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

\[ b = \text{span} \]
\[ C_d = \text{section profile drag coefficient} \]
\[ C_l = \text{section lift coefficient} \]
\[ c = \text{chord length} \]
\[ e_o = \text{quantization error} \]
\[ M = \text{resolution of A/D converter} \]
\[ Re = \text{chord Reynolds number} \]
\[ Re = \text{Reynolds number based on distance \( x \) along endplate} \]
\[ U_\infty = \text{freestream velocity} \]
\[ x = \text{distance from leading edge of endplate} \]
\[ \alpha = \text{angle of attack} \]
\[ \delta = \text{boundary-layer thickness} \]

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 \( 2 \times 10^5 \) to about \( 2 \times 10^7 \) 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 \( Re \) was always less than \( 5 \times 10^5 \), 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

\[ \delta = \frac{5x}{\sqrt{Re}} \]  

(1)

The distance between the leading edge of the endplates used and the wing leading edge varied between 11.5 in. (29.2 cm) \((Re_e \approx 8.6 \times 10^4)\) and 10.5 in. (26.7 cm) \((Re_e \approx 7.9 \times 10^4)\). The models tested had a chord length of either 4 in. (10.2 cm) or 8 in. (20.3 cm). For a wing-chord Reynolds number of \( 6 \times 10^5 \), 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 and Barber, 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 \( C_{\text{diss}} \). For an 18% thick airfoil (NACA 6618018), Mueller and Jansen showed that the interaction between the endplates and the model resulted in a 20% increase in \( C_{\text{diss}} \) at Reynolds numbers between \( 6 \times 10^5 \) and \( 2 \times 10^7 \). 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 x 2 ft (61 x 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 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 suggest that the gap be less than 0.005 in. 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.
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 $8 \times 10^4$ 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.

### 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 Holder12 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 technique13 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 $e_Q = \frac{\text{range of volts}}{2^M}$. 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 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 $Re$ 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 for the NACA 66–018 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

Conclusions

It has been shown that the presence of endplates for two-dimensional aerodynamic testing at low Reynolds numbers can lead to errors in $C_l$ and $C_d$. 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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**References**