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Technical Notes

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Active Control of Tip-Flap Loads

David Greenblatt*
*Technion—Israel Institute of Technology,
32000 Haifa, Israel*

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Nomenclature

AR	=	aspect ratio
C_{dp}	=	sectional form-drag coefficient
C_l	=	sectional lift coefficient
C_M	=	model moment coefficient
C_p	=	time-mean pressure coefficient
C_R	=	model rolling moment coefficient
C_Y	=	model yawing moment coefficient
C_μ	=	slot oscillatory momentum coefficient, $h/c(U_j/U_\infty)^2$
c	=	model chord length
F^+	=	reduced excitation frequency, fL_f/U_∞
f	=	separation control excitation frequency
h	=	slot width
L_f	=	flap length, from slot to trailing edge
q_∞	=	freestream dynamic pressure
Re	=	Reynolds number based on chord length
s	=	wing semispan length
s_f	=	flap span length, $s/3$
U_j	=	peak jet slot blowing velocity
U_∞	=	freestream velocity
x, y, z	=	coordinates measured from model leading edge and root (left-hand system)
α	=	angle of attack
α_s	=	static stall angle
Δ	=	difference between baseline control coefficients
δ	=	tip-flap deflection angle
ξ	=	streamwise distance from slot
ψ	=	spanwise distance from flap

I. Introduction

SIMPLY hinged segments at the trailing edges of wings and stabilizers are used on virtually all modern aircraft. The same basic device takes on different names depending on its purpose, the most common being simple flaps and control surfaces: ailerons, elevators, rudders, flaperons (combined flap and aileron), and elevons (combined elevator and aileron). Their ubiquitous use stems from a combination of their simplicity and aerodynamic effectiveness. A factor that severely limits their performance is flow separation at the shoulder line, which reduces lift or control authority and increases drag. Not surprisingly, active control of the separated flow over a two-dimensional flap has received widespread attention, originally by means of steady blowing and suction [1], but more recently by means of zero mass flux or pulsed blowing [2,3]. Overwhelming attention has been focused on two-dimensional studies, in which the primary technological motivation is "simplified high lift" [4,5]. Far less common are studies relating to finite-span flaps typically corresponding to the aforementioned control surfaces. These flows are often dominated by strong wing tip or flap-edge vortices that are partially rolled up on the surface itself.

Recent investigations considered different aspects of control near flap edges and wing tips [5–8] and produced some surprising observations. For example, when compared with control on a two-dimensional flap, control on a finite-span flap at low angles of attack produced smaller lift changes (ΔC_l) locally, but the opposite was true at higher angles [8]. Additionally, at low angles of attack the effect of control on ΔC_l was comparable at the flap centerline and its edges; however, at higher angles ΔC_l generated at the flap edges exceeded that at the flap centerline [8]. When control was applied to a semispan wing with a large full-span flap deflection (40 deg), the wing tip pressure signature was materially different to those inboard and consistent with a strong vortex rolling up over flap [7]. In contrast to two-dimensional studies, the loading on the flap in the wing tip region increased dramatically, but changes to the main element loading upstream of the flap were small to negligible. This phenomenon was not observed in the absence of control; thus, it represents a form of controlled or on-demand "vortex lift" that appears to be particularly effective at large flap deflections. Indeed, dramatic changes to the centroids, strengths, and velocities of trailing vortices several chord lengths downstream were observed in the presence of both active and passive flap edge and wing tip control [6,9].

The global objective of this investigation was to explore the utility of the controlled tip vortex within the context of a simple finite-span flap mounted at the tip of a semispan wing model. The control input was limited to zero mass-flux blowing. The specific objectives were 1) to gain a basic understanding of the controlled flowfield principally by means of surface pressure measurements, and 2) to assess the effect of control on pitch, roll, and yaw on the semispan wing. The pressure data were complemented by surface tuft flow visualizations and two-dimensional particle image velocimetry (PIV).

II. Experimental Setup

Wind-tunnel experiments were performed on a rectangular planform semispan NACA 0015 model ($AR = 4$, semispan $s = 609.6$ mm, and chord $c = 304.8$ mm) at nominal Reynolds numbers ($Re = 500,000$ and 1×10^6) ($U_\infty = 24.5$ and 49 m/s). The model incorporated a tip flap of span $s_f = 1/3s$ hinged at $0.7c$ with $L_f = 0.3c$ (see Fig. 1) and was equipped with a corresponding flap-shoulder flow control slot ($h = 0.76$ mm) that was joined to an interior plenum. Forcing was supplied to the plenums via voice-coil-based actuators, and the resultant zero mass-flux control slot velocities were calibrated using a hot-wire anemometer. Uncertainty in the perturbation amplitude was estimated at $\Delta C_\mu / C_\mu \leq 20\%$. The model was equipped with 165 static pressure ports arranged in a perpendicular spanwise and chordwise grid, with additional rows of pressure ports on the flap. All ports were connected to a high-speed

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*Senior Lecturer, Faculty of Mechanical Engineering; davidg@technion.ac.il. Senior Member AIAA

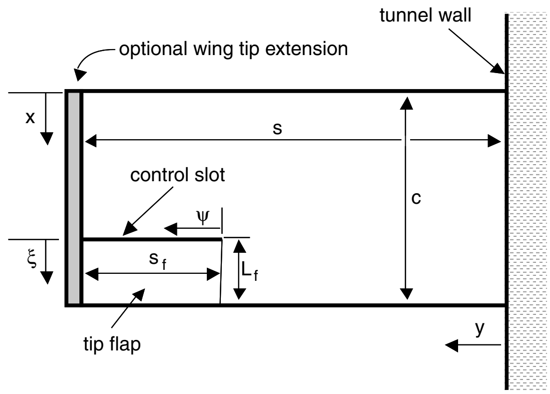


Fig. 1 Schematic of the semispan model showing the tip-flap region, coordinate system, and PIV measurement plane.

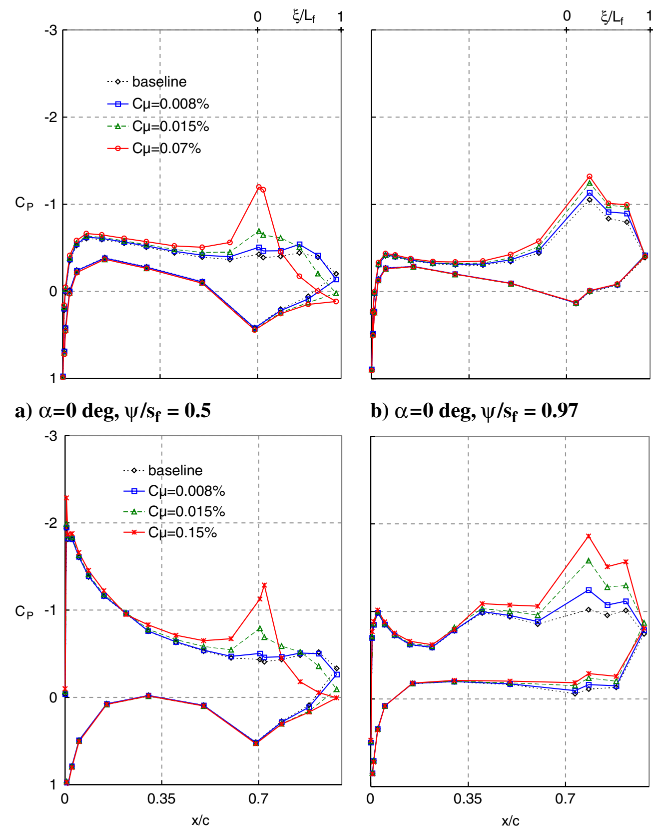
pressure scanner into which the acquired data were integrated to estimate aerodynamic forces and moments. The main source of error was due to precision, with $\Delta C_p \leq \pm 0.02$, based on 95% confidence intervals. Tests were conducted both with a wing tip extension of span $0.094 s_f$ (not instrumented with pressure ports; see Fig. 1) and without it to locate the flap edge flush with the wing tip. Test were performed for angles of attack in the range of $-4\ \text{deg} \leq \alpha \leq 18\ \text{deg}$ and tip-flap deflection angles of $\delta = 20$ and 40 deg. More details relating to the model can be found in [6–8]. Corresponding two-dimensional PIV measurements were performed above the flap surface at the flap center span, and these data are reported in [9].

III. Discussion of Results

A. Twenty-Degree Flap Deflection

Consider initially the case of $\delta = 20\ \text{deg}$, in which zero mass-flux perturbations are applied at a fixed frequency ($F^+ = 0.4$) and at various forcing amplitudes. Pressure coefficient distributions are shown for $\alpha = 0$ and 8 deg at the flap center span ($\psi/s_f = 0.5$) and near the tip ($\psi/s_f = 0.97$) in Figs. 2a–2d without the wing tip extension present. The effect of control at the flap midspan (Figs. 2a and 2c) has both similarities and differences when compared with the equivalent two-dimensional case [7]. Control has a marked effect on the local flap pressures, consistent with two-dimensional studies. But, in contrast, there is virtually no influence on the pressure distribution on the forward 50% of the wing chord, irrespective of α; hence, there is no meaningful increase in local circulation. This is so even when the midspan C_p distribution is consistent with that of a fully attached boundary layer ($C_p > 0$) at the trailing edge. Furthermore, relatively small C_μ are required to produce significant changes to the pressure distribution over the flap. At $\alpha = 0\ \text{deg}$ and $C_\mu = 0.015\%$ ($U_j/U_\infty \sim 0.2$), the pressure distribution is consistent with that of a bubble enclosed on the upper surface, as characterized by the relatively low pressure downstream of the slot and subsequent pressure recovery with $C_p > 0$ at the trailing edge; at $\alpha = 8\ \text{deg}$, $C_\mu = 0.15\%$ produced a similar result. These results should be contrasted with separation control inboard on the same model and at the same F^+, for which an order of magnitude larger momentum coefficient was not capable of fully attaching the flow [6,7]. The lower pressures on the flap act to further increase the nose-down pitching moment; this is discussed in more detail in Sec. III.C.

As the wing tip is approached (Fig. 2b), control has a diminishing effect on the flap surface pressures. At low α, the pressure changes at the tip are small even when the center span pressures indicate a full pressure recovery (Fig. 2a). Consistent with previous investigations on inboard finite flaps [8], control is *more effective at larger* α. For example, compare the effect at $C_\mu = 0.015\%$ in Figs. 2b and 2d for $\alpha = 0$ and 8 deg, respectively. The reason appears to be that the uncontrolled vortex is partially attached to the surface at low α, as can be seen from the baseline flap pressure signature in Fig. 2b; thus, control has a negligible effect. However, at higher α, the vortex is fully detached from the flap, as can be seen from the pressure



a) α=0 deg, ψ/s_f = 0.5 **b) α=0 deg, ψ/s_f = 0.97**

c) α=8 deg, ψ/s_f = 0.5 **d) α=8 deg, ψ/s_f = 0.97**

Fig. 2 Pressure coefficient distributions in the wing tip region showing the effect of control at $F^+ = 0.4$ with $\delta = 20\ \text{deg}$.

signature in Fig. 2d; hence, control attaches or partially attaches the vortex, producing a relatively large effect.

The low C_μ required to effect control and the absence of any meaningful effect on the local circulation requires some explanation. An important difference between the tip-flap case described herein and two-dimensional airfoil studies is that at the tip fluid is entrained from above the flap and over the wing tip, whereas clearly the latter is absent on airfoils. On airfoils, the reduced pressure on the flap that results from control has a similar effect to that of a larger flap deflection, producing increased circulation as detected by upstream surface pressure measurements [2,3]. Similar observations were also made inboard on the semispan wing where the flow was effectively two dimensional [7]. However, in the present case, the natural tendency of the tip vortex to transport momentum to the upper surface as a result of the preexisting pressure difference across the surfaces is enhanced by the low pressure produced by control. Thus, a lower control perturbation is required effect a similar flap pressure recovery. The additional circulation, always observed on airfoils, is expended in strengthening the tip vortex, as noted by measurements of the trailing tip vortex several chord lengths downstream [9]. Control at higher excitation frequencies ($F^+ = 0.8$ and 1.1) produced similar results, although control effectiveness diminished with increasing frequency (not shown). Mean velocity profiles measured with a two-dimensional PIV at the flap center span (not shown; see [9]) indicated that control deflected the shear layer successively closer to the flap surface with increasing C_μ, consistent with the pressure data discussed earlier.

Representative examples of the lift and form-drag span-loading data are shown in Figs. 3a and 3b, respectively, at the two angles of attack that also show the effect of the wing tip extension (see Fig. 1). The presence of the wing tip extension has two related effects on the baseline flow: 1) the vortex now rolls up partially on the wing tip extension and, hence, the pressure signature is qualitatively different; and 2) the overall lift is slightly higher and the corresponding form drag lower because the negative effects of the tip vortex are displaced

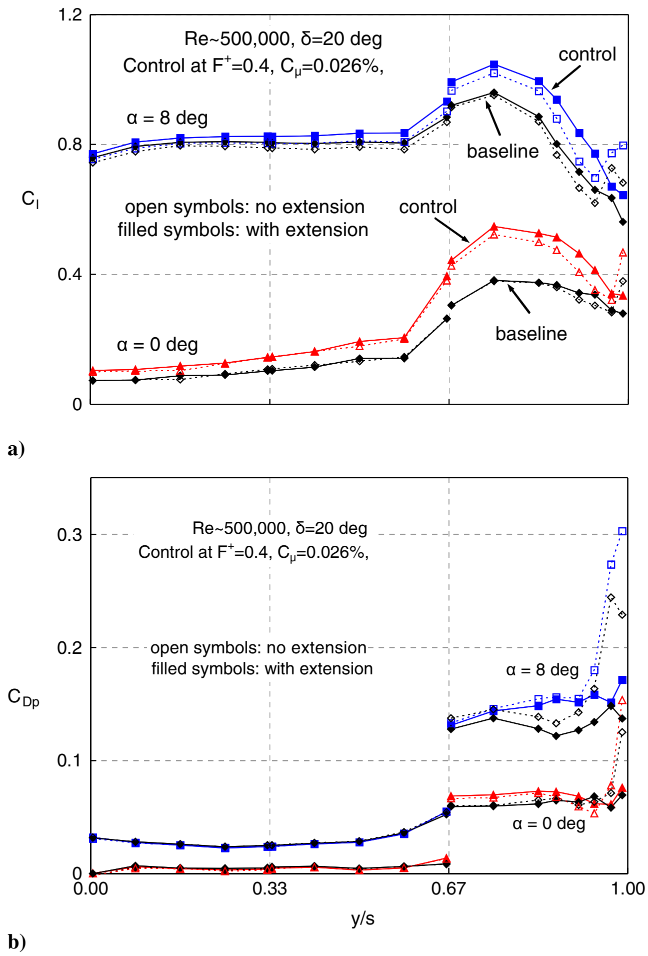


Fig. 3 Spanwise variation showing the effect of control at $\delta = 20$ deg: a) lift coefficient, and b) form-drag coefficient.

further from the flap. With control, the relatively small changes in the wing loads and the larger changes at higher α are consistent with the observations made in Figs. 2a–2d. Nevertheless, control is effective over the entire flap and the potential for affecting the rolling and yawing moments can clearly be seen in Figs. 3a and 3b, respectively. These effects are also observed when control is applied in the presence of the wing tip extension; in addition, the overall load changes between baseline and controlled states are generally slightly greater due to the presence of the extension. Irrespective of the wing tip configuration and angle of attack, the increase in C_L/C_{Dp} is small, typically around 3.

B. Forty-Degree Flap Deflection

Control in combination with the larger flap deflection ($\delta = 40$ deg) produced a significantly greater effect over the entire flap (i.e., Figs. 4a–4d), although a larger C_μ was required to achieve this (note the different C_p scaling as compared with Figs. 2a–2d). In stark contrast to the smaller flap deflection, the pressure over the highly defected flap at the tip is dramatically reduced, with $\Delta C_p \approx 3.4$ just downstream of the slot (Fig. 4d). It is conceivable that the pressure in this region is even lower, but this could not be verified because the surface immediately upstream and downstream of the flap shoulder ($0.6 < x/c < 0.78$) could not be instrumented with pressure ports due to the presence of a flap hinge. Nevertheless, the pressure signature is consistent with a larger and powerful tip vortex being partially rolled up on the flap as a result of the control input and, in this sense, it represents an "on-demand" tip-flap vortex. Despite these relatively large changes to the pressure on the flap, and consistent with the $\delta = 20$ deg case, the forward part of the wing chord corresponding to the defected flap remains virtually

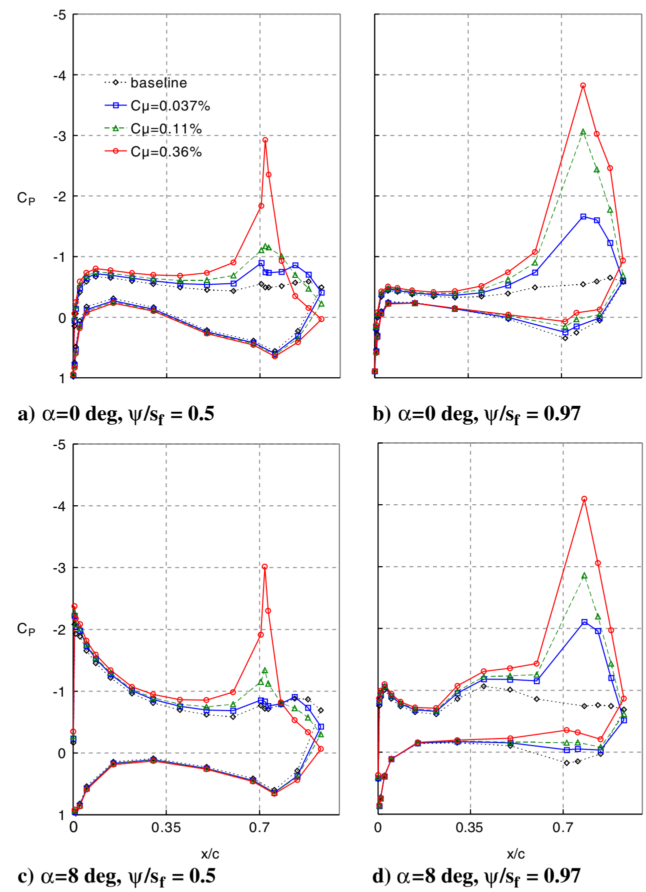


Fig. 4 Pressure coefficient distributions in the wing tip region showing the effect of control at $F^+ = 0.4$ with a large tip-flap deflection.

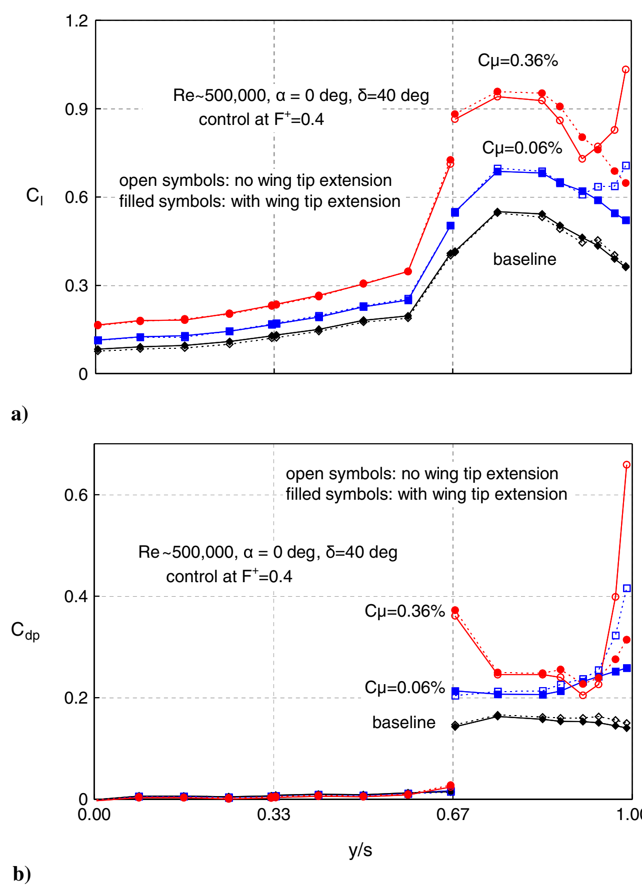


Fig. 5 Spanwise variation showing the effect of control with a large tip-flap deflection: a) lift coefficient, and b) form-drag coefficient.

unaffected. Unlike two-dimensional cases, this indicates that increases in local lift will be accompanied by large increases in drag.

Figures 5a and 5b show the effect on the lift and form-drag distributions at $\alpha = 0$ deg for relatively low- and high-amplitude perturbations. As expected, large changes are seen, particularly in the tip-flap region, and the effect of the extension is qualitatively similar to that for the $\delta = 20$ deg flap deflection. At the higher forcing amplitude, a larger increase in C_l and particularly C_{dp} can be seen at the inboard edge of the flap ($y/s = 0.67$, $\psi/s_f = 0$). This indicates that in addition to the outboard tip vortex a weaker but increasingly powerful counter-rotating vortex is beginning to form at the inboard edge of the flap. For both forcing amplitudes, the changes to C_L/C_{dp} are negligibly small.

C. Effect on Moment Coefficients

The changes to pitching, rolling, and yawing moment coefficients (ΔC_M, ΔC_R, and ΔC_Y) with and without the wing tip extension (Figs. 6a–6f, respectively) were assessed by integrating the surface pressures; the results for fixed angles of attack of 0 and 8 deg are shown for a fixed reduced frequency ($F^+ = 0.4$) and an increasing C_μ. Most qualitative trends associated with all three coefficients were similar and also not dependent on the presence or absence of the wing tip extension; thus, apart from noted exceptions, the following discussion applies to all. Consistent with the pressure data presented earlier, a relatively small control effect is observed on the moment coefficients at small flap deflection angles ($\delta = 20$ deg), and this effect saturates at $C_\mu \approx 0.01$ or 0.02% depending on the angle of

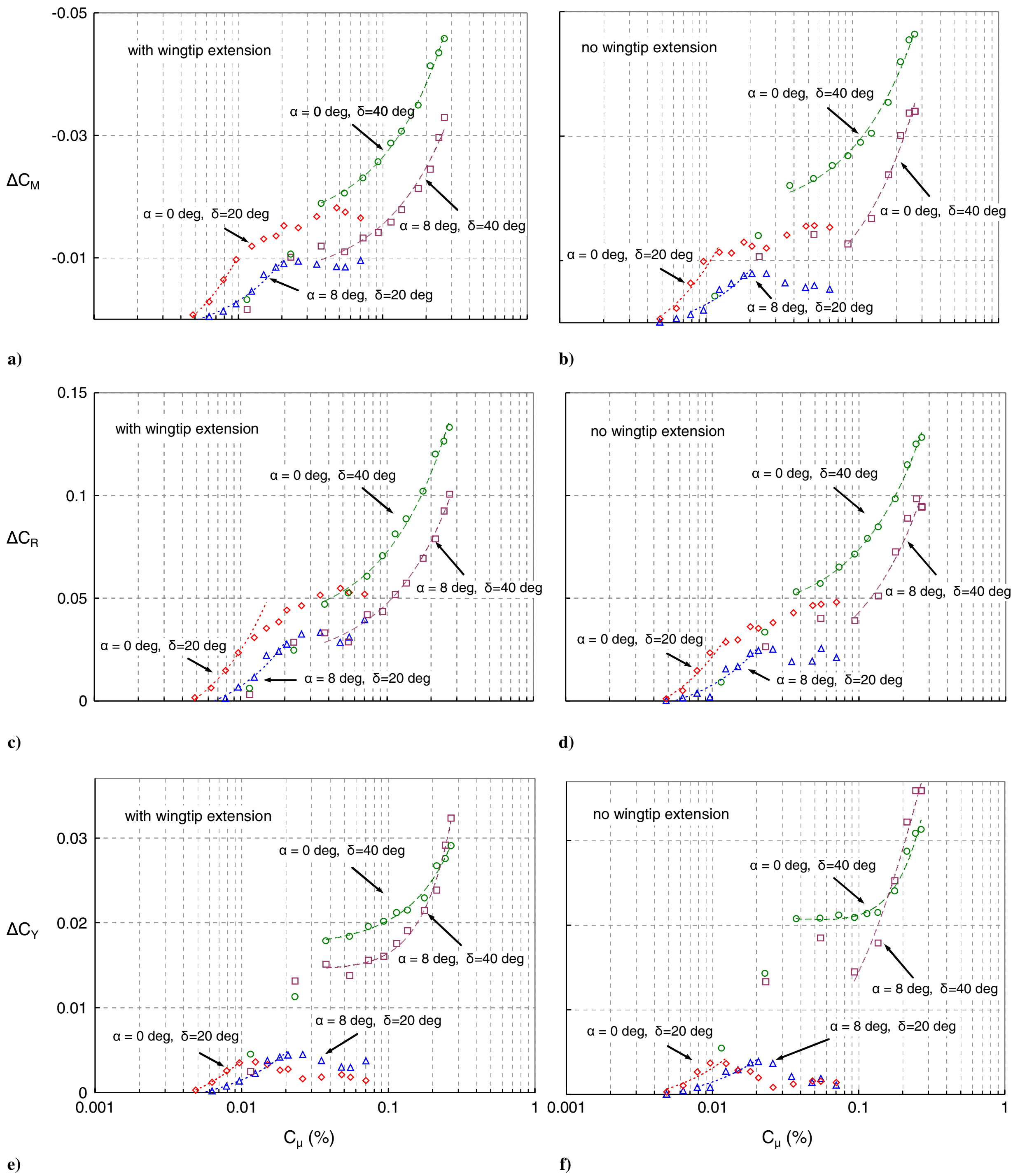
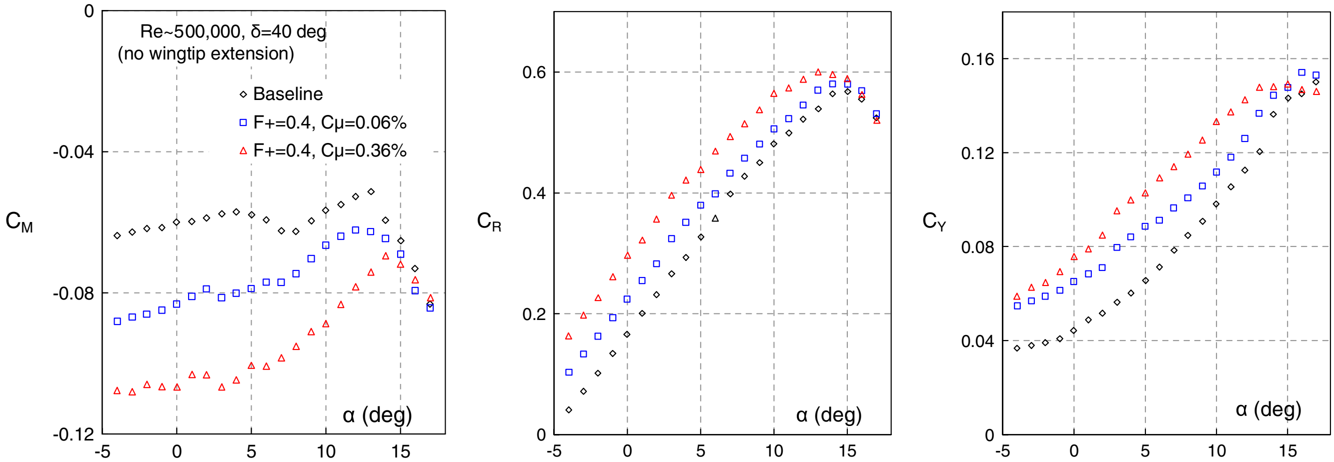


Fig. 6 Effect of control amplitude on moment coefficients: a) and b) pitching moment, c) and d) rolling moment, and e) and f) yawing moment.



a) b) c)

Fig. 7 Wing moment coefficients as a function of angle of attack for low- and high-amplitude control: a) pitching moment, b) rolling moment, and c) yawing moment.

attack (e.g., Fig. 6a). The small changes reflect the small pressure reduction and redistribution occurring on the flap without any meaningful effect upstream. Saturation occurs because the flow on the flap is essentially attached, although enclosing a bubble (see Figs. 2a and 2c), and further increases in C_μ serve only to reduce the bubble length without markedly affecting the local load on the flap. On the other hand, with larger flap deflection ($\delta = 40$ deg), a larger separated shear layer is formed, and a larger C_μ brings the shear layer and accompanying tip vortex successively closer to the surface. At the lower angle of attack, the pressure distribution indicates a full pressure recovery for relatively large amplitudes, $C_\mu = 0.36\%$. Clearly, the larger control authority comes with a cost, and this can be quantified by noting that the ratio of dC_R/dC_μ at $\delta = 20$ deg relative to $\delta = 40$ deg is greater than 10. Although greater authority could conceivably be achieved at the maximum flap deflection considered here by increasing C_μ, it should be expected that control authority is close to saturation as the flap midspan pressure recoveries are consistent with, or approaching, that of an attached boundary layer (Figs. 4a and 4c, respectively).

For both flap deflections, the dependence of ΔC_M and ΔC_R on C_μ is linear, providing C_μ exceeds some threshold and is less than that when control saturates. For C_M and C_R, the control authority achieved at $\delta = 20$ deg, when control saturates, is comparable to that achieved with the minimum threshold C_μ at $\delta = 40$ deg. This is not true for C_Y, for which the authority jumps by approximately 0.01 between the two different flap deflections. This can be explained by considering the different components of the load on the controlled flap. In the former cases (C_M and C_R), we can assume to a first order of approximation that control only affects the flap load with no change to the wing load upstream of the control slot; the basis for this assumption is shown in Figs. 2 and 4. Furthermore, we observe that the load on the controlled flap increases with flap deflection. Thus, the change in flap angle has two opposing effects on C_M and C_R: 1) the load *component* contributing to the moments is *reduced* by approximately 18% [(cos 40 deg − cos 20 deg)/ cos 20 deg], whereas 2) the absolute flap load increases. The net effect is an enhancement of both C_M and C_R due to the significant flap-load increase. However, in the case of C_Y, the change in flap angle *increases* the contributing component by approximately 88% [(sin 40 deg − sin 20 deg)/ sin 20 deg], thereby producing the jump and relatively large changes in C_Y (see Figs. 6e and 6f). It should therefore be expected that, providing the flow can be attached to the flap, larger flap deflections would produce diminishing authority over C_M and C_R and increasing authority over C_Y. For example, using this same reasoning, an increase of the flap deflection angle to 60 deg will decrease C_M and C_R components by 47% and increase the C_Y component by 153%. Simultaneously, a substantially larger load can be expected on the flap. It can therefore be asserted that large controlled flap deflections of $\delta > 40$ deg will produce moments well in excess of conventional control surfaces; yawing moment coefficients will be dramatically larger.

The linear dependence of ΔC_M and ΔC_R on C_μ should be contrasted with flapped airfoils and inboard flaps, for which two scenarios are generally observed. At small δ and/or α, the flow attaches to the flap when some threshold is reached and then control saturates with larger C_μ producing negligible additional performance increments [7]. For large δ and/or α, the changes to lift, for example, are typically logarithmic and $C_\mu > 1\%$ is generally required to produce pressure recoveries consistent with those of fully attached flap flows. It should be noted that the yawing moment changes (Figs. 6e and 6f) exhibit a nonlinear dependence on C_μ, and this is believed to be related to the formation of the inboard vortex discussed with respect to Fig. 5b. Finally, it is observed that yaw control effectiveness (ΔC_Y) at $\alpha = 8$ deg exceeds that at 0 deg with high-amplitude control perturbations, particularly in the absence of the wing tip extension (Fig. 6f).

Similar results were obtained at different reduced frequencies in the range of $0.3 < F^+ < 2$ with and without the wing tip extension (not shown). The moment coefficient data as a function of α, with the wing tip extension removed, is shown for $\delta = 40$ deg (Figs. 7a–7c). The two control data sets correspond to forcing amplitudes just above the threshold necessary for linear control ($C_\mu = 0.06\%$) and close to control saturation ($C_\mu = 0.36\%$). Both produce a significant effect on moments throughout the α range. In the case of C_M and C_R, the effect approximately doubles with a factor of 6 increase in C_μ. In the case of C_Y, small C_μ produces a relatively large effect at low α, and this effect diminished as α approached the stall angle.

IV. Conclusions

The control of flow separation over a tip flap is fundamentally different from its two-dimensional counterpart. Two features that stand out are that virtually no effect is observed upstream of the flap, irrespective of the degree of boundary-layer attachment, and that small perturbation amplitudes ($U_j/U_\infty \sim 0.2$) can produce a full pressure recovery. Both of these observations were attributed to a tendency of the tip vortex to transfer momentum over the wing tip.

Moreover, the response to control was strongly dependent on the flap deflection angle. At relatively mild deflection angles (20 deg), changes to the flap loads and, hence, the wing moments were relatively small. At large flap deflection angles (40 deg), control produced dramatically larger loads on the flap consistent with a strong vortex rolling up over the flap edge, although substantially larger perturbation amplitudes were required. This effect, combined with negligible changes to the loads upstream of the flap, has the potential to produce significant increases in yawing moments or controlled aerodynamic braking.

In contrast to two-dimensional cases, the response of pitching and rolling moments was linearly dependent on the control momentum input. Yawing moments associated with control at large flap deflections, however, were not linearly dependent on momentum input due to the existence of an additional counter-rotating inboard vortex.

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J. Cooper
Associate Editor