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Effect of Endplates on Two-Dimensional Airfoil Testing at Low Reynolds Number

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The presence of endplates (or sideplates) in two-dimensional wind-tunnel force measurements on airfoils has a strong effect on lift and drag coefficients at low Reynolds numbers. Results on an Eppler 61 airfoil indicate that the endplates are responsible for a sharp decrease in the airfoil performance. The lift coefficient is reduced and the drag coefficient is increased due to the interaction of the airfoil boundary layer with the sideplate boundary layer.

Nomenclature

b = span
C_d = section profile drag coefficient
C_l = section lift coefficient
c = chord length
e_Q = quantization error
M = resolution of A/D converter
Re_c = chord Reynolds number
Re_x = Reynolds number based on distance x along endplate
U_∞ = freestream velocity
x = distance from leading edge of endplate
α = angle of attack
δ = boundary-layer thickness

Introduction

RECENTLY, the need for small micro air vehicles (MAVs) has surfaced. These MAVs would have a wing span of no more than 6 in. (15.2 cm) and weigh only a few ounces ($\approx$100–200 g) (Ref. 1). They could be used as reconnaissance vehicles and carry visual, acoustic, chemical, or biological sensors. They should be able to fly for from 20 min to 2 h at a maximum speed of up to 30 mph (50 km/h). For these vehicles, root-chord Reynolds numbers ranging from about 2×10^4 to about 2×10^5 are of interest. Aerodynamic characteristics of low-aspect-ratio wings at low Reynolds numbers are presented in Ref. 2. In those tests, semispan models were used where one endplate was inserted in the test section. Two endplates were used for some two-dimensional tests to determine the airfoil characteristics. The problem with using endplates at low Reynolds numbers is the thickness of the boundary layer growing on the endplate. For all experiments conducted in this study, Reynolds number Re_x was always less than 5×10^5, which means the boundary layer was always laminar. The laminar boundary-layer thickness can be approximated by the Blasius solution (see Ref. 3) and is given by

$$\delta = 5x\Big/\sqrt{Re_x} \tag{1}$$

The distance between the leading edge of the endplates used and the wing leading edge varied between 11.5 in. (29.2 cm) ($Re_x \approx 8.6 \times 10^4$) and 10.5 in. (26.7 cm) ($Re_x \approx 7.9 \times 10^4$). The models tested[2] had a chord length of either 4 in. (10.2 cm) or 8 in. (20.3 cm). For a wing-chord Reynolds number of 6×10^4, based on $c = 8$ in., this implies a freestream velocity of $U_\infty = 4.58$ m/s. The boundary-layer thickness at $x = 10.5$ in. is $\delta = 0.19$ in. (0.5 cm). This can be a serious problem for short-span models because the interaction between the boundary layer growing on the endplates and the wing creates a corner flow, as depicted in Fig. 1, which acts over a significant portion of the wingspan and significantly alters the two dimensionality of the flow over the wing. This phenomenon of the corner flow has been investigated by several authors, including Hawthorne[4] and Barber,[5] who looked at the flow around struts near a wall. Barber indicated that the corner flow could be a horseshoe vortex or a zone of separated flow. Also, if transition from laminar to turbulent flow occurs, it most likely would occur first in the corner flow regions.

It has been shown in previous experiments at the University of Notre Dame that the presence of the endplates during two-dimensional tests usually leads to a larger $C_{d_{\min}}$. For an 18% thick airfoil (NACA 66_3–018), Mueller and Jansen[6] showed that the interaction between the endplates and the model resulted in a 20% increase in $C_{d_{\min}}$ at Reynolds numbers between 6×10^4 and 2×10^5. It was then decided to study the effect of the endplates on the aerodynamic characteristics of thinner airfoils at low Reynolds numbers.

Apparatus

Wind Tunnel

Tests presented in this paper were conducted in a low-speed, low-turbulence wind tunnel at the University of Notre Dame. The tunnel had a 2 × 2 ft (61 × 61 cm) test section. The freestream turbulence intensity was approximately 0.05% over the range of interest.

Thin aluminum endplates were mounted in the test section. The bottom plate could be removed to conduct three-dimensional tests on models of different semispan aspect ratios. All wings tested were held at the quarter-chord point, and the sting was covered by a streamlined sting covering. The gaps between the wing and the endplates were adjusted to approximately 0.03 in. (0.08 mm). Mueller and Burns[7] showed that gap sizes varying between 0.1 and 1.4 mm are usually acceptable and do not affect the results. Moreover, Rae and Pope[8] suggest that the gap be less than 0.005 × span. For a 12-in. (30.5-cm) span model, this corresponds to a maximum gap size of 0.06 in. (1.5 mm), which is larger than the gap used in the current investigation.

Force Balance

All results presented in this paper were obtained with a three-component platform aerodynamic balance. This balance can measure lift, drag, and pitching moment about the vertical axis using strain gauges mounted in full Wheatstone bridges. The balance is an external balance placed on top of the test section. A complete balance description and performance characteristics is presented in Ref. 9. Figure 2 shows a schematic of the balance setup in the test section.

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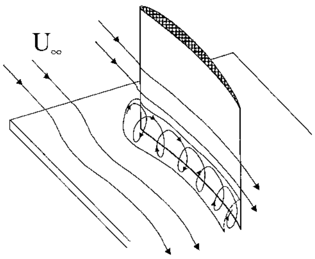


Fig. 1 Schematic of corner flow on wing.

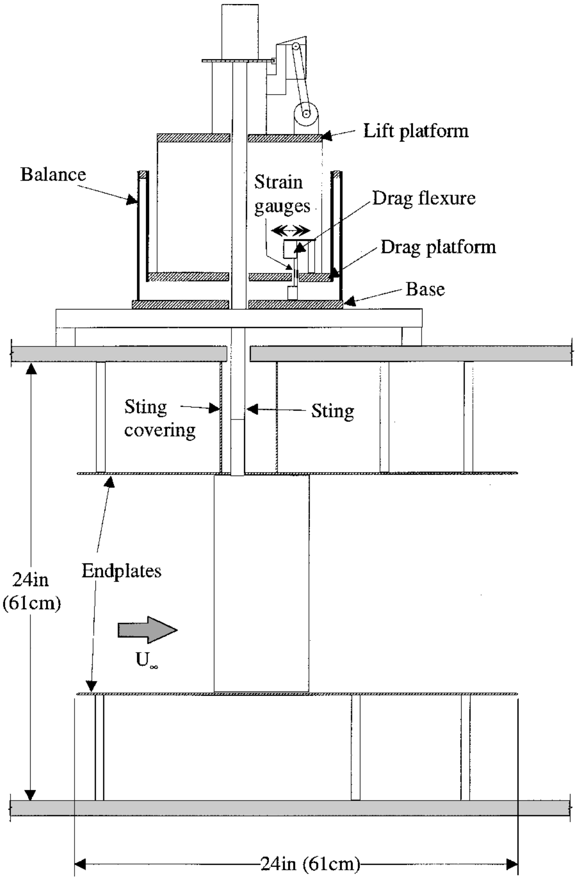


Fig. 2 Balance arrangement in the test section.

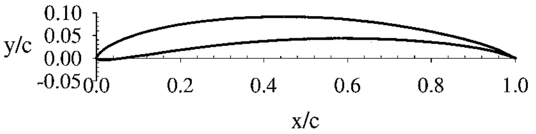


Fig. 3 Eppler 61 airfoil profile.

Models

For this investigation, the Eppler 61 airfoil geometry was selected over the thin flat-plate and thin cambered-plate wings used in Ref. 2 for reasons explained later. The Eppler 61 airfoil was originally developed for model airplanes with a chord Reynolds numbers of about 8×10^4 and has a thickness of 5.63 and 6.3% camber. Figure 3 shows the airfoil geometry of the Eppler 61 airfoil. The coordinates of this airfoil are given in Refs. 10 and 11. A model with a chord $c = 4.906$ in. (12.5 cm) and a span $b = 12$ in. (30.5 cm) was tested between two endplates to determine the two-dimensional lift and drag coefficients.

To verify the effect of the endplates on the aerodynamic characteristics of the Eppler 61 airfoil, a three-piece Eppler 61 model, shown in Fig. 4, was also used. This arrangement eliminated the endplate boundary-layer interactions with the airfoil. With this setup, a section of an Eppler 61 model was free to move between two other sections of the same airfoil. These two other sections were fixed to the endplates in the wind tunnel at the same angle of attack as the middle section. A small gap (approximately 0.0315 inches or 0.8 mm) was present between the end pieces and the center piece connected to the force balance. The thickness of the Eppler 61 profile was large enough to fit a small sting [diameter = 0.16 in. (4 mm)] through the upper piece. This would not have been possible with the models used in Ref. 2 due to the small thickness of the models (a thickness to chord ratio of close to 2%). Figure 5 shows schematics of the two test section configurations used.

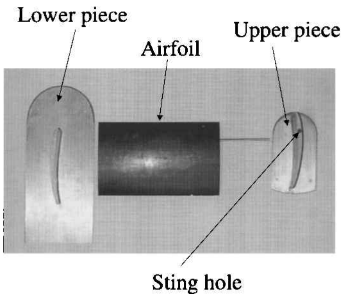
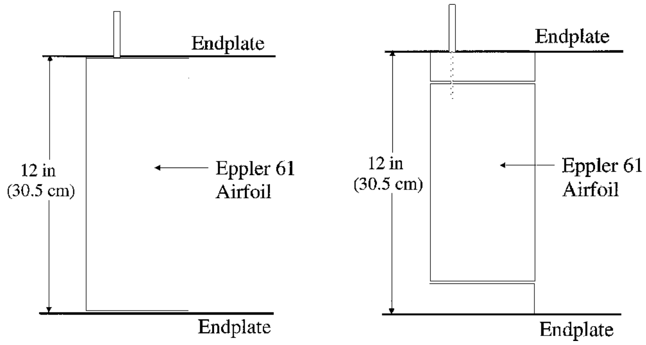


Fig. 4 Three-piece Eppler 61 airfoil model tested in wind tunnel.



Full model **Three-piece model**

Fig. 5 Eppler 61 airfoil test section configurations.

Data Acquisition System

Signals from the force balance strain gauges were measured with very sensitive instrumentation. An excitation voltage of 5 V was used for all of the strain gauge bridges. The bridge signals were read with an instrumentation amplifier circuit, with available gains from 1 to 8000. The amplified analog signals were sent to the computer where they were then converted using a four channel, 12-bit A/D converter. Four data channels (lift, drag, moment, and dynamic pressure) could be measured quasi simultaneously. All of the data were acquired using a personal-computer-based data acquisition system running the LABVIEW® 5 graphical programming language.

Discussion of Results

Throughout the tests, the aerodynamic force coefficients were obtained by averaging 4000 samples acquired at a frequency of 500 Hz. Moreover, all results presented in this paper have been corrected for solid blockage, wake blockage, and streamline curvature using techniques presented by Pankhurst and Holder[12] and Rae and Pope.[8] Because of the small thickness, volume, and angles of attack of the models tested, blockage was less than 8%, which leads to small blockage effects.

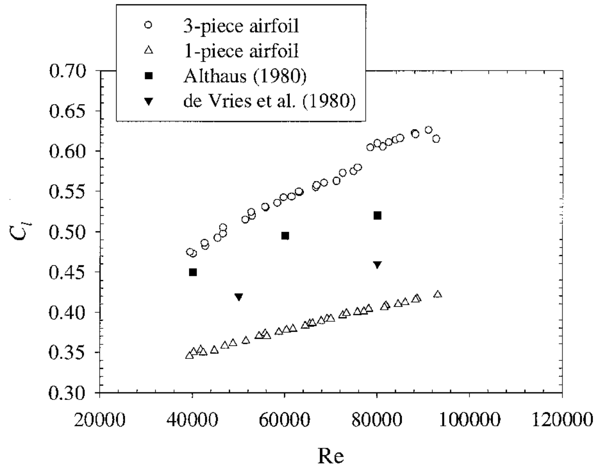
Uncertainty

Uncertainties in the two-dimensional measurements were determined using the Kline–McClintock technique[13] for error propagation. The quantization error and the uncertainty arising from the standard deviation of a given mean output voltage from the strain gauges of the force balance were the main sources of uncertainty. The quantization error is $e_Q = \frac{1}{2}$(range of volts/2^M). Optimizing the range of the output voltages can help to reduce the uncertainties. When the gain is increased, the standard deviation of the mean is also increased, whereas the ratio of the standard deviation to the mean basically remains the same. However, the uncertainty from the quantization error is reduced because the quantization error is a fixed value (a function of the range and the resolution of the A/D converter). The ratio of the quantization error to the mean voltage is then smaller if a larger gain is used and a larger balance output mean voltage is obtained.

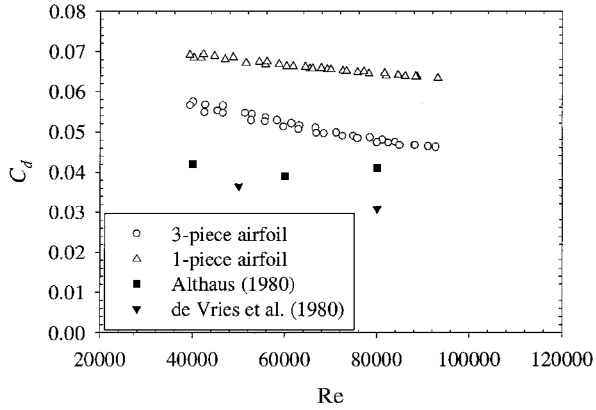
The uncertainty in the angle of attack was determined to be on the order of 0.2–0.3 deg, and the uncertainties in C_l and C_d were about 6%.

Effect of Endplates on Two-Dimensional Measurements

With the current setup in the wind tunnel, it was not possible to change the angle of attack of the end pieces without stopping the wind tunnel. Therefore, obtaining C_l and C_d as a function of angle of attack was difficult. It was then decided to fix the angle of attack and sweep through different values of Reynolds number. Reynolds numbers were first increased and then decreased to look for hysteresis. No hysteresis was observed in the results. From previous two-dimensional results[9] on the Eppler 61 airfoil, it was determined that $C_{d_{\min}}$ occurred at $\alpha = 0$ deg, and the angle for zero lift was about $\alpha = -2$ deg. The behavior of C_d vs Reynolds number Re_c was then obtained at these two angles of attack. Figures 6 and 7 show that the drag coefficient with the three-piece Eppler 61 model was much smaller than with the full model. This behavior is similar to that reported by Mueller and Jansen[6] for the NACA 66_3–018 airfoil. The lift coefficient with the three-piece model was higher than with the full model. The aerodynamic characteristics with the three-piece model were believed to be closer to true two-dimensional results because of the larger C_l and smaller C_d, as would normally be expected. The behavior of C_l and C_d with Reynolds numbers also followed the expected trends. A reduction in C_d and an increase in C_l were observed with increasing Reynolds numbers. Results from Althaus[10] and de Vries et al.[14] are also included in Figs. 6 and 7 for comparison. These investigators used a strain gauge force balance to measure lift and a wake rake to measure drag. Because the drag measured with a wake rake is usually obtained at the midspan of the model, it does not take end effects, or three-dimensional effects, into account. These end effects can be significant at very low Reynolds numbers. Therefore, drag coefficient results from Althaus[10] and de Vries et al.[14] were expected to be smaller than the present results, and this trend was observed. Moreover, the slopes of the C_d vs Reynolds number Re curves at $\alpha = 0$ deg follow the same trends as the laminar Blasius solution for drag over a flat plate. However, as expected, the magnitude of the values are approximately five times larger due to thickness, camber, and so forth.

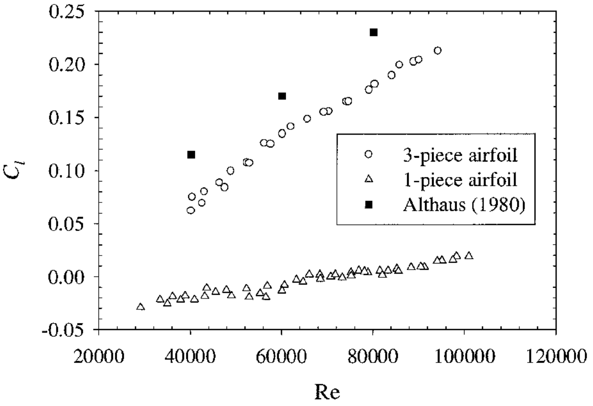


Lift coefficient

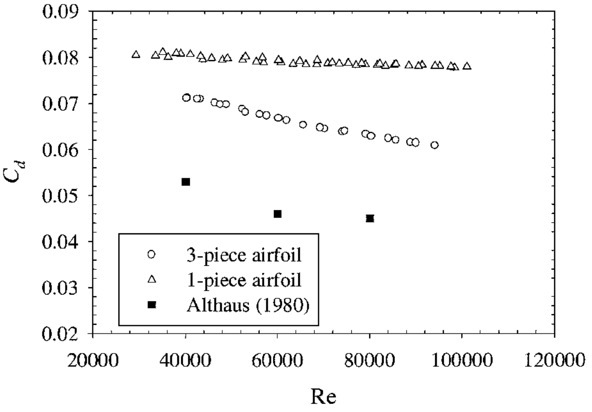


Drag coefficient

Fig. 6 Endplates effect on two-dimensional characteristics of Eppler 61 airfoil at $\alpha = 0$ deg.



Lift coefficient



Drag coefficient

Fig. 7 Endplates effect on two-dimensional characteristics of Eppler 61 airfoil at $\alpha = -2$ deg.

Selig et al.[15] also encountered the effect of endplates at low Reynolds numbers by measuring drag at different spanwise locations behind an airfoil using a wake rake and the momentum technique. For low Reynolds numbers ($Re_c = 6 \times 10^4$ and 1×10^5), they showed a large variation in C_d with spanwise location. At $Re_c = 2 \times 10^5$ and especially at $Re_c = 3 \times 10^5$, drag was relatively constant along the span, and a nearly two-dimensional flow was believed to exist. This serves to emphasize the effect on endplates on two-dimensional testing at Reynolds numbers below 1×10^5.

Tests were not conducted at large angles of attack, for instance at the angle for maximum lift-to-drag ratio ($\alpha = 8$ deg) (Ref. 2) because of the large deflection of the middle piece of the three-piece model. The sting holding the middle piece had to be very small to fit through the upper end piece of the model, which led to a weak sting easily bent at large angles of attack due to the large forces acting on the model. At low angles of attack, the deflection was very small.

Conclusions

It has been shown that the presence of endplates for two-dimensional aerodynamic testing at low Reynolds numbers can lead to errors in C_d and C_l. The presence of a corner flow and boundary layers growing on the endplates leads to a reduction in lift and an increase in drag. Therefore, three-dimensional effects are significant for the two-dimensional testing of airfoils at very low Reynolds numbers.

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