STUDY OF WINGTIP VORTEX CHARACTERISTICS IN THE FAR-FIELD OF A NACA 0015 AIRFOIL

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Abstract

A study of wingtip vortices is currently underway in Utah State University's 4-ft. x 4-ft. subsonic wind tunnel on a NACA 0015 rectangular wing section. The purpose of this study is to investigate the characteristics of the flow field, which govern the size, the structure, and the oscillatory motion of the vortex core. These characteristics can be obtained by collecting and analyzing accurate velocity measurements at several locations downstream of the wingtip for different Reynolds numbers and angles-of-attack. One triple-sensor and two single-sensor hot wire probes are used to collect the data. The axial velocity profiles generated from the data will help determine how the Reynolds number and angle-of-attack modifies the structure of the vortex core and the conditions that cause it to transition from a "wake-like" to a "jet-like" profile. In addition, the tangential velocity profiles will help determine the effects Reynolds number and angle-of-attack have on the size and strength of the vortex core. In addition, a database of vortex characteristics for varying experimental parameters will be established that will help identify consistent trends in vortex behavior and lead to a better understanding of the governing physics. This database will be used by colleagues to validate and improve their computational algorithms.

Nomenclature

c = wing cord length [in.]
Re_c = Reynolds number based on cord length $= U_\infty c / \nu$
U_x = axial velocity [ft/s]
U_∞ = freestream velocity [ft/s]
x = axial (streamwise) coordinate [in.]
y = spanwise coordinate (along the wing) [in.]
z = normal coordinate (normal to the wing) [in.]
α = angle-of-attack [degrees]
θ = tangential coordinate
U_θ = tangential velocity [ft/s]

Introduction

The development of a wingtip vortex occurs any time a lifting surface, or wing, terminates in a fluid. The formation of this vortex can be understood if one considers the pressure field that exists near the wing tip. As a wing moves through a fluid, lift is generated when a low pressure field is hydrodynamically produced on the top surface or suction side of the wing and a relatively higher pressure field is produced on the bottom surface or pressure side of the wing. This large pressure difference between the two sides of the wing causes the fluid to accelerate around the tip of the wing from pressure side to suction side, thus forming a vortex. This vortex trails from the wingtip and remains relatively strong for many chord lengths downstream.

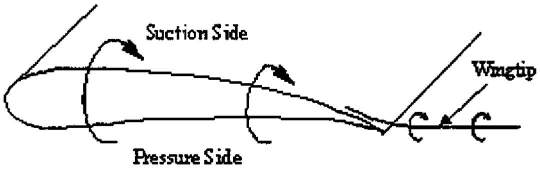

Figure 1: Wingtip vortex interpretation due to a pressure field around the wing.

The characteristics, which determine the behavior of wingtip vortices, have been the subject of numerous experimental and numerical studies. The popularity of such studies has primarily been driven by the important effects vortices have on practical problems such as: separation distances between landing aircraft, the interactions between shed vortices and following helicopter rotor blades, and vibrational noise caused by propeller cavitation on ships. A general goal of these studies is to reduce the hazardous effects trailing vortices have on following lifting surfaces. Despite the numerous studies performed to date, the exact nature of trailing vortices is not well known. A more detailed understanding of the strength of a vortex and the mechanisms, which encourage its dissipation in the far field, or several chord lengths behind the lifting body, will help make progress towards this goal.

Literature Review

A review of published papers on the subject of wingtip vortices reveals a plethora of experimental and numerical data on several specific areas of vortex behavior. Two of these areas, in particular, warrant further investigation do to their incomplete or conflicting results, and are of primary interest to this thesis research. These two areas are the vortex velocity profile and the oscillatory wandering motion. This section will present a brief review of the published papers, which discuss these two areas of interest.

Vortex Velocity Characteristics

The foundation of our current understanding of wingtip vortex behavior stems predominately from experimentally collected velocity data. These measurements are made at discrete locations within the vortex flow field with the use of such tools as hot wire anemometers, particle image velocimeters, laser Doppler velocimeters, and pressure probes. The vortex is typically described by two velocity components U_x and U_θ, where x and θ are the streamwise and tangential directions respectively. Plots of the variation of these velocity components at a specific downstream location of the wingtip provide the basis of comparison between different experimental studies

Due to widely varying experimental conditions, significant differences in the axial and tangential velocity profiles makes it difficult to define what might be called a "typical" wingtip vortex. The axial velocity profile seems to be the main source of inconsistencies between studies. For example, Dacles-Mariani et al. (1995)[3] performed a numerical and experimental study of a wingtip vortex generated from a rectangular NACA 0012 rectangular wing with an aspect ratio of 0.75. The airfoil was positioned at 10 degrees angle-of-attack while measurements were taken at approximately 0.16, 0.25, 0.45, and 0.67 chord lengths downstream. Data from each of these locations produced a "jet-like" velocity profile where the magnitude of the maximum axial velocity was approximately $1.7U_{inf}$ decaying only slightly from the wingtip to 0.67 chords.

A similar study using a NACA 0012 rectangular wing was performed by Devenport et al. (1996)[4]. Their results show that the axial velocity data produce a "wake-like" profile where the maximum core velocity is less than the free stream velocity. In addition, the magnitude of the maximum velocity deficit changed very little from 5 to 30 chord lengths downstream. It is likely that the varying results produced by the studies of Dacles-Mariani et al.[3] and Devenport et al.[4] is due to the difference in their test parameters. Dacles-Mariani et al.[3] and Devenport et al.[4] used a Reynolds number of 4.6×10^6 and 5.3×10^5, an aspect ratio of 0.75 and 4.33, an angle of attack of 10 and 5 degrees, and a test location in chord lengths downstream of the wingtip of <0.67 and > 5.0, respectively. Furthermore, their data acquisition methods were different in that Dacles-Mariani et al.[3] used a 7-hole pressure probe and Devenport et al.[4] used a 4-sensor hot wire probe. Which of these parameters, or perhaps which combinations of these parameters, produce a "jet-like" vs. "wake-like" profile is not exactly clear.

Two separate studies by Chigier and Corsiglia (1972)[1] and McAlister and Takahashi (1991)[7] show a valuable correlation between the angle-of-attack of the wing and the maximum axial velocity. Both studies indicate that the "wake-like" profile transitions to a "jet-like" profile as the angle-of-attack increases between 4 and 12 degrees. The results of Chigier and Corsiglia[1] were for measurements taken 9 chord lengths behind the wingtip at 4, 8, and 12 degrees angle-of-attack. Interpolation of these results shows that a "wake-like" profile is generated for angles-of-attack less than 9 degrees and a "jet-like" profile for angles-of-attack greater than 9 degrees. Similarly, McAlister and Takahashi[7] show that transition occurs at approximately 8 degrees angle-of-attack at for a distance of 4 chord lengths downstream. However, neither study provides data for more than two locations downstream of the wingtip, which makes it impossible to conclude that the maximum axial velocity is only a function of angle-of-attack. In fact, Green (1995)[6] suggests that the axial velocity is strongly dependent on the Reynolds number, but admits that no one has yet given adequate evidence supporting this relationship. At this point, the difference between the results of Chigier and Corsiglia[1] and McAlister and Takahashi[7] is evidence that the maximum axial velocity might be a function of downstream location, Reynolds number, and possibly other test parameters.

Vortex Wander

Beginning as far back as 1957 investigators of wing tip vortices have encountered the problem of vortex meandering (Gasparek 1957[5]; Corsiglia, Schwind, & Chigier 1973[2]; Green 1995[6]). This problem is characterized by some mode of oscillation, which may or may not be periodic. This oscillatory motion causes a smearing of the time averaged velocity measurements collected using a fixed hot-wire probe. Spalart (1998)[8] suggests that the effects of this wandering motion cause artificial diffusion in the time-averaged vorticity. Until recently, most investigators attributed the wandering motion to tunnel unsteadiness and failed to correct for its effects on their data. Davenport et al.[4], however, proposed an analytical method that would correct the effects of vortex wander on collected velocity data.

Their solution involves predicting the absolute position of the vortex core using a probability density function (p.d.f.). Though this solution is the most extensive and complete solution to date, many feel that it does not adequately describe the true oscillatory motion of the vortex core. In fact, Spalart[8] points out that the oscillatory motion of the vortex is likely to be periodic giving the shape of a sine wave, which has a much different p.d.f. than the bell-shaped Gaussian distribution assumed by Devenport et al.[4]

Purpose

The main purpose of this study is to investigate the characteristics of a wingtip vortex generated from a NACA 0015 rectangular airfoil. Of primary interest are the characteristics of the flow field, which govern the size, the structures, and the oscillatory motion of the vortex core. These characteristics are obtained by collecting and analyzing accurate velocity measurements at several locations downstream of the wingtip for different Reynolds numbers and angles-of-attack. Then by comparing the tangential velocity profiles at each location, the size and strength of the vortex core can be calculated. Furthermore, the use of two single wire probes positioned in a plane just downstream of the triple wire probe will determine the magnitude of the expected wandering motion and provide a means for correcting this motion through conditional averaging of the velocity data. In addition to the tangential velocity profiles, the axial velocity profiles obtained at different downstream locations will be compared. The profiles at each location will show the effects of changing the Reynolds number and angle-of-attack on the maximum axial velocity in the center of the vortex core. These results will help determine if and when the vortex core transitions between the "wake-like" and the "jet-like" profile. Moreover, this comparison will show the effect of Reynolds number and angle-of-attack on the maximum axial velocity. In all, a database of vortex characteristics for varying experimental parameters will be established that will help identify consistent trends in vortex behavior and lead to a better understanding of the governing physics.

A secondary purpose of this study is to provide accurate and detailed information on the characteristics that govern vortex flow fields, which can be extended to the behavior of a vortex generated from a real airplane flying in the atmosphere. Because the unbounded conditions that apply to a vortex generated in the atmosphere are more easily simulated in the unbounded domain of a computer model than in a wind tunnel, the information collected in this study will be used to validate and improve current computational algorithms. This will be done by providing the database of vortex characteristics collected in this study to Dr. Spall at the USU CFD laboratory and to Dr. Spalart at the Boeing Aircraft Company.

Apparatus and Instrumentation

The current investigation of wing tip vortices is performed at Utah State University's 4-ft. x 4-ft. subsonic wind tunnel shown in *figure 2*. A 200-hp direct drive motor turns a four-blade prop that produces a maximum test section velocity of 115 mph. The flow inside the empty test section is nearly uniform with a turbulence intensity of less than 0.5%. Through the use of National Instrument's LabView software, the speed of the motor and the pitch of the propeller can be controlled from within the control room.

A NACA 0015 rectangular planform wing with a 30-inch chord and 24-inch span, shown in *figure 2*, is used to generate the vortex. This model has a solid foam core cut to shape using a hot wire and two ¼-inch thick aluminum templates. These templates and a 2½-inch diameter aluminum pipe located at the quarter-chord of the wing make up the structure of the model. Twelve layers of fiberglass composite and a painted finish protect the foam core. Twenty-five pressure ports, twelve on each side and one at the leading edge, are positioned mid-span on the surface of the model. These ports are used to determine the surface pressure on the suction and pressure sides of the wing.

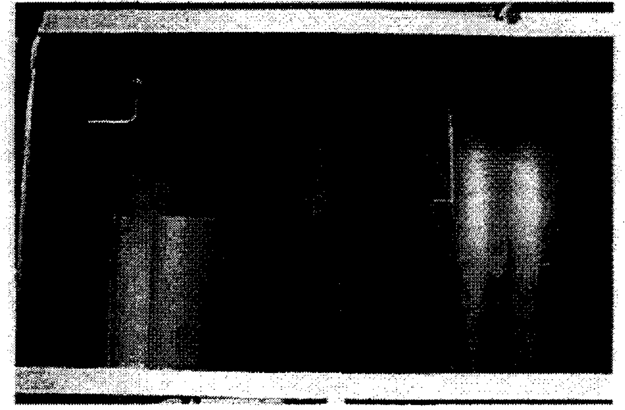

Figure 2: The position of the NACA 0015 rectangular wing in the 4-ft. x 4-ft. test section of USU's subsonic wind tunnel.

A triple-sensor hot wire probe fabricated by Auspex Corporation is used to resolve the three components of velocity at several locations downstream of the wingtip. The sensor configuration is capable of measuring a volume of approximately 0.5 mm^2. The triple-sensor probe is shown in *figure 3*. The sensors are connected to a data acquisition system made up of a fully automated two-axis traverse and a TSI IFA 300 five channel anemometer and Thermal Pro software package. This integrated system is used to calibrate the sensors, move the probe to discreet locations within the velocity field, and convert the voltage output signals from the sensors to velocity vector time series data.

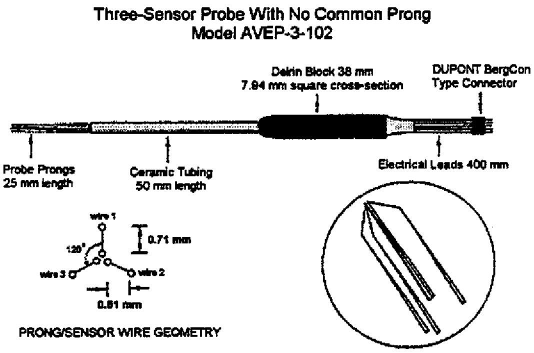

Figure 3: The triple-sensor probe and probe holder.

National Instruments Inc.'s LabView data acquisition software is used to control and monitor the tunnel parameters and ambient conditions. This system monitors electronic transducers that measure the ambient pressure and temperature conditions in real time while the probe is collecting velocity data. Furthermore, LabView is used to control the speed of the motor and the pitch of the propeller from within the control room. Integrating this system and the data acquisition system through a Micron Mellinia 266 MHz and 400 MHz computer gives one investigator complete control over the vortex study from within the control room.

Preliminary Results

The collection of velocity data for this study has just recently begun. At the present time, the traverse system of the wind tunnel is set up to take data at only one point, 0.5 chord lengths downstream of the wingtip. Even though this axial location is not defined in this study as being in the far-field, the velocity data can still give insight to the structure of the vortex that should persist further downstream. The data at this location was collected at a Reynolds number of 1.1 x 10^6 and at the angles-of-attack of 4, 5, 6, and 8 degrees.

Plots of the axial velocity profiles for 4, 6 and 8 degrees angle-of-attack are shown in *figure 4*. From these plots it can be seen that as the angle-of-attack increases the magnitude of the maximum axial velocity decreases. This indicates that the profiles become more "wake-like" at larger angles-of-attack. It is possible that the point of transition is at an angle-of-attack less than 4 degrees. This plot also shows that the vortex is moving inward with relation to the wing. This trend is consistent with almost all wingtip vortex studies.

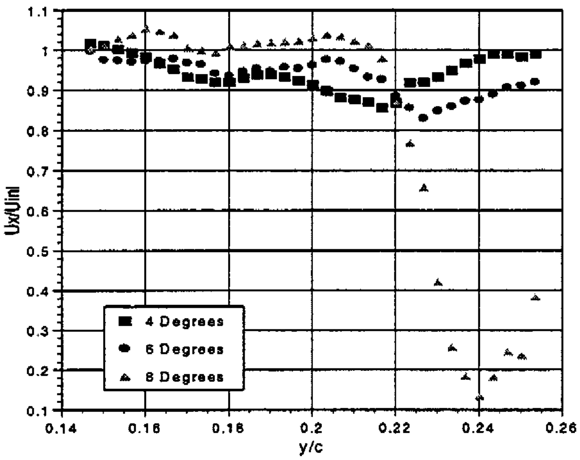

Figure 4: Axial velocity profiles for angles-of-attack of 4, 6, and 8 degrees.

The tangential velocity profiles shown in *figure 5* are for angles-of-attack of 4, 5 and 6 degrees. As the angle-of-attack increases the magnitude of the maximum tangential velocity also increases. This is evidence that the strength of the vortex is directly proportional to the angle-of-attack of the wing, or the strength of the circulation generated on the wing. The figure also shows that the core radius, defined by the location of maximum tangential velocity, does not increase significantly with angle-of-attack.

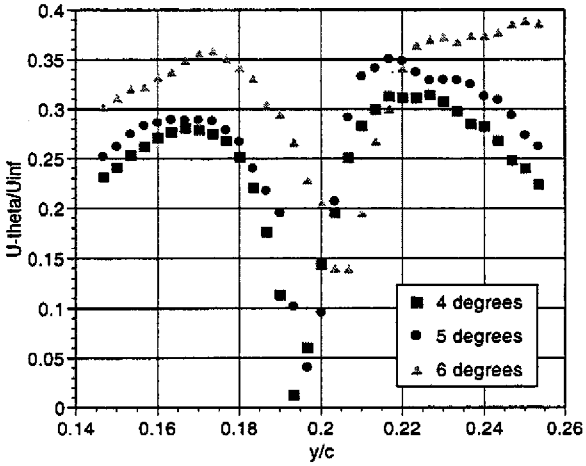

Figure 5: Tangential velocity profiles for angles-of-attack of 4, 5, and 6 degrees.

Future Work

This study will continue through the summer of 1999. During this time, velocity data will be collected at five locations downstream of the wingtip starting with one and ending with five chord lengths from the trailing edge. At each location, velocity measurements will be collected for angles-of-attack of $4^\circ \leq \alpha \leq 12^\circ$ and for Reynolds number of 1.0×10^6, 1.5×10^6, and 2.0×10^6. With this data, the axial and tangential velocity profiles at each downstream location and for different angles-of-attack and Reynolds numbers will be plotted. A comparison of the axial profiles with the varying parameters will help determine where and when the vortex core transitions from a "jet-like" to a "wake-like" profile given a specific downstream location, angle-of-attack, and Reynolds number. Similarly, the tangential velocity profiles can be compared to show how the size and strength of the vortex core changes with these parameters.

Because of the expected wandering motion of the core, two single-sensor probes will be placed in the flow near the edge of the vortex core downstream of the triple-sensor probe. These probes will provide a set of velocity data that corresponds to the data collected by the triple-sensor probe. This data will be analyzed using a conditional averaging technique that will provide the means of quantifying the wandering motion. The results of technique will correct the smearing effects on the data collected by the triple-sensor probe caused by the wandering motion

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