JOURNAL OF AIRCRAFT
Vol. 38, No. 1, January–February 2001

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Dynamic Stall Control by Intermittent Periodic Excitation

D. Greenblatt,* D. Neuburger,† and I. Wygnanski‡
Tel Aviv University, Ramat Aviv 69978, Israel

Nomenclature

c = airfoil chord
C_{Dp} = form-drag coefficient: Dp/cq
C_L = lift coefficient: L/cq
C_M = pitching moment coefficient: M/c^2q
C_P = pressure coefficient: $(p - p_\infty)/q$
C_μ = oscillatory momentum coefficient: J'/cq
F^+ = reduced excitation frequency: $f_e X_{te}/U_\infty$
f_a = airfoil oscillation frequency
f_e = excitation frequency
h = slot height
J' = rms oscillatory jet momentum: $\rho U_J'^2 h$
k = reduced airfoil frequency: $\pi f_a c/U_\infty$
p = local pressure
q = freestream dynamic pressure: $\rho U_\infty^2/2$
Re = chord Reynolds number: $\rho U_\infty c/\mu$
U_∞ = freestream velocity
U_J' = rms jet velocity (for excitation)
X_{te} = distance from slot to trailing edge
α = instantaneous incidence angle
$\bar{\alpha}$ = mean incidence angle
δ_f = flap deflection angle
ρ = air density
μ = air dynamic viscosity

Subscripts

exc = excursion of coefficient: $()_{max} - ()_{min}$
max = maximum value of coefficient
min = minimum value of coefficient

Introduction

RECENTLY, two-dimensional periodic excitation, in the form of alternating blowing and suction, was demonstrated as an effective method for controlling incompressible dynamic stall.[1–3] Two airfoils, an NACA 0015 and an NACA 0012, were subjected to a wide variety of excitation frequencies and amplitudes while the airfoils oscillated sinusoidally in pitch at typical rotorcraft reduced frequencies. For both airfoils, the dynamic stall vortex was eliminated by applying excitation at the airfoil leading edge, resulting in maximum-lift increases with the simultaneous attenuation of pitching-moment excursions.[1,2] For the NACA 0015, excitation was also applied at the shoulder of a deflectable flap, where the flap deflection angle ($0° \le \delta_f \le 20°$) remained constant while the airfoil oscillated in pitch. Unlike traditional dynamic stall control, incidence angles were confined to predynamic stall ranges where lift was augmented and drag was reduced by applying excitation at the flap shoulder. For the NACA 0015 airfoil, flap-shoulder excitation was found to be superior to leading-edge excitation.

The principle of dynamic separation and attachment control by periodic excitation was initially demonstrated on a stationary generic flap.[4–6] It was further shown that dynamic separation and attachment are dependent upon excitation frequency and amplitude, as well as flap deflection angle, flap length, and inflow conditions.[6] Examination of dynamic separation and its control revealed that a large time-scale disparity exists between the excitation frequencies and those characterizing airfoil pitching frequencies typical to rotorcraft (i.e., $f_e \gg f_a$).[6] This observation served as a rudimentary means for understanding dynamic stall control and paved the way for further performance optimization, as reported in this Note, by varying the excitation amplitude within the airfoil pitch cycle.

A dynamically pitching rotorcraft airfoil must generate high $C_{L,max}$ as well as large lift excursions: $C_{L,exc} \equiv C_{L,max} - C_{L,min}$ to achieve high flight speeds. One objective of this Note is to demonstrate how this can be achieved by initiating and terminating excitation within the airfoil pitching cycle. Additional benefits of intermittent excitation, such as improved system efficiency, drag reduction, and pitching-moment control, are illustrated. Thus, intermittent excitation is used in the current context to achieve predetermined objectives, although the mechanisms and parameters associated with dynamic separation and attachment are not investigated. Two light-stall cases are considered here. The first case involves leading-edge excitation, where the mean airfoil incidence angle is located in the vicinity of the static stall angle, and the second case considers flap-shoulder excitation.

Experimental Setup

All experiments reported here were carried out on an NACA 0015 airfoil, equipped with surface pressure taps and two slots (leading-edge and flap-shoulder), described previously.[1] The airfoil was installed in the test section of a closed-loop, low-speed wind tunnel and pitched sinusoidally ±5 deg about its one-fourth chord position by a pitching mechanism driven by a dc motor. Dynamic surface pressure measurements were made with a multichannel array of pressure transducers and a shaft-mounted encoder signal was used to ascertain instantaneous incidence angles. As in previous work, zero net mass-flux excitation (alternating blowing and suction) was achieved by means of a blower-valve mechanism connected by a pipe to the airfoil plenum chamber and calibrated by means of a hot-wire anemometer. Excitation intermittency was achieved by placing a pneumatically operated valve in the pipeline, between the blower-valve and airfoil plenum. The valve was opened and closed independently by solenoid valves, which were driven by micro-switch-generated signals on the motor shaft. This allowed arbitrary initiation and termination of the excitation signal relative to the phase of the pitch oscillation. The system inertia and valve response time (approximately 50 msec) were calibrated by

Received 1 November 1999; revision received 6 July 2000; accepted for publication 20 July 2000.

*Postdoctoral Fellow, Department of Fluid Mechanics and Heat Transfer, Faculty of Engineering. Member AIAA.
†Graduate Student, Department of Fluid Mechanics and Heat Transfer, Faculty of Engineering.
‡Lazarus Professor of Aerodynamics, Department of Fluid Mechanics and Heat Transfer; currently Professor of Aerospace Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, PO Box 210119, 1130 N. Mountain, RM N614, Tucson, AZ 85721. Fellow AIAA.

slot velocity measurements in the absence of airfoil oscillation and with no freestream present.

Results

Leading-Edge Excitation

Figures 1a and 1b show phase-averaged, surface-pressure, integrated lift and moment data for the airfoil pitching within the light-stall regime, where the mean incidence angle ($\bar{\alpha} = 13$ deg) is 1 deg above the static stall angle, α_{stall}. For all dynamic data presented here, solid and dashed lines denote airfoil pitchup and pitchdown, respectively. A comparison of baseline and excitation data for the pitching airfoil shows that excitation increases $C_{L,\max}$, eliminates lift stall, and halves the moment excursion ($C_{M,\text{exc}}$), bringing it to typical prestall values (prestall $C_{M,\text{exc}} \approx 0.05$ for all data presented here, as indicated in Fig. 1b).[2] When excitation is initiated and terminated in the vicinity of the static stall angle (i.e., on the up- and downstrokes, respectively), the excitation results are not materially altered. Thus, excitation can be applied for less than half of the cycle without loss of effectiveness, representing a more efficient system. For the above data, as well as the remainder of the data presented here, the number of airfoil oscillations performed for phase averaging was based on maximum allowable errors of $\Delta C_{L,\max}/C_{L,\max} < 2\%$, $\Delta C_{Dp,\text{mean}}/C_{Dp,\text{mean}} < 2\%$, and $\Delta C_{M,\text{exc}}/C_{M,\text{exc}} < 4\%$ with 95% confidence limits. This typically required from 25 to 50 cycles for baseline cases and 5 to 25 loops for cases with excitation.

A previous investigation[1] indicated that leading-edge excitation, when applied at certain effective excitation frequencies, increased time-mean form drag. This problem was traced to unnecessary excitation in the prestall regime and is illustrated by the form-drag and leading-edge ($x/c = 0.4\%$) pressure coefficient data presented in Figs. 2a and 2b, respectively. With intermittent excitation initiated and terminated near the static stall angle, this effect is almost completely eliminated, as can be seen by the form-drag loops presented in Fig. 2a. Time-mean form drag increased by 32% over the baseline with continuous excitation, but this increase was reduced to 5% with intermittent excitation. This effect is emphasized by the phase-averaged pressure coefficient data at $x/c = 0.4\%$, which shows how continuous excitation increases pressure (decreases $-C_P$) in the vicinity of the leading edge whereas intermittent excitation eliminates the pressure increase in the prestall regime. Thus, intermittent excitation in the current context can, in fact, increase excitation effectiveness. The figures also indicate that the static stall angle is probably not the optimum location for excitation initiation and termination, that is excitation initiation at a larger angle may further reduce form drag while simultaneously reducing the pitch-cycle fraction during which excitation is active. Such an optimization was not carried out here.

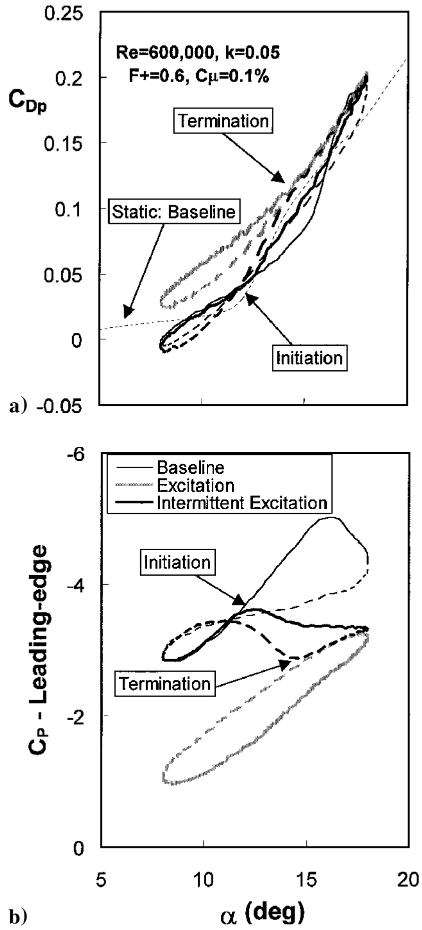

Fig. 2 Comparison of dynamic form-drag and leading-edge pressure for continuous and intermittent leading-edge excitation (same conditions as in Fig. 1).

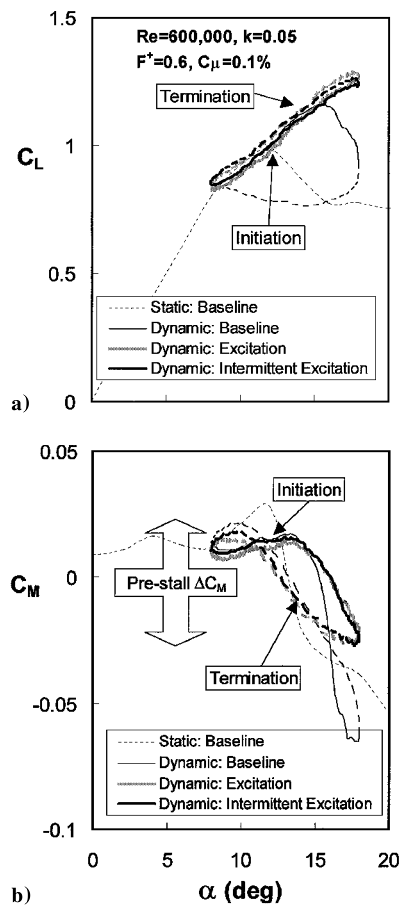

Fig. 1 Comparison of dynamic lift and moment data for continuous and intermittent leading-edge excitation under the conditions α = 13 deg + 5 deg sin(ωt), δ_f = 0 deg.

Flap-Shoulder Excitation

Darabi et al.[7] recently studied the dynamic attachment of an initially separated flow to a stationary deflected flap by initiating excitation in a manner similar to that described here. They established that the minimum time required to achieve full flow attachment to the flap occurs at $F^+ \approx 1$. Using this as a guideline, intermittent flap-shoulder excitation at $F^+ = 1.1$ and $C_\mu = 2\%$ was attempted on the dynamically pitching NACA 0015, with flap deflection $\delta_f = 20$ deg (see Figs. 3a and 3b). Although the maximum incidence angle is 4 deg above the static stall angle, severe dynamic stall is avoided for the baseline case, as can be seen from the light-moment stall (Fig. 3b) due to the relatively high rotorcraft pitch rate ($k = 0.1$) considered here. Unlike the leading-edge excitation case (see Fig. 1), continuous excitation brings about lift increases that are maintained

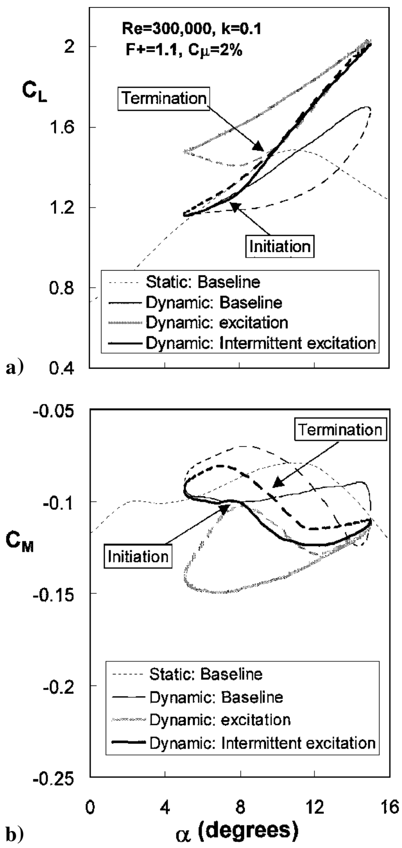

Fig. 3 Dynamic stall control by means of intermittent flap-shoulder excitation for the conditions α = 10 deg + 5 deg sin(ωt), δ_f = 20 deg.

throughout the entire cycle because of attachment of the flow to the flap. In contrast, however, instantaneous $dC_L/d\alpha$ is not significantly affected. In addition to lift increases, the light-moment stall is eliminated, resulting in a 20% reduction in moment excursions, while excitation induces a further mean nose-down pitching moment of $C_{M,\text{mean}} \sim 0.05$. Although intrinsically different from the preceding case, a similar control strategy was applied for flap-shoulder excitation. Here, excitation is initiated soon after the commencement of pitchup and terminated in the region where the continuous excitation downstroke lift data begin to increase. As indicated in the figure, this control strategy brought about the maximum possible lift excursions, namely between the minimum baseline and maximum excitation limits ($C_{L,\text{exc}} = 0.8$). In addition, the light-moment stall, which was effectively eliminated by continuous excitation, is also eliminated by intermittent excitation.

Conclusions

The data presented in this Note illustrate some preliminary results of intermittently varying the excitation amplitude within the airfoil pitch cycle during incompressible dynamic stall. The following specific conclusions were drawn:

1) For the light-stall case, similar lift and moment results were attained with excitation continuously active or active for only half of the airfoil pitch cycle.

2) The cessation of excitation for incidence angles below α_{stall} virtually eliminated form-drag increases evident during continuous excitation.

3) Intermittent flap-shoulder excitation resulted in maximized lift excursions because the airfoil attained $C_{L,\max}$ of the continuous excitation case and $C_{L,\min}$ of the baseline case. Moreover, light moment stall control was achieved by both continuous and intermittent excitation.

Acknowledgments

This work was sponsored in part by a grant from the Research and Development Office of the Israel Ministry of Defense, monitored by A. Kuritzki, and is an assigned task of the US/ISRAEL Memorandum of Agreement on rotorcraft aeromechanics.

References

[1] Greenblatt, D., and Wygnanski, I., "Dynamic Stall Control by Oscillatory Forcing," AIAA Paper 98-0676, Jan. 1998.

[2] Greenblatt, D., and Wygnanski, I., "Parameters Affecting Dynamic Stall Control by Oscillatory Excitation," AIAA Paper 99-3121, June 1999.

[3] Greenblatt, D., "Dynamic Stall Control by Oscillatory Excitation," Ph.D. Dissertation, Dept. of Fluid Mechanics and Heat Transfer, Tel Aviv Univ., 1999.

[4] Nishri, B., "On the Dominant Mechanisms Governing Active Control of Separation," Ph.D. Dissertation, Dept. of Fluid Mechanics and Heat Transfer, Tel Aviv Univ., 1995. (In Hebrew).

[5] Greenblatt, D., Darabi, A., Nishri, B., and Wygnanski, I., "Separation Control by Periodic Addition of Momentum with Particular Emphasis on Dynamic Stall," American Helicopter Society, Paper T3-4, April 1998.

[6] Greenblatt, D., Darabi, A., Nishri, B., and Wygnanski, I., "Some Factors Affecting Stall Control with Particular Emphasis on Dynamic Stall," AIAA Paper 99-3504, June 1999.

[7] Darabi, A., Lourenco, L., and Wygnanski, I., "On Flow Reattachment by Periodic Excitation," *8th European Turbulence Conference*, Euromech, Barcelona, Spain, 2000.

Use of Periodic Excitation to Enhance Airfoil Performance at Low Reynolds Numbers

David Greenblatt* and Israel J. Wygnanski†
Tel Aviv University, 69978 Ramat Aviv, Israel

Nomenclature

C_D = total-drag coefficient
C_{Dp} = form-drag coefficient
C_L = lift coefficient
C_μ = momentum coefficient, $2h/c(U_{\text{rms}}/U_\infty)^2$
c = airfoil chord
$\bar{c}$ = mean wing chord
F^+ = reduced frequency, $f_e X_{\text{TE}}/U_\infty$
f = frequency
h = slot width
m = mass
Re = Reynolds number, $U_\infty c/\nu$
St_r = rotor reduced frequency, $f_r c/V_{\text{rel}}$
St_w = wing reduced frequency, $f_w \bar{c}/V$
U = air velocity
V = wing or blade velocity
X_{TE} = distance from slot to trailing edge
x = distance measured from the leading edge
α = incidence angle

Subscripts

e = relating to excitation
max = maximum value
r = relating to rotors
rel = relative to air velocity
rms = root mean square

Received 9 May 2000; revision received 7 July 2000; accepted for publication 20 July 2000.

*Postdoctoral Fellow, Department of Fluid Mechanics and Heat Transfer. Member AIAA.

†Lazarus Professor of Aerodynamics, Department of Fluid Mechanics and Heat Transfer; currently Professor of Aerospace Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, PO Box 210119, 1130 N. Mountain, RM N614, Tucson, AZ 85721. Fellow AIAA.