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Measured aerodynamic characteristics of wings at low Reynolds numbers

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ABSTRACT

An experimental program was conducted to study the low Reynolds number aerodynamics of ten wings having aspect ratios ranging from 2 to 5. In this low-to-moderate aspect ratio range, experimental data for use in validation of computational methods and design is lacking in the literature, yet this range spans that of many typical modern small-scale UAVs that operate in the 50,000 to 150,000 Reynolds number range. A custom three-component force balance for measuring lift, drag, and moment is described in detail and validated. Both straight and tapered wings were wind tunnel tested, and flow visualization was performed to characterize the flow. The measurements showed that all wings exhibited sensitivity to changes in aspect ratio and Reynolds number. Oswald's efficiency factors derived from the measurements ranged from a low value of 0.3 to more typical values near 0.8. Additionally, the aerodynamic performance trends relating to the maximum lift coefficient, lift curve slope, and aerodynamic center are computed from the measurements and discussed for the flat-plate wing models. Finally, no hysteresis in angle of attack was observed over the range of Reynolds numbers tested.

1. Introduction

With small-scaled unmanned aerial vehicle (UAV) design and development coming to the fore in the aerospace industry, there is a great need for accurate experimental data for the purposes of aerodynamic modeling and simulation of various UAV configurations. Small-scaled fixed-wing UAV platforms currently in service (e.g., Desert Hawk, Wasp III, Raven) operate primarily in the low Reynolds number regime ($Re \leq 300{,}000$).

As has been noted in literature, airfoils operating at low Reynolds numbers are primarily inhibited by the effect of the laminar separation bubble where an initially laminar boundary layer flow over an airfoil separates upon encountering an adverse pressure gradient, transitions to turbulent flow, and subsequently reattaches onto the airfoil surface. Carmichael [7] mentions in his low Reynolds number survey that there exists a range of Reynolds numbers ($70{,}000 \leq Re \leq 200{,}000$) where airfoil performance (primarily drag) is greatly affected by the formation of the laminar separation bubble, its size, and its hysteresis effects.

The performance of low Reynolds number airfoils is therefore strongly dependent on the magnitude of the drag rise attributable to the bubble. Two dimensional airfoil data [25,42–45] plays an essential role for wings of high aspect ratio ($A\!\!\!/R \geq 7$), as the local flow over the central section of these wings behave two dimensionally, and wing performance can be easily calculated by correcting for downwash effects (lifting line) with limited loss of accuracy.

For low aspect ratio wings ($A\!\!\!/R \leq 2$) however, the lifting-line concept becomes of limited value as the local flow around a wing section is no longer nominally two-dimensional. Numerous experimental results [9,14,18,24,29,30,35,46,47,51] have shown that low aspect ratio wing performance is affected by both linear and nonlinear sources of lift, and that the effect of the laminar separation bubble is attenuated by the re-energizing effect of wing-tip vortices. The linear source of lift is derived from the bound vortex flow. The nonlinear source of lift can be explained by applying Polhamus' leading-edge suction analogy [37,38] to the side edges of wings [20,21]. The strong wing-tip vortices of low aspect ratio wings create low pressure peaks inboard of the side edges thereby yielding increasing nonlinear lift with growing tip vortex strength. For the past two decades, significant inroads have been made into the development of 6–12 in (15–30 cm) wingspan Micro Air Vehicles (MAVs) of low aspect ratio [1–3,11,12,15,16,23,28,31,32,48].

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Nomenclature

AR	aspect ratio
b	wingspan
$\bar{c}$	mean aerodynamic chord
C_D	wing drag coefficient $(= D/\frac{1}{2}\rho V_\infty^2 S_{ref})$
C_d	airfoil drag coefficient $(= D/\frac{1}{2}\rho V_\infty^2 \bar{c})$
$C_{D_{min}}$	wing minimum drag coefficient
C_L	wing lift coefficient $(= L/\frac{1}{2}\rho V_\infty^2 S_{ref})$
C_l	airfoil lift coefficient
C_{L_α}	wing lift curve slope
C_{l_α}	airfoil lift curve slope
$C_{M_{c/4}}$	wing moment coefficient at quarter chord $(= M/\frac{1}{2}\rho V_\infty^2 S_{ref}\bar{c})$
$C_{m_{c/4}}$	airfoil moment coefficient at quarter chord
C_{M_α}	wing moment curve slope
D	wing drag
e_0	Oswald's efficiency factor
k	constant of proportionality giving the rate of increase of C_d with $C_l{}^2$
L	wing lift
LE	leading edge
M	wing moment at quarter chord
Re	Reynolds number based on mean aerodynamic chord $(= V_\infty \bar{c}/\nu)$
S_{ref}	wing reference area
TE	trailing edge
V_∞	freestream velocity
$\bar{x}_{ac}$	normalized location of the aerodynamic center from the leading edge of the mean aerodynamic chord
α	wing angle of attack
$\alpha_{C_{Lmax}}$	wing stall angle of attack
δ	induced drag factor
λ	taper ratio
ν	kinematic viscosity
ρ	density of air

Subscripts

ac	aerodynamic center
$c/4$	quarter-chord

Despite this, the payload capacity and endurance of MAVs have not reached levels that are practical for use [36].

The current level of technology though has produced a plethora of small UAVs (man-portable UAVs, hand launch UAVs) that are in service both in military and civilian environments. The wings and tail surfaces of most of these UAVs fall into the low-to-moderate aspect ratio category ($2 \le \mathit{AR} \le 6$). In this aspect ratio range where finite wing effects still play a large effect for low Reynolds numbers, the reliance on two-dimensional experimental data would be insufficient. Limited experimental data however is available in literature [6,18,27,33,35,47,49]. In addition, there have yet to be detailed experimental results that relate the variation of aspect ratio, taper ratio, and Reynolds number for low-to-moderate aspect ratio wings in the critical 70,000 to 200,000 Reynolds number range.

In a bid to supplement the limited data currently available for low-to-moderate aspect ratio wings at low Reynolds numbers, ten flat-plate wings of varying aspect ratio ($\mathit{AR} = 2$, 3, 4, and 5) and taper ratios ($\lambda = 0.5$, 0.75, and 1) were tested using a custom-designed and fabricated low speed external platform balance over a range of Reynolds numbers between 60,000 and 160,000. General observations from the wind tunnel results are presented together with specific trends related to the maximum lift coefficient, lift curve slope, aerodynamic center, and Oswald's efficiency factor of the models tested.

This paper is arranged as follows. A detailed description of the wind tunnel test models is first given. A detailed summary of the experimental setup and force-balance validation is then described. Finally, typical wind tunnel results and overall aerodynamic trends obtained for all wings tested are presented and discussed, and conclusions realized.

2. Experimental methods

2.1. Models tested

A total of ten flat-plate straight wings were tested. As detailed in Ananda [4], flat plates were chosen for testing as they serve as a good baseline to observe and interpret the effects of Reynolds number, aspect ratio, and taper ratio variation. In addition, the wing aspect ratios and Reynolds numbers tested are also typical for small-scaled UAV wings and tail surfaces.

The models were rapid prototyped using stereolithography (SLA) to tolerances of approximately ±0.005 in (±0.13 mm) ensuring model accuracy and surface quality. A mean aerodynamic chord length ($\bar{c}$) of 3.5 in (88.9 mm) was chosen for all wings. In addition, the model span fraction of all the wings tested was less than 0.8. The model span fraction is the ratio of the wing span to the width of the test section along the length of the wing. According to Refs. [5] and [34], a model span fraction that is less than 0.8 is desirable in order for standard wind tunnel corrections to apply. Further, the wind tunnel facility used for testing (discussed in Section 2.2) has an increasing cross-section to account for boundary layer growth.

A flat-plate wing with an aspect ratio (AR) of 3, taper ratio (λ) of 1, and zero sweep was chosen as a benchmark for the flat-plate measurements. The rectangular flat-plate AR-3 wing was designed to be directly compared with the wings that were tested by Pelletier and Mueller [35] and Shields and Mohseni [47]. Owing to structural considerations, the thickness-to-chord ratio of the flat-plate model tested was 4.3% in comparison with 2.6% used in Refs. [35] and [47]. The 4.3% thickness-to-chord translated to a wing thickness of 0.15 in (3.81 mm). The flat-plate model was also designed to have a 10-to-1 elliptical trailing edge thickness ratio in comparison with the 5-to-1 ratio used by Refs. [35] and [47]. Therefore, as shown in Fig. 1(a), the flat-plate airfoil has a 5-to-1 elliptical leading edge thickness ratio (semi-major axis of 0.375 in) and a 10-to-1 elliptical trailing edge thickness ratio (semi-major axis of 0.75 in).

In addition to the rectangular flat-plate AR-3 wing, nine more flat-plate wings with varying geometry were tested as defined in Table 1. All the models tested were manufactured to the same airfoil configuration as that of the rectangular flat-plate AR-3 wing. Also, variations in the taper ratio for all wings were done about the quarter chord line, which was straight. An annotated illustration of the airfoil and the ten planforms tested is shown in Figs. 1(a, b) respectively.

2.2. Facility

The experiments were conducted in the low turbulence subsonic wind tunnel in the Aerodynamics Research Laboratory at the University of Illinois at Urbana–Champaign (UIUC). The wind tunnel is an open-return tunnel with a rectangular test section