edge thrust due to a flap is most sensitively indicated in the balance axial force component. Figure 10 plots the axial force versus normal force coefficients and includes the flap-off data for reference. The vertical gap between the flap-on and flap-off data (i.e. a negative  $\Delta C_A$ ) indicates the aerodynamic thrust attained. At 20 deg flap angle, the cavity flap is seen to generate more thrust than the leading-edge flap throughout the  $C_N$  range. At 40 deg deflection, the onset of cavity vortex is delayed to a higher angle of attack, and as a result the cavity flap begins to show an advantage only above  $C_N = 0.6$ .

Figure 11 presents the corresponding drag reductions. On the left is absolute  $\Delta C_D$  and on the right,  $\Delta C_D$  as a percentage of the basic drag (i.e. flap off). It is noted that the 40-deg cavity flap advantage appears at higher angles of attack when the percentage drag reduction has already peaked and is rapidly declining. It is reasonable to expect therefore that a more moderately deflected cavity flap (say at 30 deg) might be advantageous in the region of peak percentage drag reduction. Note also that the hinge line position remains to be optimized in combination with flap deflection, which should yield additional improvement in the cavity flap performance.

Since both the leading edge and cavity flaps produce reductions in lift as well as in drag, the final evaluation must be in terms of L/D ratio as a function of lift coefficient. Figure 12 shows the 20-deg cavity flap to be advantageous across  $(L/D)_{max}$ . The 40-deg cavity flap evidently is over-deflected, but catches up with the leading-edge flap at  $C_L = 0.7$  and thereafter yields the same L/D improvement. The L/D results again suggest that flap angles between 20 and 40 deg deserve investigation and that a coordinated study of hinge-line position should also be conducted.

#### CAVITY FLAP FOR HIGH ALPHA CONTROL

It is interesting to speculate on the ways of exploiting the vortex lift modula-

tion capability of the cavity flap for high-alpha control (fig. 13). A spanwise segmented cavity flap system is envisaged with two segments per leading edge, each flap segment being under independent control. For maximum drag reduction, all four flap segments will be deployed; the attendant loss in vortex lift is proposed to be compensated by the use of a trailing-edge flap. By deploying the inner segments only, the vortex lift forward of the c.g. will be reduced, thus generating a nose-down moment for accelerated recovery from high alpha. When both segments are deployed on the right leading edge only, the excess of vortex lift prevailing on the left wing panel will produce a right roll. At the same time, a side force component towards the right will be generated by the flap thrust, favorable in a right turn. The inner left and outer right segments deployed at their maximum thrust setting will develop a nose-left yawing moment. Not included in this figure is the additional use of the cavity flap for aerodynamic braking at low angles of attack.

### CONCLUSIONS

A cavity vortex flap has been postulated in which the forward extension and deflection are independently controlled to allow vortex lift modulation while producing thrust.

The cavity vortex postulate was verified on a 65-deg oblique wing, demonstrating alleviation of the leading-edge vortex effect on the wing and generation of cavity suction through a range of flap extension, deflection and angle of attack.

Balance tests on a 60-deg delta wing indicated that the cavity flap was at least equal to the conventional leading-edge flap in L/D improvement and could be better with optimized combinations of extension and deflection. High-alpha pitch, roll and yaw control possibilities of the cavity flap concept, as well as its effectiveness as a drag brake, should be evaluated in future investigations.

### REFERENCES

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2. Campbell, James F. and Osborne, Russell F.: Leading-Edge Vortex Research: Some Nonplanar Concepts and Current Challenges. Vortex Flow Aerodynamics - Volume I, NASA CP-2416, paper no. 2, 1986.
3. Rao, Dhanvada M. and Johnson, T. D., Jr.: Investigation of Delta Wing Leading Edge Devices. J. Aircraft, Vol. 18, No. 3, pp. 161-167, March 1981.

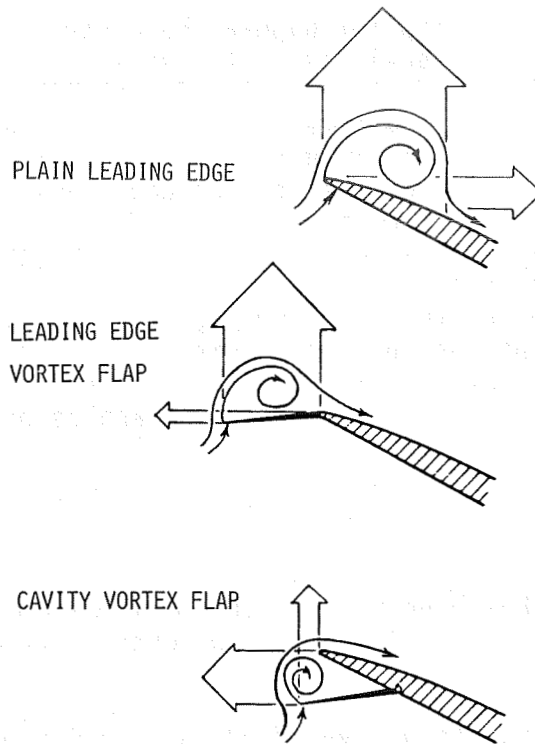


Figure 1 The cavity vortex flap concept.

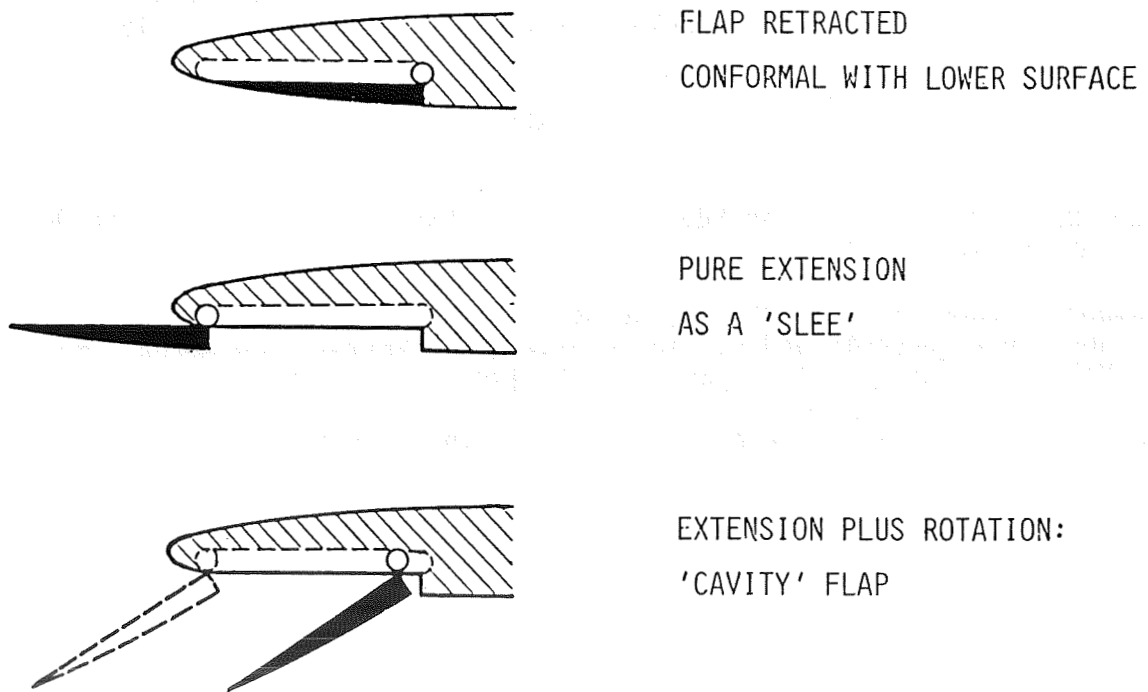


Figure 2 Cavity flap arrangement with independent extension and rotation.

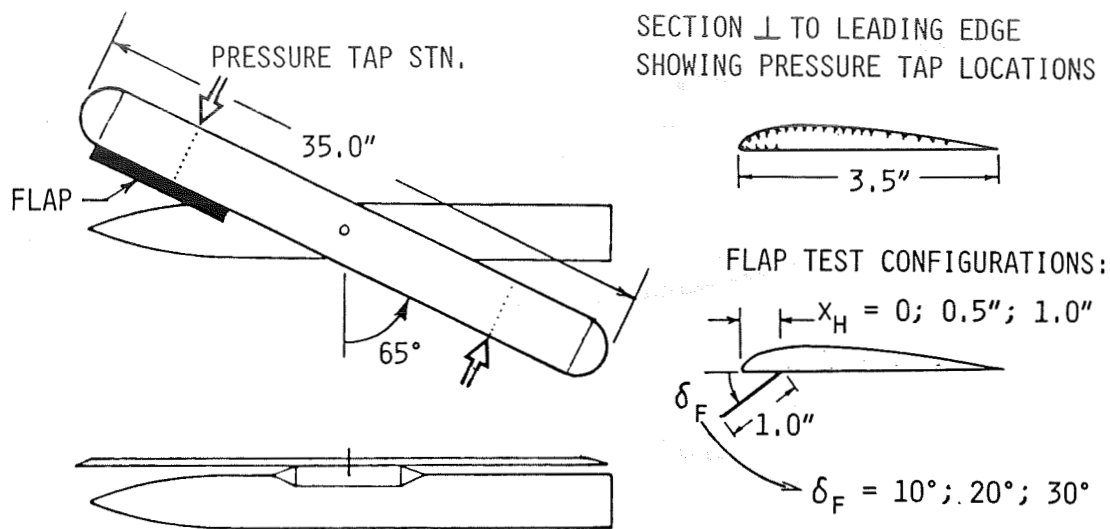


Figure 3 Oblique wing model tested in North Carolina State University Subsonic Wind Tunnel.

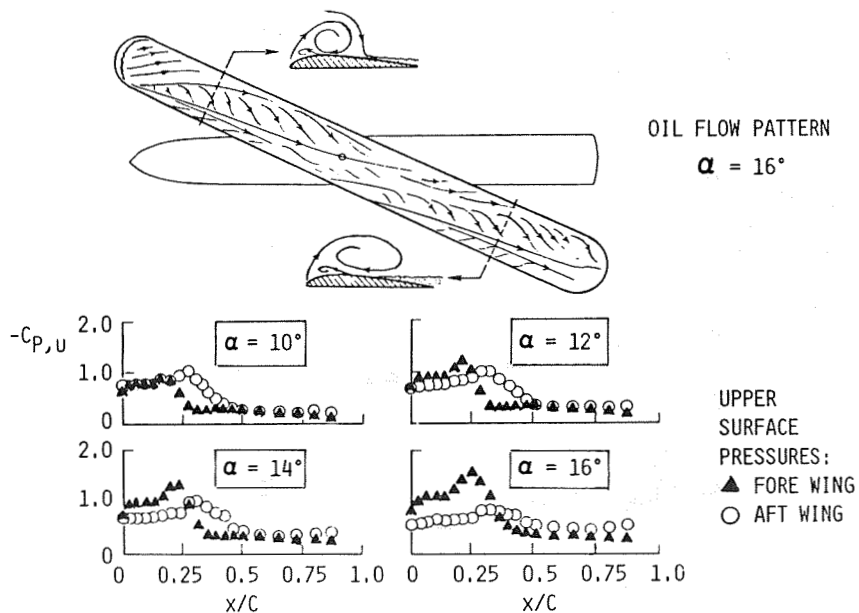


Figure 4 65-deg oblique wing flow and pressure characteristics with flap off.

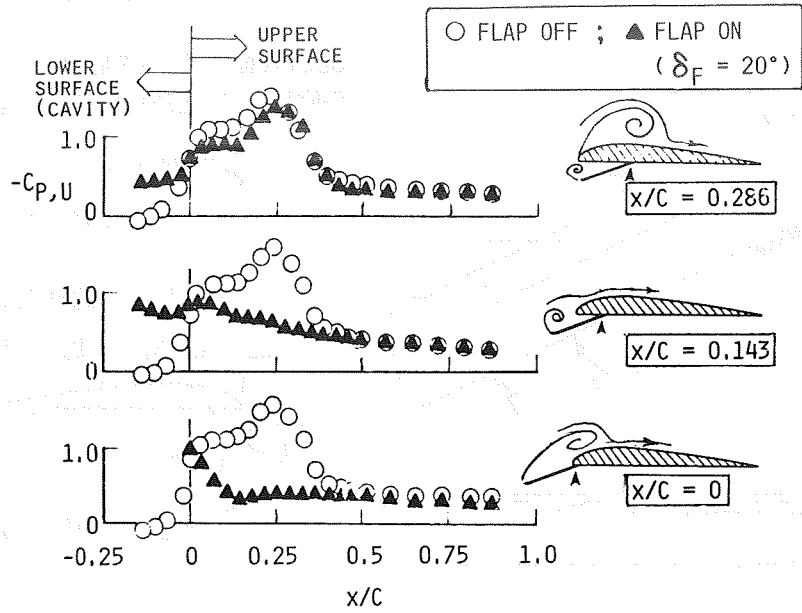


Figure 5 Pressure distributions showing effect of flap hinge position at 16-deg angle of attack.

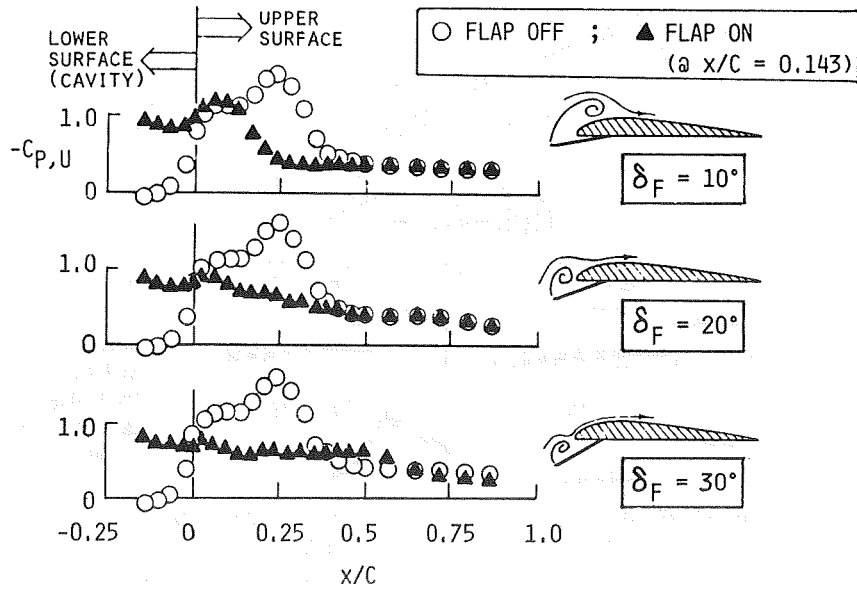


Figure 6 Pressure distributions showing effect of flap angle at 16-deg angle of attack.



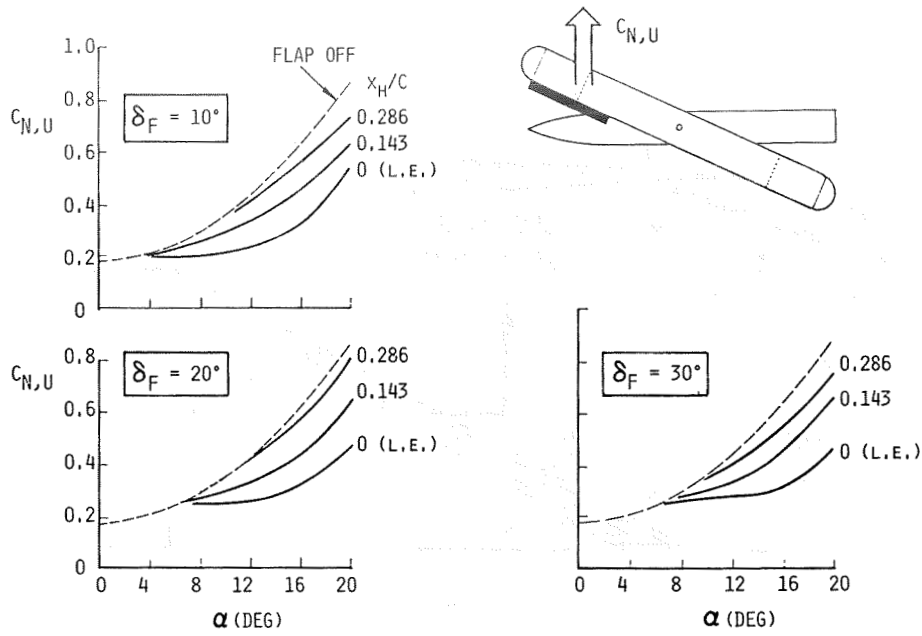


Figure 7 Pressure-integrated upper surface normal force characteristics.

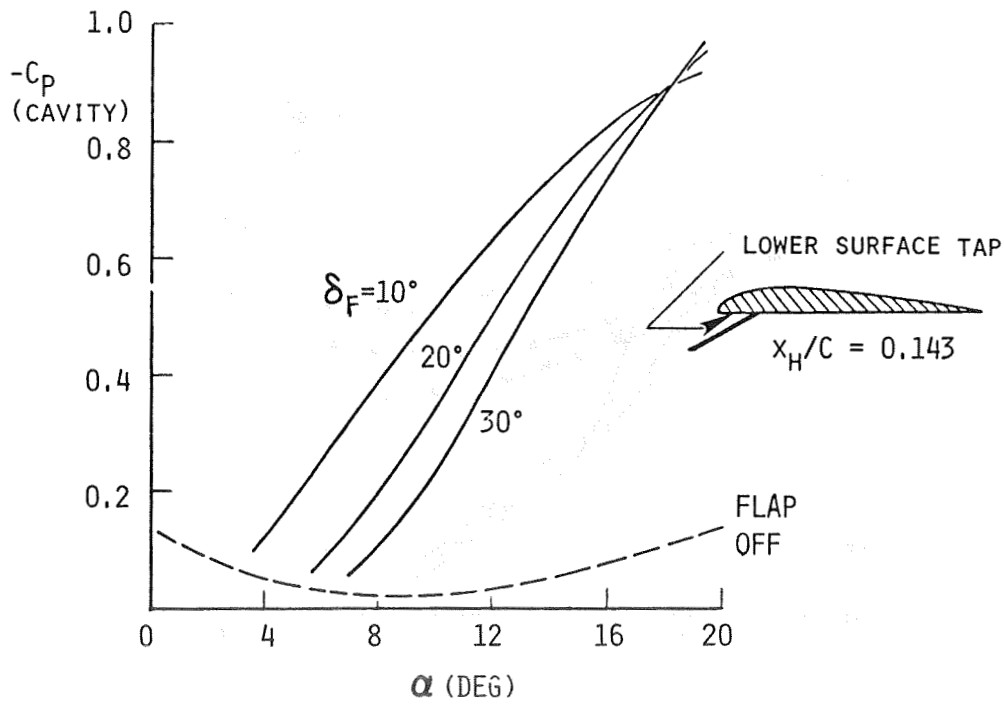


Figure 8 Cavity suction characteristics showing effect of flap angle.

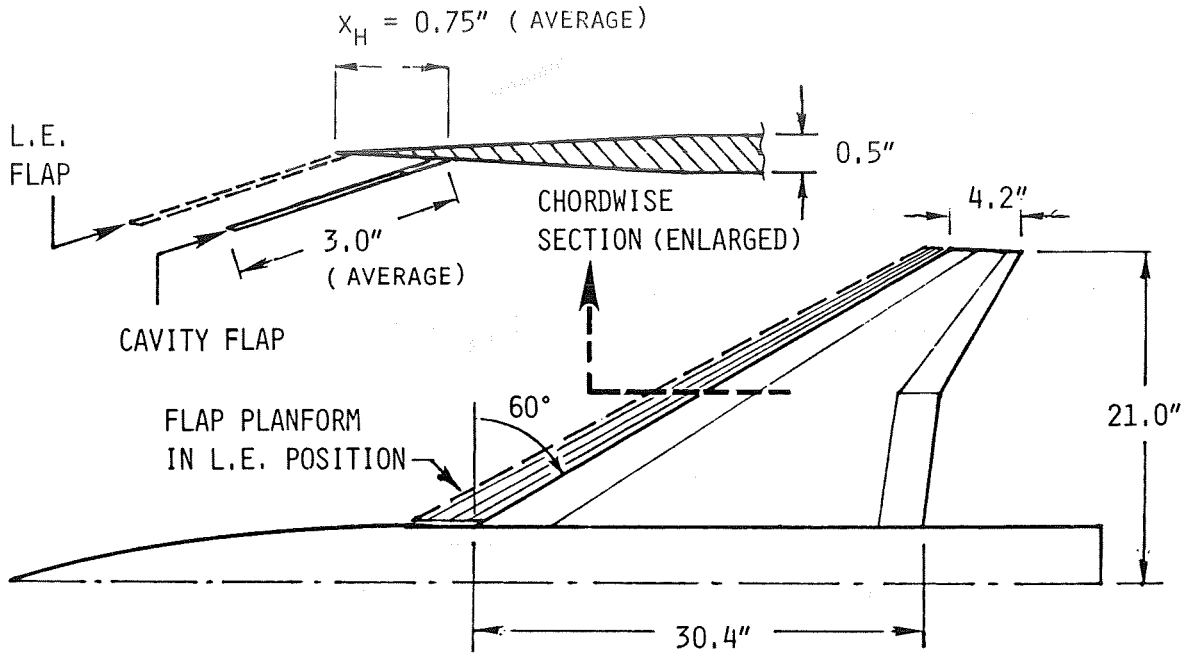


Figure 9 60-deg delta wing axial versus normal force characteristics.

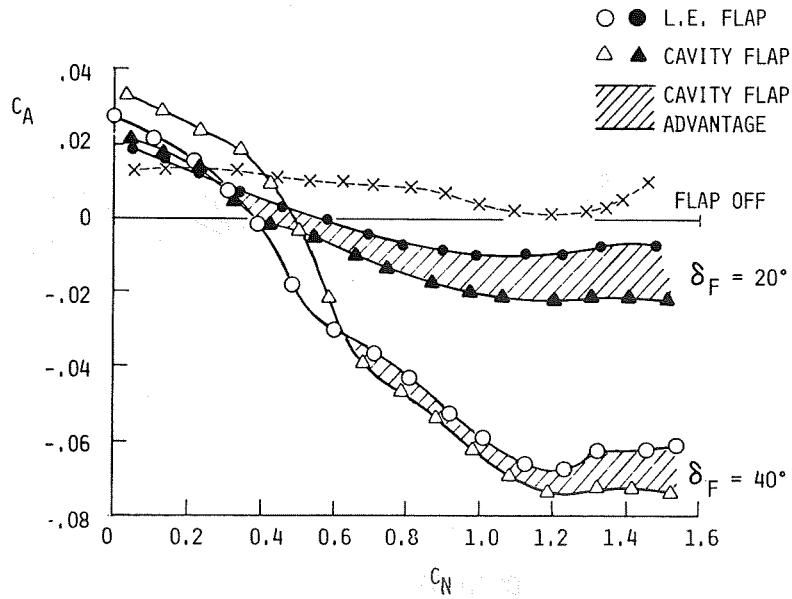


Figure 10 60-deg delta wing drag reduction with leading-edge and cavity flaps.

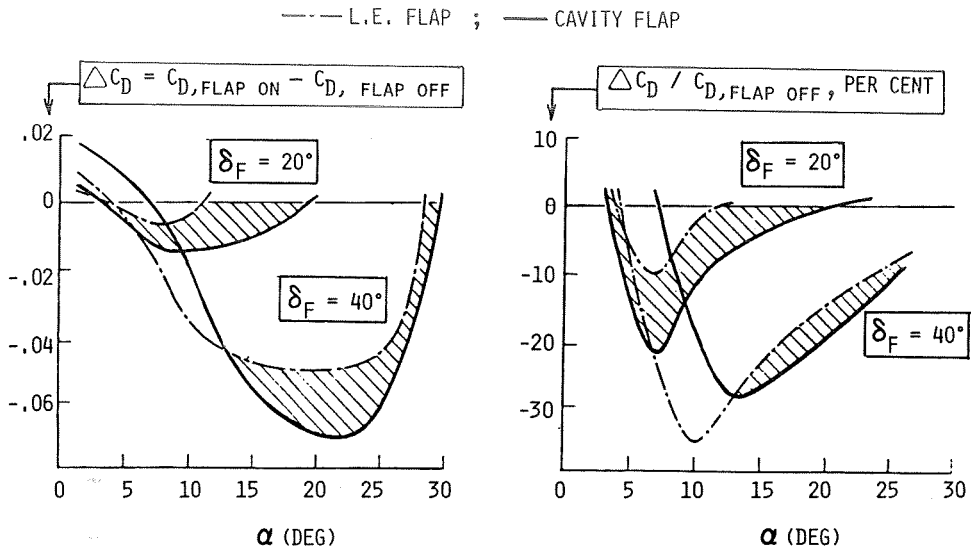


Figure 11 60-deg delta wing drag reduction with leading-edge and cavity flaps.

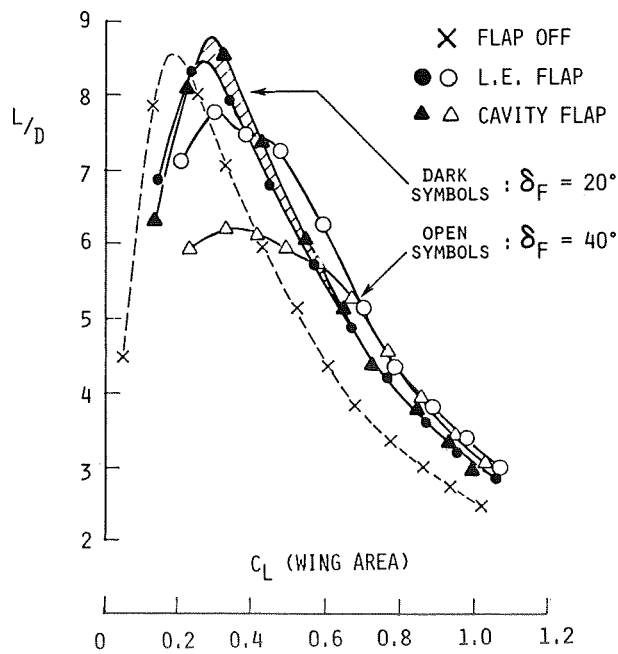


Figure 12 60-deg delta wing lift/drag ratio with leading-edge and cavity flaps.

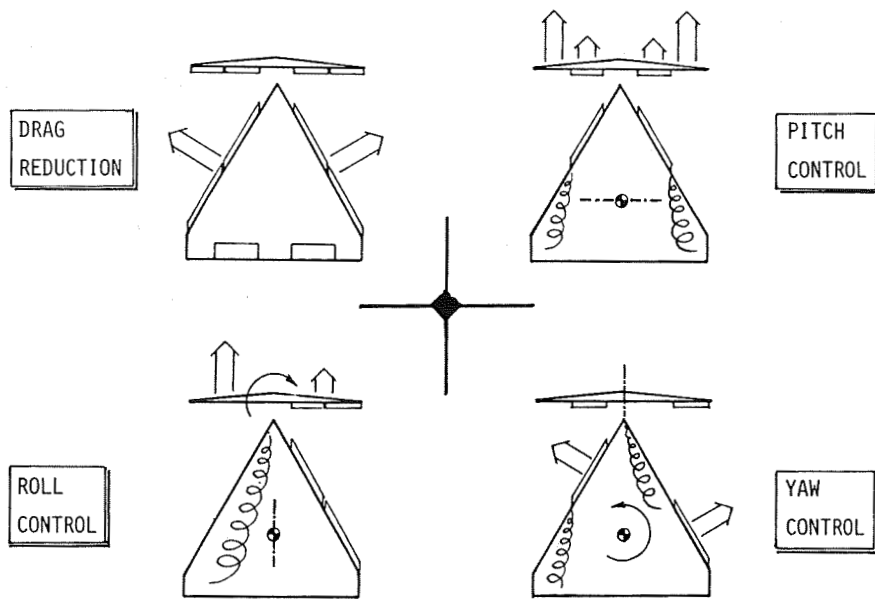


Figure 13 Cavity flap applications for control at high angles of attack utilizing thrust and lift modulation.