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FORUM

APPLICATION OF LOW SPEED WIND TUNNELS IN TEACHING BASIC AERODYNAMICS

Randolph S. Reynolds

ABSTRACT

Undergraduate programs that include one or more courses on basic aerodynamics, including those that are introductory to undergraduate engineering programs, can benefit from the use of low speed wind tunnels. At ERAU’s Prescott Campus two low speed wind tunnels have been used to give Aeronautical Science and beginning Aerospace Engineering students hands on experiences use of these tunnels in determining the lift curve slopes for various airfoils.

The objectives of these lab experiences as listed in the course syllabus are:

Objectives: The student is expected to familiarize him/herself with:
- Fundamental wind tunnel testing techniques.
- The use of an open return wind tunnel to measure the static pressure acting on an airfoil.
- The variation in the static pressure on the surface of an airfoil at various angles of attack.
- The use of surface tufts to assist in airflow visualization.

Objectives: Using the data taken in the experiment, the student is also required to:
- Plot the pressure pattern on the top and bottom of an airfoil at four different angles of attack.
- Calculate the lift coefficients for each of these angles of attack.
- Plot the coefficient of lift against the angle of attack measurements.

This paper describes a specific experiment given to undergraduate aeronautical science students. In this lab all the learning objectives can be met by using small groups of students and providing them with detailed instructions. This is one of the most popular portions of the course on basic aerodynamics.

DESCRIPTION OF WIND TUNNELS

There are two wind tunnels which are available to the undergraduate in Aeronautical Science. Both are open circuit low speed tunnels. The smaller of the two has a capability of producing 100 knots velocity in a 12 inch by 12 inch by 24 in test section. The larger tunnel has a test section of 24” X 24” with an extension. The latter is rigged so that data can be recorded electronically and presented under the lab view program. In the case of the Aeronautical Science student’s part of the lab work is to observe and record the pressure data from a manometer. These manometers provide an accurate display of the static pressures on the upper and lower surfaces of any airfoil section that we have set up. (See Appendix 1)

There are two additional wind tunnels in the lab. There is a blow down supersonic tunnel with a 3” x 6” test section that can attain Mach 4. There is a closed circuit low speed tunnel and the test section is 42” x 48” and has been equipped with a sting type mount.
Low Speed Wind Tunnels

The complete apparatus for this lab is listed below:

**Apparatus**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELD subsonic wind tunnel</td>
<td>12&quot;x 12&quot; or 24&quot; x 24&quot; test section. Maximum speed is about 0.3M. Open loop tunnel.</td>
</tr>
<tr>
<td>Absolute pressure gauge</td>
<td>Measures ambient pressure. The scale is calibrated to read in inches of mercury (in-Hg).</td>
</tr>
<tr>
<td>Thermocouple type digital thermometer</td>
<td>Measures ambient temperature. The scale is calibrated to read in °F.</td>
</tr>
<tr>
<td>Pitot-static tube</td>
<td>Measures tunnel total (stagnation) &amp; static pressures. The difference of the two pressures (dynamic pressure) is read off the Inclined Manometer. Total and static pressure are also read individually on two of the tubes on the bank manometer.</td>
</tr>
<tr>
<td>Inclined manometer</td>
<td>Measures tunnel dynamic pressure. The scale is calibrated to read in inches of water (in-H2O). Although the tube is filled with Meriam Oil, the gauge has been calibrated to read in inches of water.</td>
</tr>
<tr>
<td>Bank manometer with 50 (or 20) tubes.</td>
<td>Measures static pressures on the airfoil and the total and static pressures of the airflow in the wind tunnel. The scale is calibrated to read in one tenth of a foot of Meriam Oil (Red Gauge Oil) with a specific gravity of 0.826 (0.826 feet of water generates the same pressure as 1.000 feet of oil).</td>
</tr>
<tr>
<td>In 12” WT</td>
<td></td>
</tr>
<tr>
<td>NACA 4412 airfoil section</td>
<td>12&quot; span, 4&quot; chord/ 24&quot; span, 6&quot; chord; symmetric section (no camber) and 12% (0.48 or 1.68 in) maximum thickness. Tufts are attached on the upper surface of the airfoil for flow visualization on the section. There are seven or nine pressure ports on the upper surface of the airfoil. The location of those ports are listed in Table 2.</td>
</tr>
</tbody>
</table>
PROCEDURES

The instructions for Part I that covers the lab work and data "reduction" along with the instructions for the Part II individual report that covers the analysis are issued to the student. Each student group, 3-4 students per group, is issued a data package, see attachment 1. There are several tasks that the groups must accomplish in the 20-30 minutes that they have on the 12 inch tunnel. After one group finishes with the 12" data collection they move to the 24 inch tunnel and demonstrate for them selves three or four parameters such as stagnation point, flow separation and re-attachment, and the difference in the calibration of the manometer gages.

The small 4412 (or 0012) airfoil that is placed into the 12 inch test section is tufted for flow visualization. The lab is not equipped with a functioning smoke generator and flow visualization is of paramount importance in the basic aerodynamic course. There some limitations to this set up. At very high angles of attack the airflow into the small test section would be so altered that accurate measurements of pressure distribution were hindered and the tunnel would experience vibrations from the turbulent air hitting the upper and lower walls. The best Reynolds numbers that could be achieved were in the range of 198,000 to 220,000 so that the lift curves produced tended to flatten out just before the stall.

In spite of these limitations this set up was ideal for letting students experiment with the lift patterns and the stall patterns on the wing and it led to more in-depth learning about the nature of creating lift on wings than hours of lecture alone could have accomplished.

The procedure for each class was to record the manometer readings from fourteen ports, seven on the upper surface and seven on the lower surface. The advantage of using the smaller 4 inch chord wing section in the 12 inch tunnel was that these ports were aligned where as the longer, 6 inch chord 4412 wing section in the larger test section had offset upper and lower ports even though there were seven more built into the model.

Each group was to take the readings from the manometers that were in tenths of feet of Miriam oil and convert the readings from each port on the wing into a coefficient of pressure normal to the surface of the wing. They were also to keep control of the dynamic pressure in the tunnel and once set for each angle of attack to record from an inclined manometer the pressure in inches of water. This would be checked against the difference between the static and total pressures measured from a small 'pitot' tube mounted in the test section. The readings from the upper surface were subtracted from the lower surface ports readings and multiplied by the distance between the ports and averaged over the four inch chord to approximate the following relationship:

\[ N = \int_{0}^{c} (p_x) dx - \int_{0}^{c} (p_y) dx \]

which sums the upper and lower pressures over the chord per unit span. N is the total force normal to the surface. The conversion to coefficients of pressure is the static pressure minus the measured pressure at each station divided by the dynamic pressure. This relationship is:

\[ C_{r_n} = \frac{p_u - p_w}{q} \]

and likewise for the lower pressures. The static pressure was measured from the pitot static probe in the tunnel and was free of disturbances until very high alphas, those approaching 20 degrees. The dynamic pressure, \( q \), was taken from an inclined manometer fed off the same pitot static probe. The inclined manometer made setting of the wind tunnel speeds easier to accomplish. Almost all experiments run in this configuration were targeted for 3 inches of water on the inclined manometer.

It was a simple matter of taking the direct readings for static pressure and the pressure at each station or port, n in the equation, and writing the data sheets so that the student could step by step calculate by hand the \( C_{r_n} \). The average Aeronautical Science undergraduate does not have the computational skills to solve the equation for the coefficient of normal force:

\[ C_{n} = \int_{0}^{c} C_{p_n} dx - \int_{0}^{c} C_{p_s} dx \]

from equation (1) and (2) above. Therefore an average of all the "blocks" of pressure between the ports is taken. This method of handling the pressure measurements is remarkable accurate. It is explained to the students that this process has been used for nearly a hundred years. In addition to the pressure patterns and the computation of the average coefficient of lift for each angle of attack, the group calculates the velocity in the wind tunnel and the Reynolds number (Re).

INDIVIDUAL PROJECT

The next step for the students is to plot the \( C_{L_n} \) curve for the data obtained. Since each group only takes data for 4 to 5 angles of attack (the lab period is limited) so all data is compiled by the instructor, placed on a spreadsheet and
Low Speed Wind Tunnels

returned to the individual students to complete. The student then must take all the \( C_{la} \) for each of the pairs, upper and lower, of stations and calculate the corrected data for the average coefficient of the normal force, then adjust it for the angle of attack to produce an average lift coefficient. He then uses the excel program to plot the \( C_{la} \) curve representing the wing. The instructor provides on this spreadsheet any angles of attack that the class did not have time to do. Because the 4412 airfoil is asymmetric, that is the zero lift angle of attack is about a negative 4 degrees, the angles of attack are set in one degree increments from -4 degrees to +16 degrees and the instructor supplies about five more data points from that angle of attack to 30 degrees. If the dynamic pressure is maintained around 3 inches of water this results in a good representation of the NACA plots. The stall angle of attack shows to be the same as the NACA plot and the zero lift alpha is usually within a degree of that produced by the NACA. The variances that occur have normally been due to problems with accurate readings in the manometers, usually one port, and often this is due to restrictions in the manometer tubes or connections.

The student is then required to compare the class \( C_{la} \) curve to the NACA curve and to a similar curve found in their textbook. They are supposed to answer the following questions as part of the learning process:

A. What is the limitation with measuring the pressures between the ports on the 4 inch 4412 airfoil as we did?

B. What Reynolds numbers would you think would be required to have the \( C_{la} \) you got look like the NACA plots? Explain your answer.

C. Where are the major differences in your (class) \( C_{la} \) curve where the plotted points were not aligned and why were there large excursions in the plots?

D. Address in your report the following:
   (1). The effect of a boundary layer in the test section.
   (2). Turbulence or other effects from all the holes (penetrations) in the test section.
   (3). Location of the pitot static probe in the test section.1

E. What did you learn from the 24” x 24” wind tunnel work? Explain the following:
   (1). Location of stagnation point.

(2). Differences in stall angles of attack between the 4” wing section and the 6” wing section.

F. How would you judge the scientific accuracy of working with this wind tunnel set up and what might help to improve the plot of the data into the \( C_l \) vs \( \alpha \) curve?

RESULTS

In almost all cases the classes have had excellent results and the consistency of the data and the plots over fourteen classes presented with this project have been worthy of the engineering students. As a matter of motivation data plots from engineering student lab reports using the same airfoil are given to the students so that they can see the similarities.

The success of this wind tunnel project stems from the simple and reliable low speed wind tunnel set-ups that this campus has available. In addition, this project is not compounded by attempting to measure the drag on the surface of the airfoil. In the small test section this is not possible to do but it is an expectation that it can be accomplished using the small sting and strain gauges available for use in the 24 inch tunnel. The difficulty is that the test model would have to be altered and as of this date there are no plans to pursue that as a requirement for the Aeronautical Science program. In part this is due to the lack of wind tunnel time available and the demand by the senior Aerospace Engineering students for wind tunnel time on their senior projects.

CONCLUSION

The use of a wind tunnel project for undergraduate, non-engineering, aviation students has been very successful. The students participate in the “discovery” phase of the production of lift and as this topic is thirty percent of the course content is provides them with a solid foundation for continued learning in the courses that follow. Student opinionairies tend to support the notion that this laboratory time, usually four class periods, is well worth the experience.

There is a secondary feature to laboratory work that helps in the classroom. The teams are formed so that slower learning students are mixed in with the better students. This helps generate a little competition to work as a team member and forces learning.

Some of the Individual Part II reports are down well enough to be used as references for other students. The total effort taxes not only the students understanding of aerodynamics but of his organizational and writing skills.†

† Spring 2004 edition
Randolph S. Reynolds is currently on the faculty of the Prescott Campus of Embry-Riddle Aeronautical University where he teaches basic aerodynamics and aircraft performance. He holds a Master of Science in Aerospace Engineering from the University of Arizona and a Bachelor of Science in Engineering Sciences from the United States Air Force Academy. Mr. Reynolds received a fellowship from NASA in 1993 that he applied to graduate studies in optics and spectroscopy. He has extensive experience as a USAF pilot primarily in fighter aircraft. He completed a tour in fighter-bombers (F-105s) over North Vietnam and later flew as an F-105 and F-4 Instructor Pilot. In 1988 he joined NASA at the Ames Research Center in California as an engineer and research pilot and finished his government career at NASA Dryden Flight Research Center in 1999. He retired from the Air Force after 30 years of commissioned service in 1994. Mr. Reynolds has been active in many organizations and is currently participating with Prescott Air Fair Corporation in their annual air show held in Prescott each October.
REFERENCES


APPENDIX I

Photographs:

4412 Airfoil in 12”x12” test section

Low Speed Wind Tunnel: 12” X 12”
Low Speed Wind Tunnels

6 inch 4412 airfoil in 24" x 24" test section

Inlet and manometer tube connections to 12" x 12"
Typical Manometer bank

Graph showing data for RAE 4412 wing sections.

Section angle of attack, $\alpha$, deg 10 20 30

Angle of attack, $\alpha$, deg
Lift curve slope from Spring 2004 Class: This plot is from the raw data and is not smoothed. Error bars would indicate that the plot around 0° angle of attack is offset. The airfoil section was mounted and calibrated in the test section with zero angle of attack one degree high. Therefore the zero lift angle of attack is closer to -4 degrees than shown on this plot. The $C_{L_{max}}$ actually took place at 13 degrees alpha. Students discuss these sorts of points in class.