JOURNAL OF AIRCRAFT
Vol. 44, No. 4, July–August 2007

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following 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).

Performance of Articulated Flapping Wings with Partial Leading-Edge Suction

Todd M. Reichert* and James D. DeLaurier†
University of Toronto, Toronto, Ontario M3H 5T6, Canada

DOI: 10.2514/1.29616

Nomenclature

A	=	double amplitude of wing tip
f	=	flapping frequency
St	=	Strouhal number
U	=	freestream velocity
α	=	aircraft angle of attack to freestream velocity
α_a	=	angle of advance at wing tip
β	=	magnitude of wing folding or bending
$\Gamma(t)$	=	instantaneous bending angle at wing joint
γ_0	=	stroke amplitude at wing root
δ	=	transition time of wing folding or bending
η_s	=	leading-edge suction efficiency
$\bar{\theta}_w$	=	time-averaged washout angle at wing tip
θ_φ	=	phase angle of wing twist with respect to flapping angle
θ_0	=	magnitude of wing twist at wing tip
$\Lambda(t)$	=	instantaneous folding angle at wing joint
τ	=	downstroke ratio of wing folding or bending
φ	=	phase shift of wing folding or bending
χ	=	feathering parameter, Eq. (1)

Subscripts

opt	=	optimum value
Γ	=	wing bending
Λ	=	wing folding

Introduction

THE vast majority of birds and bats reduce their effective wing span on the upstroke by bending their wrist and elbow joints. It is not known, however, whether this wing articulation is a method of improving aerodynamic performance or the result some other physiological constraint. Conversely, the majority of successful mechanical flapping-wing aircraft fly with torsionally flexible but spanwise-rigid wings [1]. Efficient thrust production in this second flight mode is highly dependent on the leading-edge suction efficiency of the airfoil [2], whereas birds and bats are known to operate with thin leading edges that provide almost no leading-edge suction. The purpose of this research, then, is to investigate the performance of articulated flapping wings and how this performance is related to leading-edge suction efficiency.

For the most part, past research on the performance of articulated flapping wings has been from the perspective of analyzing an existing bird or bat species, rather than from a design perspective. Several aerodynamic models that account for unsteady effects have been employed to this end, notably by Rayner [3], Spedding [4–6], and Pivkin et al. [7], but the specific mechanism that makes upstroke span reduction an efficient thrust production method has not been elucidated. Another category of researchers has approached the problem of flapping flight from a fundamental aerodynamics perspective. The research of Betteridge and Archer [8], Archer et al. [9], Vest and Katz [10], Hall et al. [11], Phlips et al. [12], and DeLaurier [13] has led to a far greater understanding of some of the underlying principles of flapping flight, including the effects of leading-edge suction, but has all been limited to the spanwise-rigid flapping mode.

To properly capture the effects of upstroke span reduction, the model used in the current study extends the unsteady strip-theory model assumed in [12], which accounts explicitly for the effects of leading-edge suction efficiency. Wing articulation is added to the kinematic model with a wrist joint at the midspan, as shown in Fig. 1. A gradient-based optimizer was used to navigate the enlarged design space and converge on the optimal set of kinematics for both the rigid-span and articulated-wing flight modes. It was found that the effect of upstroke span reduction can be better understood by using the nondimensional feathering parameter χ. The feathering parameter is defined at the wingtip and describes the magnitude of the dynamic twist θ_0 normalized by the maximum angle of advance $(\alpha_a)_{\max}$, as given in Eq. (1):

$$\chi = \frac{\theta_0}{(\alpha_a)_{\max}} = \frac{\theta_0}{\arctan(\pi St)} \tag{1}$$

The relationship between the magnitude of the tip twist, the advance angle, and the Strouhal number is shown in Fig. 2, in which the

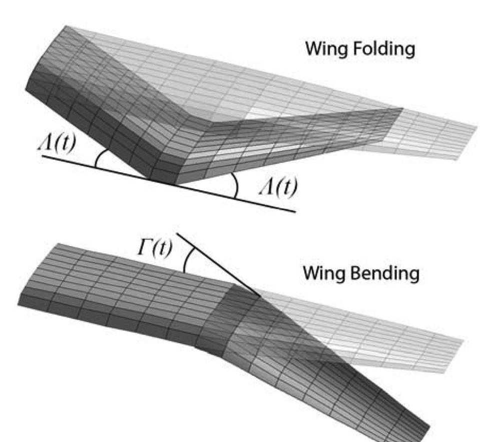

Fig. 1 Articulated wing with 2-degrees-of-freedom joint at midspan.

Received 6 January 2007; revision received 7 March 2007; accepted for publication 7 March 2007.

*Ph.D. Candidate, Institute for Aerospace Studies, 4925 Dufferin Street.
†Professor Emeritus, Institute for Aerospace Studies, 4925 Dufferin Street. Associate Fellow AIAA.

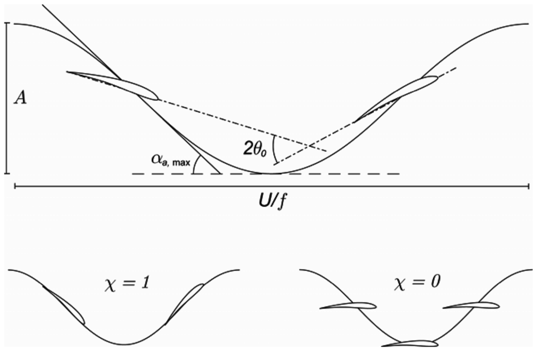

Fig. 2 Stroke kinematics for defining the feathering parameter χ.

Strouhal number is given in its usual form as $St = fA/U$. In general, the point of intersection of the chordlines is off-center due to an average positive angle of attack. In the case where $\chi = 1$, the angle of attack is constant throughout the stroke and the resulting symmetry produces no thrust. Decreasing χ produces a positive net thrust, as the relative angle of attack on the upstroke becomes less than that on the downstroke. Though other methods of thrust production are possible, this technical note will focus on those where the asymmetry of the stroke is achieved by a combination of reducing the upstroke angle of attack, regulated by χ, and reducing the effective span through wing articulation. The goal is to link wing articulation to the kinematic parameter χ and to show how upstroke span reduction can lead to performance increases when leading-edge suction efficiency is low.

Analytical Model

Kinematics

In this study, wing morphing is accomplished with a 2-degree-of-freedom joint defined by a bending angle $\Gamma(t)$ and a folding angle $\Lambda(t)$, as shown in Fig. 1. In the case of wing folding, the angle at the joint is mirrored by an equivalent rotation at the root. As the wing folds, chord lines remain parallel and the effective wing area is reduced. In the case of bending, the size of the wing does not change. The variation of each joint angle in time is parameterized by four variables: magnitude β, phase shift φ, downstroke ratio τ, and transition time δ, as shown in Fig. 3. With an 180 deg transition time and 0 deg phase shift, this converges to a sine wave. The flapping motion at the root is sinusoidal with stroke amplitude γ_0 and flapping frequency f. The time-varying twist angle of the wing is assumed to be proportional to the downward flapping velocity at each point along the span, plus a prescribed phase shift θ_p. The magnitude of the wing twist is defined at the wing tip and is given by θ_0. For spanwise-rigid sinusoidal flapping, this converges to wing twisting that is linear along the span and sinusoidal in time. Note that for this model the magnitude and phase of the tip twist are prescribed directly, instead of using an integrated aeroelastic model as in [12]. The kinematic parameters given earlier fully define the motion of each chordwise strip along the wing, from which the linear and rotational

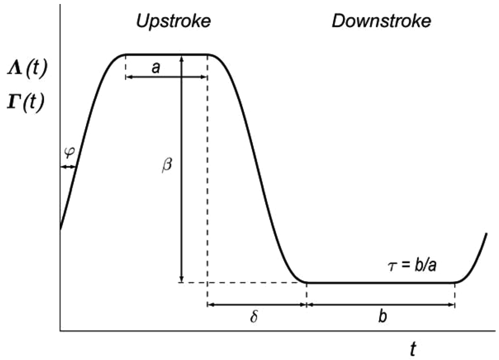

Fig. 3 Variation of joint angle in time.

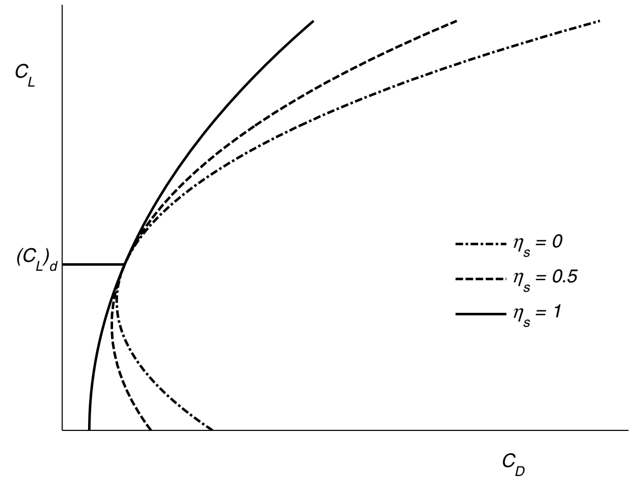

Fig. 4 Finite-wing drag polars for various η_s values.

velocities as well as the relative angles of attack can be calculated and applied in the unsteady aerodynamic model given in the next section.

Aerodynamics

As previously stated, the aerodynamic model used for this study is based on the unsteady strip-theory model from [12], which uses modified Theodorsen functions to model the effect of the unsteady wake. These functions have been derived by Jones [14], assuming sinusoidal motion; therefore, to retain accuracy, the folding and bending magnitudes have been kept below 50 deg so that the variation of the angle of attack remains at least somewhat sinusoidal. The model also has corrections for dynamic stall delay, apparent-mass effects, and partial leading-edge suction. Leading-edge suction efficiency is an important parameter in the study of flapping-wing flight because of the large variations in angle of attack. Its effect on airfoil performance is plotted in Fig. 4, in which it can be seen that airfoils with low leading-edge suction efficiency suffer a dramatic reduction in their lift-to-drag ratio at off-design angles of attack. The mechanism responsible for this loss of performance is a small separation bubble that appears when the flow is required to turn too quickly around the leading edge [15]. Thus, leading-edge suction efficiency is directly related to the leading-edge radius of the airfoil and becomes a far greater concern in the low Reynolds number flight of birds and bats.

Results

A previous successful ornithopter [1] was used as the baseline case for the computational experiments. The wing has a 0.28 m chord at the root and a 1.1 m semispan with a straight trailing edge and a 12 deg taper starting at the midspan. The airfoil at the root is a Selig S1020 with a 5.33 deg zero-lift line and 91.5% leading-edge suction efficiency, which blends into a symmetric S1080 airfoil towards the wingtip.[‡] The flapping frequency was set to 2.75 Hz, the flight speed to 13.7 m/s, and the stroke amplitude to ±27.3 deg, giving a constant Strouhal number of 0.20, which lies within the range for efficient flight noted by Nudds et al. [16]. With the Strouhal number held constant and joint articulation phased so that span reduction occurs on the upstroke, thrust becomes a function primarily of the feathering parameter χ and the magnitude of the span-reduction angles β_Γ and β_Λ. During the study it was found that thrust was often optimized when the folding magnitude was set approximately equivalent to the bending magnitude; thus to simplify further discussion β_Γ will be made equal to β_Λ and they will be referred to collectively as β.

[‡]The S1020 and S1080 airfoils were designed by Professor Michael Selig at the University of Illinois at Urbana–Champaign for specific use on this ornithopter model. The airfoil data is not published.

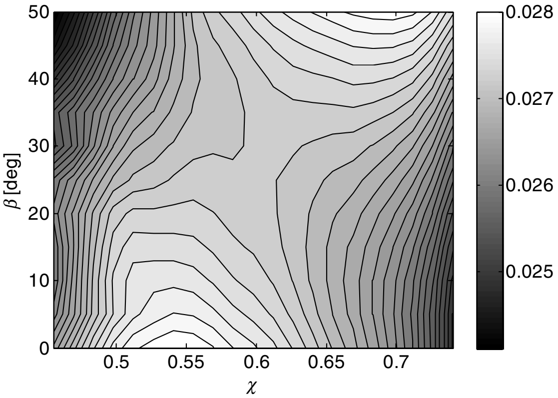

Fig. 5 Thrust coefficient vs the feathering parameter and folding magnitude.

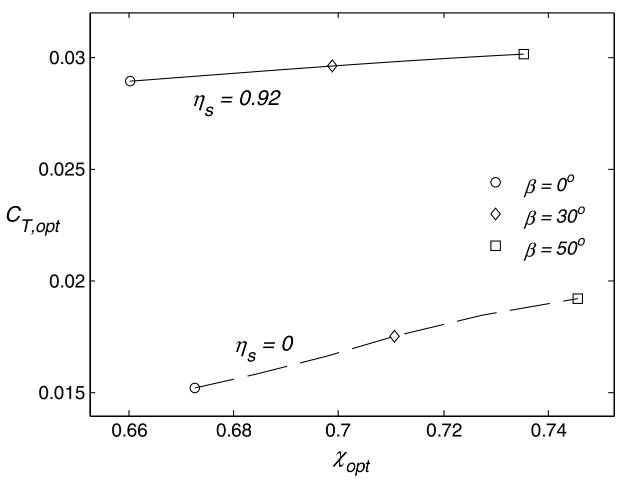

Fig. 6 Variation in thrust coefficient and χ_{opt} for different values of the β and η_s. The kinematics at each point are optimized for maximum thrust.

An initial sweep over β and χ reveals two distinct methods of producing thrust (Fig. 5): one with a small amount of wing twist and no folding, and the other with a larger feathering parameter and span reduction on the upstroke.

Figure 5 represents a single baseline configuration operating in two different flight modes, but it was found that both of these thrust peaks could be further improved by fine tuning the folding, bending, and twisting parameters in a way that was specific to each mode of flapping. Thus, a gradient-based optimizer was applied to the design variable set $[\varphi_\Gamma, \varphi_\Lambda, \tau_\Gamma, \tau_\Lambda, \delta_\Gamma, \delta_\Lambda, \theta_0, \theta_\varphi, \bar{\theta}_w, \alpha]$ so as to maximize thrust production for a given span-reduction magnitude β. Constraints were placed so that the required power and the integrated lift remained constant for all experiments. The optimization was repeated over a range of β values and for two different values of the leading-edge suction efficiency (Fig. 6).

The curves in Fig. 6, first, demonstrate the importance of having high leading-edge suction efficiency, and second, show that wing articulation can lead to increased thrust if the kinematics are properly optimized. The correlation between the increase in χ_{opt} and the increase in β reveals a tradeoff between two different mechanisms of thrust production. As upstroke span reduction is increased, the constraints on lift and power produce a corresponding decrease in the variation of the angle of attack. The overall effect is that, for the same input power, more thrust can be produced in the articulated flapping mode. For high leading-edge suction efficiencies the thrust increase is marginal considering the extra mechanical complexity required for an articulated wing, but at low leading-edge suction efficiencies the trend becomes much more prominent. This can be understood by referring to the drag polars shown in Fig. 4. A higher feathering parameter means less variation in the relative angle of attack and more time spent near the airfoil's design angle, which is important for wings with low leading-edge suction efficiency.

Conclusions

The tradeoff between two different methods of flapping-wing thrust production has been presented. In the first method the relative angle of attack is reduced on the upstroke, which results in off-design angles throughout much of the stroke. The second method involves both folding and bending the wing on the upstroke to achieve an effective reduction in the projected wing area. This second mode allows more efficient use of the airfoil because, for an equivalent amount of thrust, it can operate with a higher feathering parameter and therefore less variation in the angle of attack. This note does not make any presumptions about small-scale ornithopters with bound leading-edge vortices, but for medium to large-scale aircraft it verifies that, whenever possible, wings should be designed with high η_s airfoils. When high values of η_s can be achieved, wing articulation offers little benefit considering the added mechanical complexity, and large-scale ornithopter designers would be better off sticking with the spanwise rigid flapping mode. However, as the size of the ornithopter decreases, so does the ability to produce a leading-edge suction force; and wing articulation begins to offer a significant aerodynamic advantage. It is likely, then, that upstroke span reduction is a deliberate strategy used by birds and bats to improve the efficiency of thrust production given the limitations of their relatively thin airfoils. Thus, if it is desired to improve the efficiency of ornithopter flight within the size range of natural flyers, it may be advantageous to draw inspiration from nature's solution.

Acknowledgment

This work was supported through a Graduate Scholarship and Discovery Grant from the Natural Sciences and Engineering Research Council of Canada.

References

[1] DeLauier, J., "An Ornithopter Wing Design," *Canadian Aeronautics and Space Journal*, Vol. 40, No. 1, March 1994, pp. 10–18.

[2] DeLaurier, J., and Harris, J., "A Study of Mechanical Flapping-Wing Flight," *The Aeronautical Journal*, Vol. 97, No. 968, Oct. 1993, pp. 277–286.

[3] Rayner, J. M. V., "A Vortex Theory of Animal Flight. Part 2: The Forward Flight of Birds," *Journal of Fluid Mechanics*, Vol. 91, Pt. 4, 1979, pp. 697–763.

[4] Spedding, G. R., "The Wake of a Jackdaw (Corvus Monedula) in Slow Flight," *Journal of Experimental Biology*, Vol. 125, Sept. 1986, pp. 287–307.

[5] Spedding, G. R., "The Wake of a Kestral (Falco Tinnunculus) in Flapping Flight," *Journal of Experimental Biology*, Vol. 127, Jan. 1987, pp. 59–78.

[6] Spedding, G. R., "A Family of Vortex Wakes Generated by a Thrush Nightingale in Free Flight in a Wind Tunnel over its Entire Natural Range of Flight Speeds," *Journal of Experimental Biology*, Vol. 206, No. 14, 2003, pp. 2313–2344.

[7] Pivkin, I. V., Hueso, E., Weinstein, R., Laidlaw, D. H., Swartz, S., and Karniadakis, G. E., "Simulation and Visualization of Air Flow Around Bat Wings During Flight," *Lecture Notes in Computer Sciences*, Vol. 3515, 2005, pp. 689–694.

[8] Betteridge, D. S., and Archer, R. D., "A Study of the Mechanics of Flapping Wings," *Aeronautical Quarterly*, Vol. 25, May 1974, pp. 129–142.

[9] Archer, R. D., Sapuppo, J., and Betteridge, D. S., "Propulsion Characteristics of Flapping Wings," *The Aeronautical Journal*, Vol. 83, No. 825, Sept. 1979, pp. 355–371.

[10] Vest, M. S., and Katz, J., "Unsteady Aerodynamic Model of Flapping Wings," *AIAA Journal*, Vol. 34, No. 7, July 1996, pp. 1435–1440.

[11] Hall, K. C., Pigott, S. A., and Hall, S. R., "Power Requirements for Large-Amplitude Flapping Flight," *Journal of Aircraft*, Vol. 35, No. 3, 1998, pp. 352–361.

[12] Phlips, P. J., East, R. A., and Pratt, N. H., "An Unsteady Lifting Line Theory of Flapping Wings with Application to the Forward Flight of Birds," *Journal of Fluid Mechanics*, Vol. 112, Nov. 1981, pp. 97–125.

[13] DeLaurier, J. D., "An Aerodynamic Model for Flapping-Wing Flight,"

The Aeronautical Journal, Vol. 97, April 1993, pp. 125–130.

[14] Jones, R. T., "The Unsteady Lift of a Wing of Finite Aspect Ratio," NACA, Report No. 681, 1940.

[15] DeLaurier, J., "Drag of Wings with Cambered Aerofoils and Partial Leading-Edge Suction," *Journal of Aircraft*, Vol. 20, No. 10, Oct. 1983, pp. 882–886.

[16] Nudds, R. L., Taylor, G. K., and Thomas, A. L. R., "Tuning of Strouhal Number for High Propulsive Efficiency Accurately Predicts how Wingbeat Frequency and Stroke Amplitude Relate and Scale with Size and Flight Speed in Birds," *Proceedings of the Royal Society of London, Series B—Biological Sciences*, Vol. 271, No. 1552, Oct. 2004, pp. 2071–2076.