

Low-Reynolds-Number Airfoil Design for the M.I.T. Daedalus Prototype: A Case Study

Mark Drela*

Massachusetts Institute of Technology, Cambridge, Massachusetts

The rationale used for the aerodynamic wing design of the prototype long-range human-powered aircraft Light Eagle is presented. Three different airfoils, designed for chord Reynolds numbers of **500,000**, **375,000**, and **250,000** were used across the wingspan. The airfoil design rationale centered on minimizing the losses in the transitional separation bubbles typically occurring on airfoils at Reynolds numbers of less than 1 million. Structural and manufacturing constraints were also a consideration in the airfoil design, although to a lesser extent. Airfoil performance prediction during the design process was done entirely through numerical simulation. The numerical model employs the Euler equations to represent the inviscid flow, and an integral boundary-layer formulation to represent the viscous flow. Strong viscous-inviscid coupling and an amplification transition criterion included in the overall equation system permit calculation of transitional separation bubbles and their associated losses. Flow visualization tests performed on the Light Eagle at various lift coefficients in towed flight revealed transition occurring very near the intended position on the wing surface except within a few chords of the tip, where the flow appeared to be turbulent over most of the upper surface. Total drag aircraft polars obtained from the measured aircraft energy time history in glide contained too much scatter to be used as quantitative test data but did reproduce the basic trends of the calculations, including maximum lift coefficient levels.

Nomenclature

b	=wingspan
c	=airfoil chord
C_D	=profile drag coefficient, aircraft drag coefficient
C_L	=profile lift coefficient, aircraft lift coefficient
C_M	=profile pitching moment coefficient
C_f	=skin friction coefficient = $\frac{2\tau_{\text{wall}}}{\rho u_e^2}$
C_p	=pressure coefficient = $\frac{2(p-p_\infty)}{\rho u_\infty^2}$
H	=shape parameter = $\frac{\delta^*}{\theta}$
\tilde{n}	=exponent of most-amplified Tollmien-Schlichting wave amplitude
Re	=chord Reynolds number = $\frac{\rho u_\infty c}{\mu}$
Re_θ	=momentum thickness Reynolds number = $\frac{\rho u_e \theta}{\mu}$
u_e	=boundary-layer (BE) edge velocity
u_{inv}	=inviscid airfoil surface velocity (BL absent)
x, y	=chordwise, spanwise coordinates
α	=airfoil angle of attack
δ^*	=displacement thickness = $\int \left(1 - \frac{u}{u_e}\right) d\eta$
θ	=momentum thickness = $\int \frac{u}{u_e} \left(1 - \frac{u}{u_e}\right) d\eta$
ρ	=air density
μ	=air viscosity
τ	=shear stress
ξ, η	=boundary layer coordinates

I. Introduction

THE Light Eagle human-powered aircraft (HPA) shown in Fig. 1 currently holds the Federation Aeronautique Internationale (FAI) closed-course world distance record of 36.4 miles, established in 2 h 14 min on January 23, 1987. The Light Eagle was constructed in 1986 to serve as a prototype for the Daedalus aircraft, intended to recreate in 1988 the mythical flight of Daedalus from Crete to the mainland of Greece. The 69 mile over water distance and the rather high flight speed of 15 mph (constrained by the short duration of calm weather periods in the Aegean Sea) place extreme demands on the structural efficiency and the aerodynamic performance of the prototype aircraft. The long-duration power level available from a good athlete (about 3 W per kg of body weight) dictated an overall aircraft lift-to-drag ratio of 40:1 or better. This precluded the use of extensive external wire bracing common on low-power human-powered aircraft. Only a single lift wire was used as a concession to structural efficiency.

The extreme aspect ratio of the Light Eagle wing (39.4:1 in the final version), minimal fuselage pod and tail surfaces, and the lack of extensive external wire bracing, resulted in the wing profile drag contribution being 40% of the total drag. This placed high demands on the performance of the wing airfoil, the design of which was complicated by a myriad of structural and manufacturing constraints.

Airfoil flows on HPA's are well into the so-called low-Reynolds-number regime (less than 1 million), where airfoil performance is strongly influenced by transitional separation bubbles. These provide a mechanism for rapid transition at the beginning of an airfoil's pressure recovery region. If the bubble is kept small, its mixing losses can be kept down to reasonably low values, often less than those resulting from a mechanical transition device. The bubble also moves with angle of attack, giving a wider low-drag range than would be possible with a fixed transition strip. On the negative side, the losses in a relatively large bubble can result in dramatic airfoil drag increases. For these reasons, the control of transitional separation bubble position and size is one of the most important considerations in low-Reynolds-number airfoil design.

Separation bubble control on the Light Eagle airfoils was sought only via the surface-pressure distribution. Often, various artificial transition-inducing devices (roughness,

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*Assistant Professor, Department of Aeronautics and Astronautics. Member AIAA.