Development of the Vortex Structure in the Near Field of a NACA 0015 Airfoil

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Abstract

Current summary of research performed on a NACA 0015 airfoil in USU's low speed windtunnel. The structure and development of the vortex are to be analyzed in the near field region, extending from above the tip of the airfoil back to 1 chord length behind the trailing edge. Velocity data is collected using a triple sensor hot-wire anemometer, enabling the determination of the flow characteristics including mean flow rates, turbulence levels, and strain rates. This data is to be collected with various combinations of Reynolds number, angles of attack, and airfoil geometry. This will lead to a collection of data that will help further the understanding of how vortices are created and how the vortex is changed by the parameters listed above.

Symbols

c = chord length (30 in.)
Re = Reynolds number based on chord length $= \dfrac{U_{\text{inf}} * c}{\nu}$
U_{inf} = Freestream velocity inside windtunnel
v =velocity in the y – direction
V_θ = tangential velocity $= \sqrt{v^\wedge 2 + w^\wedge 2}$
w =velocity in the z - direction
y/c = dimensionless location along span of wing
z/c = dimensionless location perpendicular to span and chord of wing
ν = kinematic viscosity

Introduction

Vortices are shed when a lifting surface (wing) is placed in an air stream with a free end. Air from the high-pressure side of the wing rolls around the end to the suction side of the wing, thus introducing velocity components perpendicular to the main flow. After reaching the trailing edge of the wing, this structure continues to roll up into an coherent vortex, which can be quite strong and may last for 100's of chord lengths downstream.

In commercial aviation, these vortices are costly in two ways. First, they greatly increase the drag acting on a plane, increasing the amount of fuel required for air travel. Second, they can be strong enough to overpower the control ability of trailing planes, so the Federal Aviation Administration (FAA) has instituted guidelines on airplane following distances during takeoff and landing. These guidelines determine the capacity of an airport and ultimately affect the economics of the air transportation industry.

Background

There has been extensive research performed in the area of wingtip vortices, primarily in the far-field region. This has been done in an attempt to determine the decay rate of the vortex and to find ways to increase this rate. Less work has been completed in the near-field region, where the vortex first forms on the airfoil. In this region, the vortex is highly three dimensional with large velocity gradients that are difficult to measure accurately.

Dacles-Mariani et al. (1995)[1] performed a joint numerical/experimental study on a 10 degree angle of attack rectangular NACA 0012 airfoil (Re $= 4.6 * 10^6$) to investigate the near field behavior of the vortex. Their numerical and experimental results indicate that the beginnings of the vortex formation can be seen as early as the quarter chord, and by the time the vortex reaches the trailing edge the circulation is already at 87% of its greatest magnitude. They also indicate that within 2 chord lengths, the vortex has completely rolled up into an axi-symmetric structure.

This agrees with statements made by Sheldon Green (1995),[2] who reports that rollup of the vortex is essentially complete, regardless of wing geometry or Reynolds number, within 2-3 chord lengths, and with the experimental data from McAlister et al. (1991)[3], whose figures show rapid changes in the vortex measurements to approximately the same position downstream.

Ramaprian et al. (1997)[4] used a NACA 0012 airfoil with a three color LDV system to map the vortex in the near field, but lacked the ability to change airfoil geometries. Their results also indicate that the vortex rollup occurs much sooner for the same angle of attack than Dacles-Mariani, at 2/3 the chord length downstream. This experiment was performed at a much lower Reynolds number, $1.8*10^5$, and a square tip rather than the round tip used by Dacles-Mariani et al. Lacking more information, it is difficult to make a conclusion on which factor had the effect of making the vortex rollup that much quicker.

At an even lower Reynolds number, Shekarriz et al. (1993)[5] report that rather than one strong vortex, several smaller vortices are shed, and the rollup is not as evident. This experiment was performed on a submarine model in a water tunnel, at a Reynolds number ranging from $3.6*10^4$ to 2.2*105. Because this is a much lower than that typically found in the atmosphere, the difficulty of tracking several vortices will be avoided and focus will be concentrated on situations where rollup into a single vortex occurs rapidly.

McAlister et al[3], performed experiments using a NACA 0015 airfoil, using several models with different aspect ratios and end cap geometries. Their data, while very useful, only presents two components of velocity, a limitation placed on them by their use of a two-color laser-velocimeter. This data presents a clearer picture than what was previously available about the overall characteristics of the flow, but the lack of the third component of velocity makes it difficult to complete the picture.

These results show significant differences in the behavior and structure of the vortex, even when the same airfoil is used. These differences are most likely due to changes in Reynolds number or geometry, but the cause of the changes has not yet been analyzed.

Experimental Approach

The current investigation will further the understanding of vortex structure development, by investigating the changes in the vortex due to modifications of the Reynolds number, the angle of attack, and the geometry of the wing. A hot wire anemometer system will be used to measure all three components of velocity within the vortex. By doing so, a fuller picture will develop of the vortex structure, allowing for a greater understanding of mean flow rates, turbulence, and structure within the vortex. In addition, the results should provide an explanation for the cause of the discrepancies seen in previous experimental work.

Apparatus

To achieve the goals of this research, USU's low speed wind tunnel is being used. This open loop tunnel has a 4 foot square test section, with a 9:1 contraction ratio inlet. The mean flow rate is provided by a 200 horsepower AC motor attached to a variable pitch prop. This tunnel has been refurbished to improve the flow quality, completely upgrade the controls, and dampen the vibrations of the motor and fan. This refurbishment has also included installing a new variable speed drive that allows a computer to maintain a constant velocity in the tunnel over the course of an experiment. This, combined with a variable pitch prop, allows experiments to be run with a tunnel velocity up to 50 m/s.

After the refurbishment, the turbulence intensity in the wind tunnel was measured and found to be less than 0.5% for the results presented in this paper.

The model being used is a NACA 0015 airfoil with a 30 inch chord and 24 inch semispan. This model was constructed by machining two aluminum templates to the profile of the airfoil. The templates were then mounted with foam between them. A hot wire was used to cut the foam to the airfoil profile. 25 pressure ports were located along the edge of the airfoil approximately ½ the way along the span, using a sine distribution. The model was covered with fiberglass and epoxy, and sanded at each step back to the profile dictated by the templates. The fiberglass shell was built up to the appropriate thickness and length for the airfoil, then sanded very smooth and painted to reduce surface anomalies. This airfoil is mounted vertically in the windtunnel, extending up from the bottom to the center of the tunnel.

A rounded tip was built by producing a solid model in AutoCAD, which was then split into pieces of appropriate size for the rapid prototyping machine at Utah State University. After being manufactured, the pieces were epoxied together. Further work will include mounting pressure points in the tip and filling the interior to make the part solid. It will then be sanded smooth and fitted to the airfoil.

After mounting the airfoil in the wind tunnel, the pressure ports were connected to a PSI 16 port pressure scanner. Pressures on both sides of the wing were compared for different angles of attack to determine the zero degree location accurately.

Data Acquisition and Reduction

The data acquisition system consists of a 5 channel IFA 300 Constant Temperature Anemometer that is connected to 3 probes. The first probe, a triple wire array, is used to measure all three components of velocity within the vortex structure. The other two probes are single wire sensors that will be used to track the wandering of the vortex. The triple wire probe is attached to a traversing system controlled by the data acquisition software that moves in a plane perpendicular to the free stream velocity in the wind tunnel.

Data acquisition is primarily performed by TSI ThermalPro software. This software can simultaneously sample the temperature and up to 5 separate hot-wire sensors. This software is used for the initial calibration, data acquisition, and data analysis. The data analysis portion of this software allows the mean velocity components, Reynolds stress components, and correlations to be calculated.

Another program, developed using LabView data acquisition software, is used to control the velocity in the wind tunnel. At present, this software allows the tunnel to be run at a constant power setting and gives continuous feedback on the velocity in the wind tunnel, the current ambient temperature, ambient pressure and Reynolds number. Future plans for this software involve modifying it to account for variations in ambient conditions so that the tunnel can be run at a constant Reynolds number during the course of an experiment, which can last as long as several hours.

Preliminary Results

At this stage, initial data has been collected on the vortex structure at a location 0.5 chord lengths downstream of the trailing edge of the airfoil. The airfoil currently used has a square tip. Data was acquired for angles of attack equal to 4, 5, 6, 8 and 10 degrees. For each of these, a coarse measurement grid was used initially and used to locate the center of the vortex. After finding the vortex, a more detailed mapping of the vortex region was established.

The results at a 5 degree angle of attack were compared with the results presented by McAllister, et al[3] for the same configuration and Reynolds number. This helped to ensure that all systems were set up accurately and were functioning as expected.

Figures 1 and 2, comprised of data collected for the 4 and 6 degree experiments, show the profile that would be expected for a vortex, with a rotational velocity that goes to zero at the center of the vortex, then rises to a maximum and falls off again outside the vortex. This data was collected for several locations in along the z-axis near the center of the vortex, and the results of each band are shown.

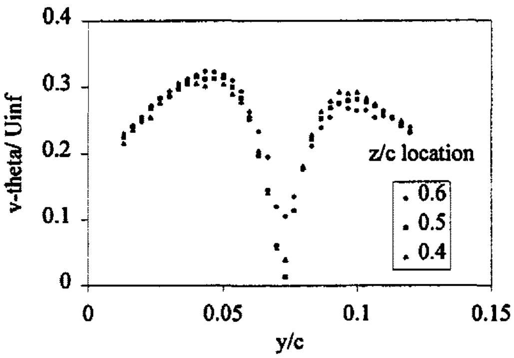

Figure 1: Rotational Velocity at 4 degree angle of attack

$$\mathrm{Re} = 1.16*10^6, U_{\inf} = 26\, m/s$$

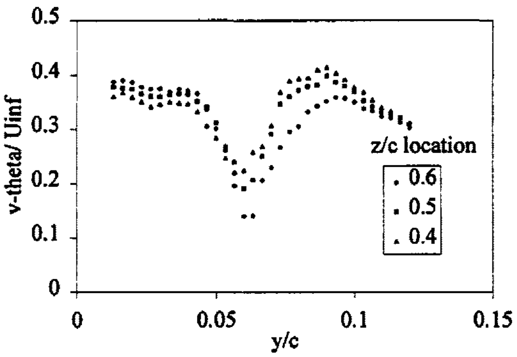

Figure 2: Rotational Velocity at 6 degree angle of attack

$$\mathrm{Re} = 1.19*10^6, U_{\inf} = 25.7\, m/s$$

At 8 and 10 degrees, Figures 3 and 4, the profiles are much more complicated. For both cases, the center of the vortex was located between 0.05 and 0.06 y/c, and this location can be seen as the second drop in rotational velocity on both plots. The first low on both plots corresponds to the location where the axial velocity also drops considerably. This may indicate that the flow over the airfoil is separating at these higher angles of attack, leading to a large wake deficit in this region, and further testing is required. Above the wing, where the separated flow would not have as much of an effect, the rotational velocity profiles are very similar to those shown in Figures 1 and 2.

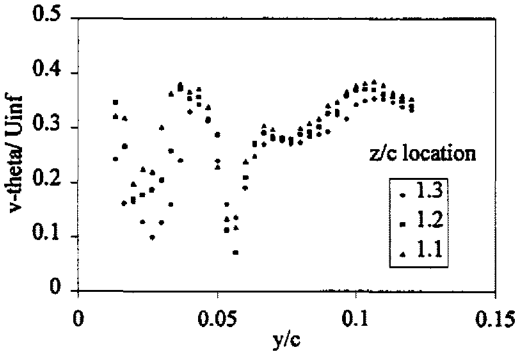

Figure 3: Rotational Velocity at 8 degree angle of attack

$$\mathrm{Re} = 1.18*10^6, U_{\inf} = 25.6\, m/s$$

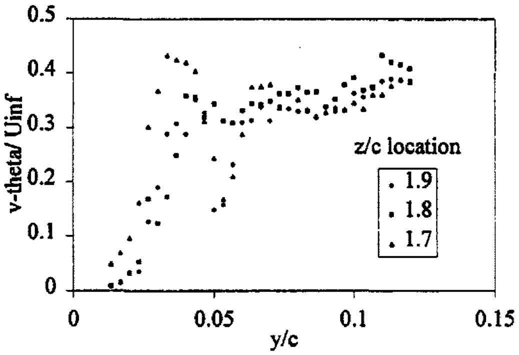

Figure 4: Rotational Velocity at 6 degree angle of attack

$$\mathrm{Re} = 1.14*10^6, U_{\inf} = 25.6\, m/s$$

Planned Testing

To complete this research, more data will be obtained by varying the Reynolds number, the angle of attack, and the airfoil geometry. The current location will be further tested to determine the variation in the vortex structure in the z direction. Then research will continue with the obtaining of the velocity and turbulence profiles at more locations in the near field, from locations directly above the airfoil to 1 chord length downstream. After data has been collected with the square end cap at several Reynolds numbers, the round end cap will be placed on the airfoil and the tests will be repeated. This data will then be used to analyze the effects of the different parameters on the structure and development of the vortex in the near field, and to assist the CFD community in developing codes that can more accurately predict the vortex formation.

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