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Engineering Notes

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Effect of Gurney Flap on Unsteady Wake Vortex

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Nomenclature

C_l	=	sectional lift coefficient
C_{la}	=	lift-curve slope, $=dC_l/d\alpha$
c	=	airfoil chord
d_{miss}	=	miss distance
f	=	oscillation frequency
h	=	flap height
L	=	lift force per unit span
l	=	length of 2-D interaction
Re	=	chord Reynolds number, $=cU_o/\nu$
r_c	=	core radius
U_o	=	freestream velocity
u_c	=	mean axial core velocity
$v_{\theta\mathrm{peak}}$	=	peak tangential velocity
α	=	angle of attack
α_{ds}	=	dynamic-stall angle
Γ	=	vortex strength or circulation
Γ_c	=	core circulation
Γ_o	=	total circulation
κ	=	reduced frequency, $=\pi fc/U_o$
ν	=	kinematic viscosity
ζ_{peak}	=	peak vorticity
ρ	=	fluid density

Subscripts

c	=	core
d	=	pitch-down
u	=	pitch-up

I. Introduction

THE Gurney flap is a simple device located at the trailing edge of the wing on the pressure side and perpendicular to the chord and was first introduced by Liebeck [1]. A number of studies [2–5] further substantiated that the observed increase in the airfoil circulation, and thus the lift force, was associated with the downward turning of the flow near the trailing edge, and that the optimum flap height h of about 2%c provided the maximum improvement in the lift force with a minor increase in the drag force. Jeffrey et al. [2] also reported that the wake downstream of a Gurney flap consisted of alternately shed vortices, which increased the suction at the trailing edge on the wing suction side, while the flow on the pressure side was decelerated and thus increased the pressure. These two changes resulted in a pressure difference acting across the wing trailing edge and subsequently generated an increase in loadings and circulation over the airfoil. However, in addition to the high lift coefficient C_l produced, the Gurney flap could also introduce an increase in the nose-down pitching moment. Gerontakos and Lee [4] extended the Gurney flap concept to the passive control of dynamic loadings of an oscillating NACA 0012 airfoil. They found that Gurney flaps were also generally applicable in terms of C_l and $C_{l,\max}$ increment except for the undesired large increase in the peak nose-down pitching moment and the promotion of dynamic stall. These undesired effects could, however, be alleviated by the use of inverted Gurney flaps at the price of a reduced $C_{l,\max}$. Their detailed surface pressure measurements also revealed that both the static and dynamic stalling mechanisms were basically unchanged compared to a wing with no passive Gurney flap control.

In the present experiment, the full-span Gurney flap concept was further applied to the passive control of the tip vortex generated behind an oscillating wing, which is of great importance in the potential alleviation of the severity of blade-vortex interaction (BVI) noise and vibration frequently observed during low-speed rotorcraft forward or descending flight. Particular attention was given to the dynamic variation of the critical vortex flow parameters, including the vortex trajectory, with Gurney flaps, both in regular and inverted arrangements, of two different heights.

II. Experimental Methods and Apparatus

The experiment was conducted in a $0.9 \times 1.2 \times 2.7$ m^3 low-speed, suction-type wind tunnel at McGill University with a freestream turbulence intensity of 0.03% at $U_o = 15$ m/s. A NACA 0015 wing, fabricated from solid aluminum, with $c =$ 20.3 cm and a semispan of 50.8 cm was used as the test model. The origin of the coordinate was located at the leading edge of the wing model with x, y, and z in the streamwise, transverse, and spanwise directions, respectively. Gurney flaps, both in regular and inverted arrangements, of $h = 2.5\%c$ (scaled with the boundary-layer thickness at the wing trailing edge) and 5%c were tested. The chord Reynolds number was fixed at $Re = 1.74 \times 10^5$. The wing was oscillated sinusoidally through the static-stall angle (=16.5 deg) by a specially designed four-bar mechanism with $\alpha(t) = 14 + 8$ deg $\sin \omega t$, which corresponds to a light-stall oscillation [6], at $\kappa = 0.09$. The airfoil pitch axis was located at 1/4-chord location. Details of the experimental setup are given by Gerontakos and Lee [4].

The three-component instantaneous velocities at $x/c = 2.0$ were subsequently ensemble averaged over 40–80 oscillating cycles to obtain phased-locked averages of the critical vortex flow properties at various phase angles during the cycle. A miniature triple hot-wire probe (Auspex Model AVEP-3-102 with a measurement volume of 0.5 mm^3), calibrated in situ before the installation of the model, was used to measure the mean and fluctuating velocity components. Probe traversing was achieved through a custom-built computer-controlled traversing system. Data planes taken in the near field of the wing models had 33×33 measuring grid points with an increment of

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$\Delta y = \Delta z = 4.8$ mm. The maximum experimental uncertainties were estimated as follows [7]: mean velocity 3.5%, vorticity component 8%, vortex radius 4%, and velocity fluctuation 3%.

III. Results and Discussion

The dynamic C_l–α loops, determined from the integration of 48 surface pressure readings along both the upper and lower surfaces of the oscillating wing with no end effects, are briefly discussed first to better understand the influence of the Gurney flap on the critical vortex flow parameters. Figure 1a shows that for an oscillating wing equipped with a Gurney flap, the C_l-α loop was shifted vertically upward, as a result of the Gurney flap-induced effective positive camber effects, and was accompanied by an increased $C_{l,\max}$ and lift slope $C_{l\alpha}$ during pitch-up compared to a baseline wing. Both $C_{l,\max}$ and $C_{l\alpha}$ were found to increase with increasing flap height. The surface pressure distributions (not shown here) also indicate that the phase angles at the formation and spillage of an energetic dynamic-stall vortex (DSV) and the dynamic-stall angle α_{ds} were only slightly promoted compared to the baseline wing. The presence of the flow reversal was, however, delayed to a much higher $\alpha_u \approx 19$ deg in comparison with $\alpha_u \approx 15$ deg of the baseline wing. The corresponding variation of the total circulation Γ_o (indicative of the bound circulation and thus C_l) of the tip vortex over an oscillation cycle is displayed in Fig. 1b. For both baseline and Gurney flap-equipped wings, the Γ_o values were found to generally follow the change observed in C_l throughout the oscillation cycle; the larger the flap height, the higher the total vortex circulation. On the other hand, the addition of inverted Gurney flaps (with $h = -2.5\%c$ and $-5\%c$) led to a substantial reduction in C_l and $C_{l\alpha}$, as a result of induced negative camber effects, especially in the trailing-edge region, but an unchanged $C_{l,\max}$ and α_{ds}, which suggests that the DSV formation and spillage were not affected by the inverted Gurney flaps. Furthermore, in contrast to Gurney flaps, the inverted Gurney flap did not render any C_l change during during-stall and post-stall flow regimes, due to the fact that the inverted Gurney flap was embedded in a DSV-induced flow separation. No significant variation in Γ_o compared to the baseline wing during pitch-down was noticed (Fig. 1b). Meanwhile, as expected, the total circulation was reduced during the entire pitch-up motion. Special attention should be given to the significantly lowered Γ_o values during the first part of the pitch-up, compared to those during pitch-down at the same instantaneous angle of attack, for the $h = -5\%c$ control case.

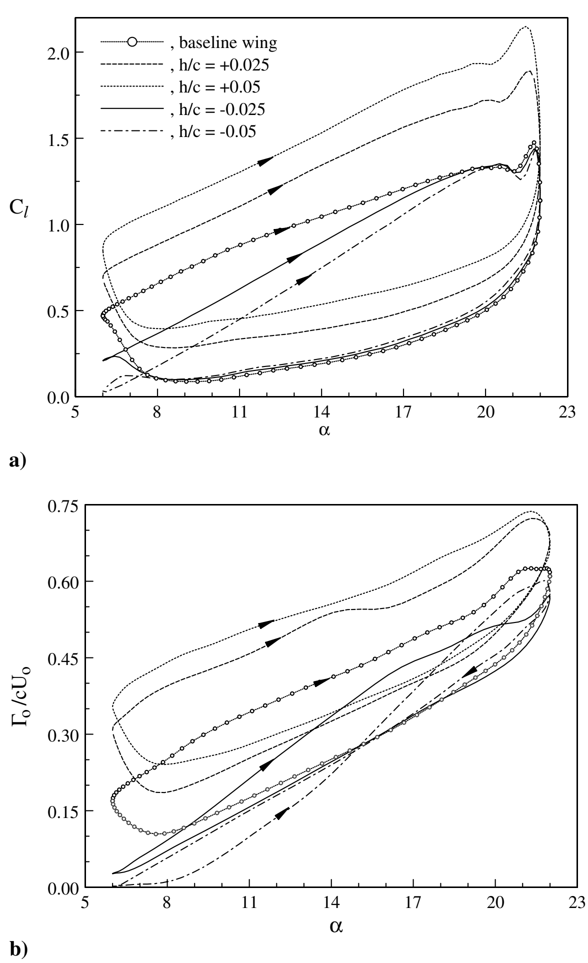

Fig. 1 Dynamic C_l and Γ_o loops.

The influence of Gurney flaps on the critical vortex flow parameters, including the vortex trajectory, is summarized in Figs. 2 and 3. For the baseline wing, the peak tangential velocity $v_{\theta\mathrm{peak}}$ increased approximately linearly during pitch-up up to the onset of flow reversal at $\alpha_u = 18.5$ deg (Fig. 2a), which is similar to the dynamic C_l–α behavior shown in Fig. 1a. With a further increase in α, the value of $v_{\theta\mathrm{peak}}$ remained unchanged briefly (during the upstream propagation of the flow reversal) and then underwent a sharp increase and decrease during DSV development and spillage (i. e., in the vicinity of $\alpha_{\max}$), respectively. During post-stall, $v_{\theta\mathrm{peak}}$ decreased continuously with decreasing α until $\alpha_d = 8$ deg and underwent a rapid recovery to the $\alpha_{\min}$ value as the wing completed the rest of the pitch-down motion. A $v_{\theta\mathrm{peak}}$ hysteresis, similar to the hysteretic property found in Γ_c (Fig. 2e) and Γ_o (Fig. 1b), was also noticed. With the addition of a Gurney flap of $h = +2.5\%c$, $v_{\theta\mathrm{peak}}$ was found to generally coincide with that of the baseline wing up to $\alpha_u = 18.5$ deg, but had a lowered value for the rest of the oscillation cycle except for the final stage of the pitch-down flow process. It is of interest to note that even though the $v_{\theta\mathrm{peak}}$ did not change significantly with a Gurney flap of $h = +2.5\%c$, there was a consistent increase in the core radius r_c (identified by the location of $v_{\theta\mathrm{peak}}$, Fig. 2c) and core circulation Γ_c (Fig. 2e). Both r_c and Γ_c were also found to increase with the flap height. The larger flap height ($h/c = +5\%$), however, led to a more drastic reduction in $v_{\theta\mathrm{peak}}$, except during the final stage of the pitch-down motion, compared to a smaller flap height. This unexpected drop in rotational speed of the vortex could be due to the increased deceleration of the flow on the pressure side of the wing, especially in the trailing-edge region, which thus produced a weakened rolling up of the separated shear layers and the subsequent downstream vortex formation. Note that it is this increased pressure on the pressure side, together with the increased suction at the trailing edge on the wing suction side, which gave rise to an increased C_l, Γ_o, and Γ_c, but at the price of increased drag force and nose-down pitching moment. Nevertheless, it can be concluded that for an oscillating wing equipped with Gurney flaps the larger the height flap the higher the r_c and Γ_c, while the lower the $v_{\theta\mathrm{peak}}$ were created. Also, note that in the present experiment, the phase lag between any instantaneous sensor reading and the position of the wing at that instant was compensated by employing the phase-lag compensation scheme suggested by Chang and Park [8].

The influence of inverted Gurney flaps (with $h = -2.5\%c$ and $-5\%c$) on $v_{\theta\mathrm{peak}}$, r_c, and Γ_c over an oscillation cycle is presented in Figs. 2b, 2d, and 2f. As expected, the reduction in the core circulation was most obvious during the pitch-up prior-to-stall flow condition (Fig. 2f), similar to that of C_l and Γ_o (Figs. 1a and 1b), as a result of the induced negative camber effects. On the other hand, the transient DSV phenomena were found to be affected to a much lesser extent, compared to prior-to-stall Γ_o values, for the $h = -2.5\%c$ control case while remaining unchanged for the $h = -5\%c$ case. Additionally, even though the DSV spillage (and thus the peak Γ_c value) was generally less affected by the height of inverted Gurney flaps, the extent and strength of the DSV-induced stalled wake or flow separation were found to increase with h. The larger inverted Gurney flap height also rendered a significantly lowered core circulation during pitch-up compared to that during pitch-down. The results also indicate that, in addition to the favorable reduction in the core circulation (as much as 55%), a substantially weakened vortex rotation speed (as much as 75%), compared to a baseline wing, was persistently exhibited, due to the presence of inverted Gurney flaps

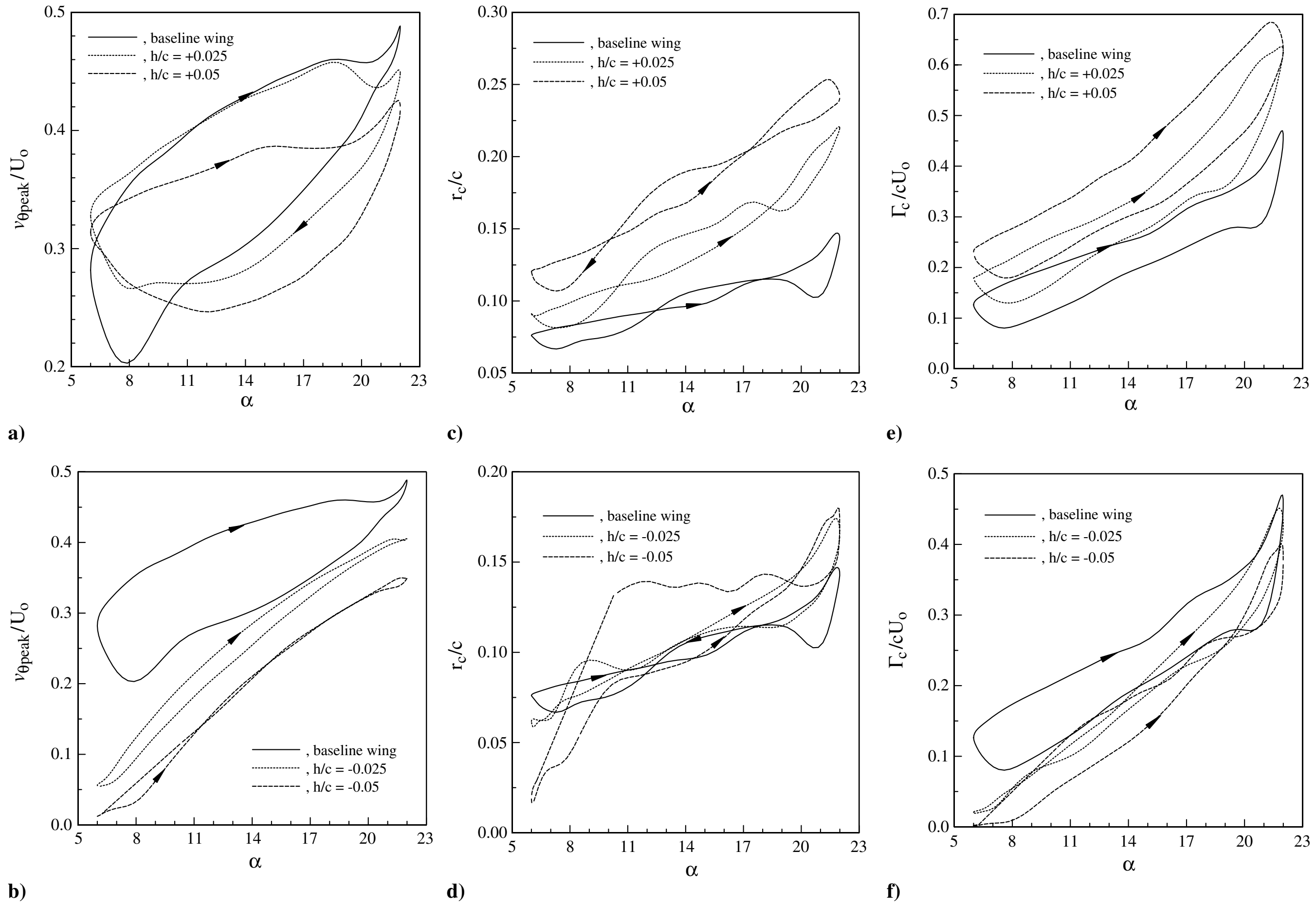

Fig. 2 Dynamic $v_{\theta\mathrm{peak}}$, r_c, and Γ_c loops.

(Fig. 2b). The reduction in $v_{\theta\mathrm{peak}}$ can be attributed to the weakening of the shear layers separating from both the upper and the lower wing surfaces, and, consequently, a much less organized vortex rollup. The larger the height of the inverted Gurney flap, the smaller the $v_{\theta\mathrm{peak}}$ and the extent of $v_{\theta\mathrm{peak}}$ hysteresis. For the $h = -5\%c$ control case, the discrepancy in $v_{\theta\mathrm{peak}}$ during pitch-up and pitch-down was basically eliminated, that is, a diminished $v_{\theta\mathrm{peak}}$ hysteresis. Also, in contrast to the well-behaved change in $v_{\theta\mathrm{peak}}$ and Γ_c, the influence of the height of the inverted Gurney flaps on the core radius was of a much irregular manner (Fig. 2d). No significant variation in r_c, within measurement uncertainty, compared to the baseline wing, was observed for a smaller h except for flow conditions covering $\alpha_u \approx 15$ deg to $\alpha_d \approx 15$ deg, which suggests that the inverted flap was most effective in diffusing or enlarging the vortex in the neighborhood of $\alpha_{\max}$. Meanwhile, for a larger inverted flap height, the reduction and increase in r_c was found to be most drastic during the first and the last one-thirds, respectively, of the pitch-up motion; a larger core radius (well above the baseline wing data) during pitch-down than during pitch-up was also noticed.

The present findings discussed previously also reveal that the addition of Gurney flaps (in both regular and inverted arrangements) always rendered a pronounced control of the peak vorticity ζ_{peak} (the vorticity evaluated at the vortex center) and the core axial velocity u_c (Figs. 3a–3d). Figure 3a shows that for the baseline wing, ζ_{peak} generally increased with α up to $\alpha_u = 18.5$ deg during the pitch-up attached flow process, which was then followed by a sharp fall and rise in the vicinity of $\alpha_{\max}$, as a result of the DSV formation and spillage. A large ζ_{peak} hysteresis was evident except in the vicinity of $\alpha_{\max}$. For an oscillating wing equipped with Gurney flaps, however, the value of the core vorticity was reduced. Also, most surprisingly, in contrast to the observed increase in r_c, Γ_c, and Γ_o, the larger Gurney flap height was found to generate an unexpected reduction (as much as 75%) in ζ_{peak}. The reduction in ζ_{peak} is similar to the reduction observed in $v_{\theta\mathrm{peak}}$ but to a much larger extent. Additionally, the core axial velocity u_c was also substantially reduced and was always wakelike, compared to the baseline wing (Fig. 3c), as a consequence of the increase in the axial pressure gradient. Note that for the baseline wing, the core axial velocity was found to be jetlike for $\alpha_u > 14$ deg to $\alpha_d > 18$ deg (except at around $\alpha_{\max}$). The value of the core axial velocity generally decreased with increasing Gurney flap height. The overwhelming influence of the inverted flaps on $v_{\theta\mathrm{peak}}$, r_c, and Γ_c during pitch-up attached flow and pitch-down flow reattachment flow regimes, as shown in Figs. 2b, 2d, and 2e, was also accompanied by a considerable reduction in ζ_{peak} throughout the entire oscillation cycle. The larger the inverted flap height, the smaller the peak vorticity and the narrower the hysteresis (Fig. 3b). No discrepancy in ζ_{peak} between pitch-up and pitch-down was observed for the $h = -5\%c$ control case. Moreover, similar to the case of the Gurney flaps, the addition of inverted Gurney flaps always resulted in a reduced u_c (below that of the baseline wing, Fig. 3d). The larger the inverted flap height, the smaller the core axial velocity.

Finally, the influence of the Gurney flaps on the vertical position of the vortex center, that is, y_c (identified by location of ζ_{peak}), over an oscillation cycle was also examined. The vortex was displaced vertically below that of the baseline wing throughout the entire oscillation cycle (Fig. 3e), as a result of the increased effective angle of attack induced by the presence of Gurney flaps. The most drastic vortex displacement was, however, observed during the DSV formation and spillage and before the beginning of the pitch-down flow reattachment flow conditions. The y_c displacement was increased with increasing Gurney flap height. The most pronounced vortex displacement was obtained for the $h = +5\%c$ control case for $\alpha_u = 14$ deg up to the during-stall flow regimes. On the other hand, instead of being displaced vertically downward below the baseline wing, the vortex was displaced above the baseline wing with the addition of inverted Gurney flaps (Fig. 3f). The larger inverted flap

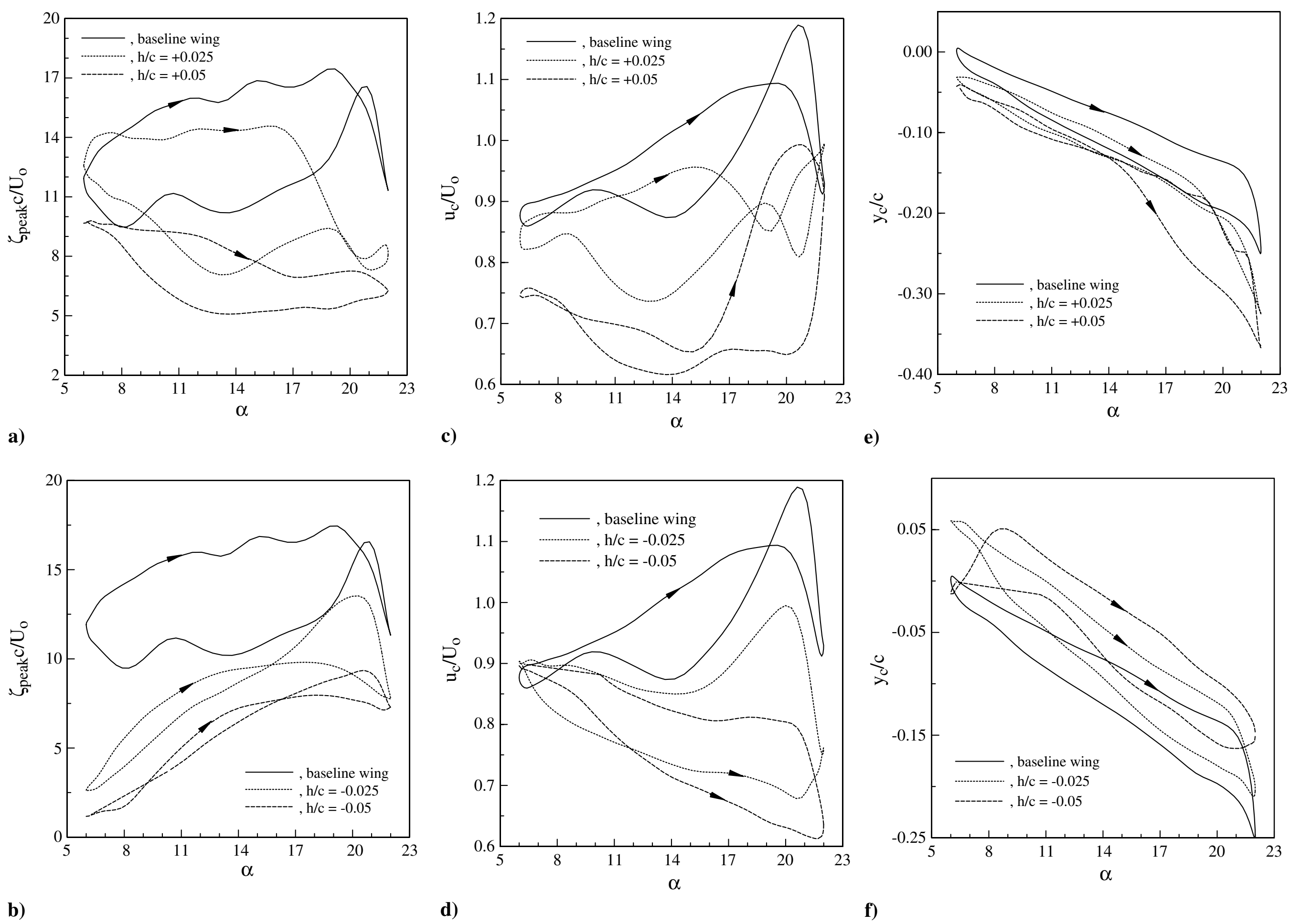

Fig. 3 Dynamic ζ_{peak}, u_c, and y_c loops.

height was found to be more effective in displacing the vortex compared to a smaller height. The present passive control of Γ_c and y_c also provides an assessment of the potential alleviation of the severity of BVI acoustic pressure time history $p(x,t) \sim \Gamma L l/\rho d_{\mathrm{miss}}$ as predicted by Hardin and Lamkin [9]. Note that d_{miss} is the miss distance between the vortex center and the blade leading edge, which is equivalent to the difference between the values of $y_c|_{\mathrm{controlled}}$ and $y_c|_{\mathrm{baseline\ wing}}$.

IV. Conclusions

The influence of a Gurney flap, in both regular and inverted arrangements, on the critical vortex flow parameters of an oscillating NACA 0015 wing was investigated. The larger the Gurney flap height, the higher the r_c and Γ_c but the lower the $v_{\theta\mathrm{peak}}$. The transient DSV formation and spillage remained largely unaffected by the flap height, whereas the extent and strength of the subsequent stalled wake or flow separation was found to increase with the flap height. The core vorticity and axial velocity were significantly reduced by the presence of Gurney flaps. For an oscillating wing equipped with an inverted Gurney flap, the reduction in $v_{\theta\mathrm{peak}}$ and Γ_c was found to be most overwhelming and was accompanied by a considerable reduction in ζ_{peak} and u_c throughout the entire oscillation cycle. The larger the inverted flap height, the smaller the $v_{\theta\mathrm{peak}}$, ζ_{peak}, and u_c and the narrower the associated hystereses. No discrepancy in $v_{\theta\mathrm{peak}}$ and ζ_{peak} between pitch-up and pitch-down was observed, within measurement uncertainty, for the $h = -5\%c$ control case. In summary, regardless of the flap height, the Gurney flap was most effective in increasing the core radius and circulation while the inverted Gurney flap was most significant in reducing $v_{\theta\mathrm{peak}}$, ζ_{peak}, and the associated hysteretic property. Also, the vortex was displaced vertically below and above the baseline wing with the presence of a Gurney flap and an inverted Gurney flap, respectively.

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