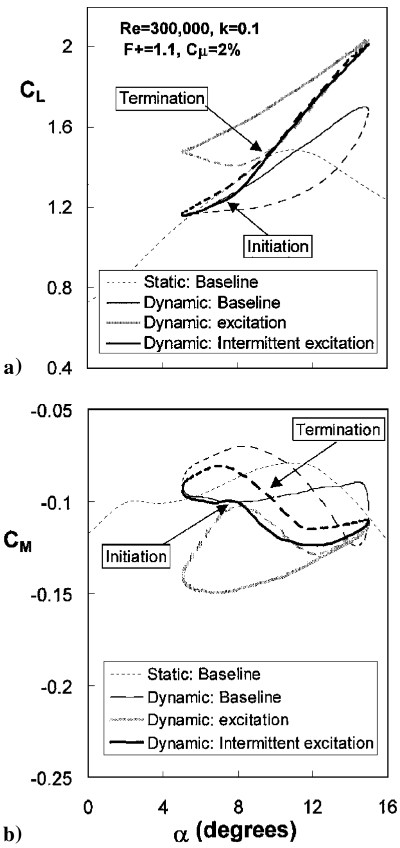

Fig. 3 Dynamic stall control by means of intermittent flap-shoulder excitation for the conditions α = 10 deg + 5 deg sin(ωt), δ_f = 20 deg.

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 $C_{M,\mathrm{mean}} \sim 0.05$. 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 ($C_{L,\mathrm{exc}} = 0.8$). 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

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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

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Nomenclature

C_D = total-drag coefficient
C_{Dp} = form-drag coefficient
C_L = lift coefficient
C_μ = momentum coefficient, $2h/c(U_{\mathrm{rms}}/U_\infty)^2$
c = airfoil chord
$\bar{c}$ = mean wing chord
F^+ = reduced frequency, $f_e X_{\mathrm{TE}}/U_\infty$
f = frequency
h = slot width
m = mass
Re = Reynolds number, $U_\infty c/\nu$
St_r = rotor reduced frequency, $f_r c/V_{\mathrm{rel}}$
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

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w = relating to wings
∞ = freestream conditions

Introduction

MICRO air vehicles (MAVs) are currently undergoing development to meet projected military and environmental needs. The small dimensions (i.e., wing span $b \leq 15$ cm) typical to MAVs bring with them certain advantages, such as structural strength and low inertia. The accompanying low flight speeds, however, result in very low Reynolds numbers (i.e., $10^4 \leq Re \leq 10^5$), where conventional low-Reynolds-number airfoils perform poorly.[1] Various innovative flight vehicles are currently being developed, many of which are based on the aerodynamics of small birds, bats, and insects that fly within this Reynolds number range and whose lifting capacity is in the range $10^1 \leq m \leq 10^2$ g. Methods currently under development include flapping or flexible wings[1,2] and boundary-layer control (e.g., blowing).[3]

This Note reports a preliminary wind-tunnel investigation of an airfoil at typical MAV Reynolds numbers, subjected to active control by periodic excitation. In the past this method has been widely studied on airfoils at low Reynolds numbers ($10^5 \leq Re \leq 10^6$) (Ref. 4), whereas NACA 0015 flow visualization[5] and measurements[6] have indicated its potential for application at $Re < 10^5$. The method differs from those just cited in that quasi-two-dimensional vortices are generated and transported over a stationary airfoil, bringing high-momentum fluid to the surface, thereby delaying separation and improving performance. Thus the objective is to enhance lift and performance by means of an unsteady mechanism, without the complexity associated with wing movement or flapping.

Experimental Setup

Experiments were performed in Tel Aviv University's Meadow-Knapp closed-loop wind-tunnel.[4] The airfoil tested was originally designed as a flap, with chord length $c = 109$ mm and maximum thickness $(t/c)_{\max} = 17\%$ (see inset in Fig. 1). The airfoil had an interior plenum in fluid communication with a nominally two-dimensional, leading-edge slot ($h = 0.5$ mm at $x/c = 2\%$) and was equipped with 18 surface pressure taps located on the center span. Static and dynamic pressure measurements were made for $3 \times 10^4 \leq Re \leq 1.5 \times 10^5$ at baseline and controlled conditions. Zero net mass-flux excitation (alternating suction and blowing) was achieved by means of a rotating valve and a small centrifugal blower connected to the airfoil plenum. Resultant velocity fluctuations at the slot exit U_{rms} were calibrated by means of a hot-wire anemometer.[4] For a given excitation frequency span-averaged and centerline peak velocity fluctuations never differed by more than 5%. In addition to excitation, flow tripping was attempted by means of 6-mm diam $\times$ 1-mm high circular tabs, spaced at 20-mm intervals along the span at the 2, 30, and 70% chord locations.

Discussion of Results

Figure 1 shows C_L vs α data for $3 \times 10^4 \leq Re \leq 1.5 \times 10^5$, where tabs are located at the 30% chord position. (Tabs at 30% chord were most effective at tripping the flow, as discussed next.) The data presented in the figure are representative of performance degradation observed on airfoils as the Reynolds number approaches, and decreases into, the MAV regime.[7] For $Re = 1.5 \times 10^5$ the airfoil performs relatively well, achieving $C_{L,\max} = 1.64$, but stalls sharply at $\alpha = 14$ deg. As α decreases for this case, there is exceptionally large lift hysteresis with full reattachment of the flow occurring only at $\alpha = 6$ deg (c.f. Ref. 7). Reducing the Reynolds number to $Re = 1.0 \times 10^5$ brings about significant performance degradation, i.e., a 40% reduction in $C_{L,\max}$ with stall at $\alpha = 6$ deg. An additional reduction to $Re = 5 \times 10^4$ results in a further severe performance degradation and is typical of conditions prevailing at these Reynolds numbers. For the lowest Reynolds number tested here, namely $Re = 3 \times 10^4$, the airfoil fails to generate useful lift. It should be noted that the lift generated by certain thin airfoils and flat plates are less dependent on Re in this range, presumably because separation is fixed at the leading-edge.[7]

The effect of tabs and active control on the baseline (clean) airfoil is shown for $Re = 5 \times 10^4$ in Fig. 2. Attempts to trip the flow using tabs at $x/c = 2$, 30, and 70%, as well as staggered combinations thereof, resulted in little to no improvement over the baseline data. The size and number of tabs demonstrated that passive boundary-layer tripping for $Re \leq 5 \times 10^4$ is difficult, if not impossible, although it should be noted that a detailed study of various tab shapes and sizes was not performed here. The best result, for tabs at $x/c = 30\%$, is shown in the figure and illustrates a modest improvement in $C_{L,\max}$. Excitation, on the other hand, results in a four-fold increase in $C_{L,\max}$ for two reduced frequencies, namely $F^+ = 1.0$ and 2.1, respectively. These reduced frequencies and momentum coefficients C_μ are typical of those effective for $10^5 \leq Re \leq 10^6$. For this airfoil the higher reduced frequency, namely $F^+ = 2.1$, requires more than twice the momentum addition in order to achieve the same $C_{L,\max}$ and stalls more abruptly.

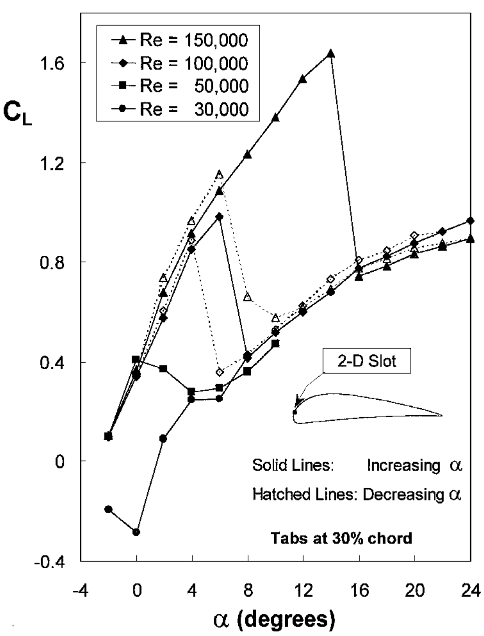

Fig. 1 Illustration of airfoil lift degradation with decreasing Reynolds number.

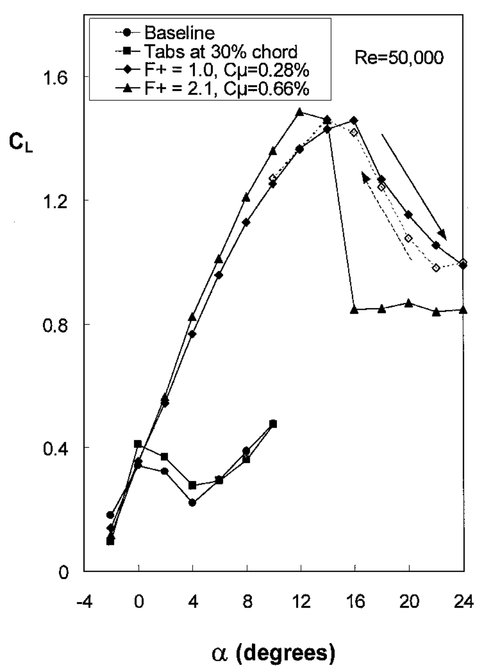

Fig. 2 Effect of tabs and excitation on lift for $Re = 5 \times 10^4$.

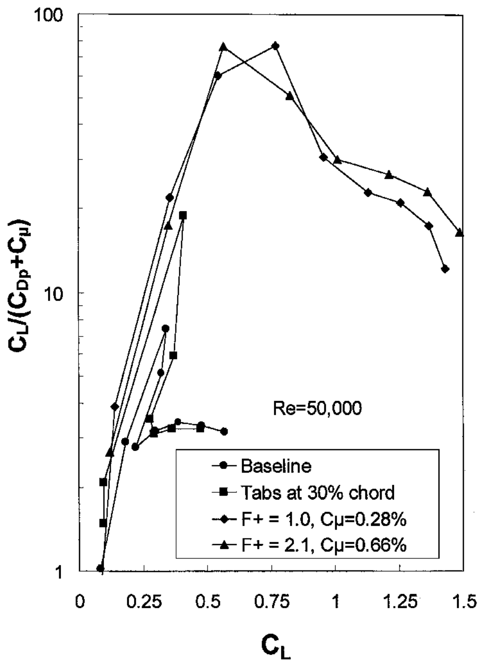

Fig. 3 Effect of tabs and excitation on airfoil efficiency for $Re = 5 \times 10^4$.

As was just shown, in addition to severe performance degradation, lift hysteresis can be excessive at low Reynolds numbers (see Fig. 1). Hysteresis was checked for the $F^+ = 1.0$ case, and the data show that the phenomenon is all but eliminated by excitation—a feature repeatedly observed when active control is applied at the leading edge of a dynamically pitching airfoil for $Re \geq 1.0 \times 10^5$ (Ref. 8). Moreover, dynamic pressure measurements revealed that maximum amplitude oscillations of lift within excitation cycles ($\Delta C_{L,\max}$) were small, with $\Delta C_{L,\max}/C_{L,\max} = 4\%$ and long time interval ($tU_\infty/c > 300$) averages resulted in effectively steady lift with $C_{L,\mathrm{rms}}/C_{L,\max} = 3\%$. These results are of the same order as those associated with conventional low-Reynolds-number excitation.[4]

Accompanying poor lifting performance for $Re \leq 10^5$, airfoil efficiency (i.e., lift-to-drag ratio: C_L/C_D) is degraded. In this preliminary investigation total drag was not measured, but form drag C_{Dp} was reduced from the airfoil surface pressure data. The results for C_L/C_{Dp} (baseline and tabbed cases) and $C_L/(C_{Dp} + C_\mu)$ (controlled cases) are presented in Fig. 3, where C_μ is included in the more general definition of efficiency to account for excitation. The figure clearly shows that, even with C_μ accounted for, excitation increases baseline airfoil maximum efficiency by an order of magnitude from 7.4 to 77 for both excitation frequencies. Moreover, the higher value of efficiency occurs at about twice the baseline value of C_L.

Data acquired at $Re = 3 \times 10^4$ and $F^+ = 1.0$ showed that four times more C_μ was required in order to achieve similar lift to that at $Re = 5 \times 10^4$. Examination of the upper surface pressures (not shown) indicated that lift is generated by means of a large bubble or "trapped vortex," which extends over more than half of the airfoil near stall. However, control still produces a remarkable improvement by transforming a nonlifting airfoil into one that approaches conventional performance.

Dynamic Stall Analogy

It is widely believed that small flying creatures of $m \leq 30$ g remain airborne by means of at least one unsteady flow mechanism.[1,2,9,10] One such mechanism is the so-called "separation bubble" or vortex, which forms during the downstroke of the wing and generates the high lift required for flight. This bubble is similar to the well-known dynamic stall vortex (DSV) that is potentially damaging to helicopter rotors and consequently avoided in conventional flight.[11]

Apart from obvious structural differences, the paradox that the DSV is damaging to helicopter rotors, yet at least partially responsible for the flight of small creatures, can be provisionally resolved as follows: From the statistical data summarized by Shyy et al.[1] for $10 \leq m \leq 100$ g, the typical reduced frequencies associated with wing flapping St_w are 0.1 to 1, whereas in hover $St_w \to \infty$. This should be contrasted with equivalent reduced frequencies associated with oscillating helicopter rotor blades, namely $St_r \sim 0.015 - 0.05$. Thus some flying creatures can generate DSVs at a rate high enough to ensure sustained flight, i.e., at least one vortex will always be present on the upper surface of the wing or body at any instant.

A similar explanation can be given in the context of excitation. Greenblatt et al.[12] have shown that an important difference between the DSV and vortices generated by excitation and transported over the airfoil surface, is that their timescales are substantially different—by one to two orders of magnitude, c.f., $St_r = \mathcal{O}(0.01)$ to $\mathcal{O}(0.1)$ vs $F^+ = \mathcal{O}(1)$. With excitation at $F^+ = 1.0$, there are typically two to three vortices present on the lifting surface (or airfoil) at any instant. This ensures stable, as well as effective, lift because the excitation-generated vortices do not bring about large variations in aerodynamic loads. Indeed, in the present investigation integration of the oscillatory pressures on the airfoil indicated relatively small oscillatory loads (e.g., $C_{L,\mathrm{rms}}/C_{L,\max} = 3\%$, as just shown), which is consistent with conventional low-Reynolds-number investigations.[4]

Conclusions

This Note demonstrated that periodic excitation, known to be effective at conventional low Reynolds numbers, is markedly effective in the MAV Reynolds-number range. Specifically, typical conventional low-Reynolds-number lift and efficiency are restored, excitation-induced lift oscillations are small, and hysteresis associated with stall is virtually eliminated. A similarity between the timescales associated with excitation and those characterizing dynamic stall in small flying creatures provided some insight into these observations. The method and associated physical dimensions are ideally suited to actuation by means of micro-electromechanical-systems-based devices. However, the effectiveness and efficiency of actuators required to supply the prescribed excitation will ultimately determine the success and limitations of the method.

References

[1] Shyy, W., Berg, M., and Ljungqvist, D., "Flapping and Flexible Wings for Biological and Micro Air Vehicles," *Progress in Aerospace Sciences*, Vol. 35, No. 5, 1999, pp. 455–505.

[2] Pornsin-Sirirak, T., Lee, S. W., Nassef, H., Grasmeyer, J., Tai, Y. C., Ho, C. M., and Keennon, M., *MEMS Wing Technology for a Battery-Powered Ornithopter*, Inst. of Electrical and Electronics Engineers, New York, Jan. 2000, pp. 799–804.

[3] Englar, R. J., "Circulation Control Pneumatic Aerodynamics: Blown Force and Moment Augmentation and Modification; Past, Present & Future," AIAA Paper 2000-2541, June 2000.

[4] Seifert, A., Darabi, A., and Wygnanski, I., "Delay of Airfoil Stall by Periodic Excitation," *Journal of Aircraft*, Vol. 33, No. 4, 1996, pp. 691–698.

[5] Neuburger, D., "An Active Delay of Separation on Two-Dimensional Airfoils," Master's Thesis, Tel Aviv Univ., April 1989 (in Hebrew).

[6] Naveh, T., "The Effect of Sweep on Separation Control over an Airfoil," Master's Thesis, Tel Aviv Univ., March 1997 (in Hebrew).

[7] McCormick, B. W., *Aerodynamics, Aeronautics and Flight Mechanics*, John Wiley and Sons, New York, 1979, pp. 152–157, Chap. 3.

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

[9] Maxworthy, T., "The Fluid Dynamics of Insect Flight," *Annual Review of Fluid Mechanics*, Vol. 13, 1981, pp. 329–350.

[10] Spedding, G. R., and Maxworthy, T., "The Generation of Circulation and Lift in a Rigid Two-Dimensional Fling," *Journal of Fluid Mechanics*, Vol. 165, 1986, pp. 247–272.

[11] Carr, L. W., "Progress in the Analysis and Prediction of Dynamic Stall," *Journal of Aircraft*, Vol. 25, No. 1, 1988, pp. 6–17.

[12] 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–July 1999.