

Cal Poly Pomona ARO 101L - Fall 2014
Low Speed Wind Tunnel Experiment – Wing Performance Measurements
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Overview: This experiment will familiarize the students with the purpose, operation, and data acquisition of the Cal Poly Pomona Low Speed Wind Tunnel. This will be accomplished by conducting a wind tunnel test of a aircraft type wing around the end of the quarter. The wing will be mounted on a sting balance system and tested in the tunnel test section at various angles of attack for the key objective of measuring the wing key performance parameters of Lift, Drag, Pitching Moment, and the angle of attack (AoA) where flow separation “stall” occurs. The experiment will also give you practice in working in teams and, by following a report template, practice in technical writing.

The experiment will be performed and documented by teams each comprised of 4-7 class members selected by the instructor. Each team will have an appointed or elected team leader and a deputy leader. The product of the experiment will be a technical report co-written by all of the members of each team. You will use Microsoft Word, 12 point Times new Roman font, single space with figures and tables integrated into the text right after they are referenced. This report will be 15 % of your ARO 101L quarter grade. The team report will consist of the topics in the template below, **which also gives the instructions for the conducting and documenting the experiment.**

To make it easy, each team can get a Word Document version of the report template below, and use it as a “fill in the blanks”, “answer the questions” and “delete the professor’s instructions” type template for your report. You can make data tables and plot the wind tunnel data using Microsoft Excel and import the data tables and plots into the Word document. You can also take digital photographs of the model and wind tunnel (as well as a photo of the team members for the title page) and import them into the Word document. Once in Word format, you then can add Figure and Table numbers and titles. You will deliver a bound color copy of your team report to the instructor the next week for grading.

Your team laboratory report must exactly follow the headings and heading numbers in the template below. The team leader should assign a team member to write a section of the report. It is suggested that the team leader write the Executive summary, and be responsible for combining all sections into the final report.

All figures must have figure numbers with a figure title under the figure, and table numbers with a table title above the table. The figure and table numbers will start with the section number and followed by a dash followed by the figure or table number (ex.: “Figure 4.2-1”), then the title. All external report or book references must be referred to by a reference number in the text of the report and listed in section 9.0.

The template for the laboratory report headings and outline (also containing the instructions to conduct the experiment) is as follows:

REPORT TEMPLATE – ARO 101L Low Speed Wind Tunnel Experiment – Wing Performance Measurements

Title Page

On separate lines:

Write the “title” of the experiment.

The class name (ARO 101L Introduction to Aeronautics, Section # __, Team # __).

Instructor name _____.

Insert a photograph of your team members together standing in front of the wind tunnel test section with each member name below their portion of the picture.

The department and school name (Aerospace Engineering Department Cal Poly Pomona).

The date that the report will be submitted to the instructor.

The name and signature of the team leader (identify who it is)

The name and signatures of each team member

i. Table of Contents

List the topic headings in the template below, and the page numbers where each section starts and list each section author’s name. List the page numbers only after the rest of the report is finished. For example, including the format with sub-section indentations:

ii. List of Figures	<u>page#</u>, <u>Author name</u>
iii. List of Tables	
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ii. List of Figures

List the Figure numbers and titles and the page numbers where each occurs.

iii. List of Tables

List the Table numbers and titles and the page numbers where each occurs.

1.0 Executive Summary

An executive summary is a one-page (or less) summary of the key aspects of the experiment. It is written so as if it could be ripped out of the report, handed to some one, who could read it and comprehend all of the most important objectives, approaches, results, and conclusions that were gleaned from the experiment without reading the rest of the report. It must include a Figure 1-1 with a title for a graphic or Table illustrating the most important result or conclusion from the test. Remember: always refer all figure or table numbers in the text before you show them in your document.

2.0 Objectives

Describe the objectives of the experiment in your own words. These should be in a bulleted or numbered format. They include the learning objectives alluded to in the overview section above, as well as the technical objective of determining the key performance parameters of the wing airfoil and plan form (what are they?) for future aircraft design studies and to provide data to verify future theoretical predictions.

3.0 Approach

3.1 Theory

Describe the theory used for any calculations in the report. Show the equations, define the variables, and explain in which sections of the report the equations are used. For example:

3.1.1 Reynolds Number - The non-dimensional Reynolds Number is a test variable (by changing the test velocity) that must be calculated and is defined in Reference 1 as

$$(3.1.1-1) \text{Re} = \mathbf{r} * \mathbf{V} * \mathbf{L} / \mathbf{m}$$

where

r = air density in slugs/ft³

V = air velocity in ft./sec

L = reference chord length, usually the mean geometric chord length (= Area/span or S/b; see Ref. 1, equation 4.90), in feet,

m = absolute viscosity coefficient of the air in slug/(ft)(sec).

3.1.2 Lift (L), drag (D), and pitching moment (M) – Describe how you transformed the balance measurements into the Lift, Drag, and pitching moment directions.

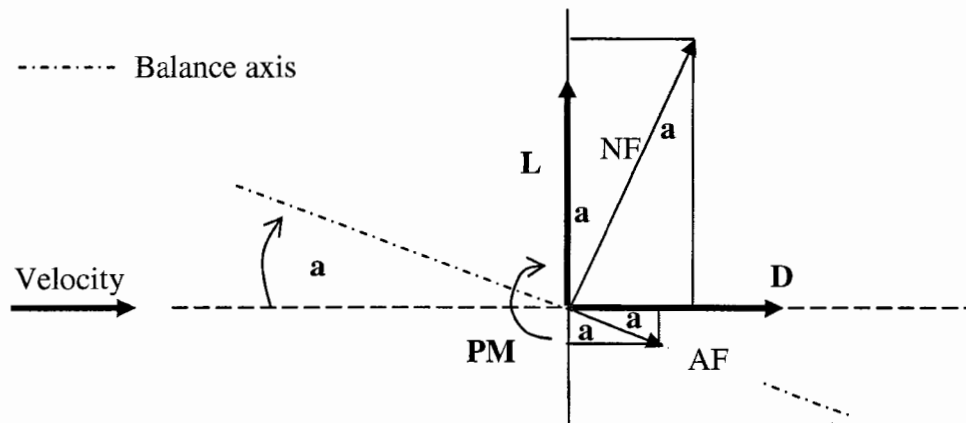
Lift, drag and pitching moment are derived from the balance measurements. At all angles of attack, you want lift measurements that are normal (perpendicular) to the test section velocity vector and drag forces that are parallel to the test section velocity vector. It is

assumed that the test section velocity vector is horizontal, and in line with the axial centerline of the test section.

Unfortunately, the cylindrical balance beam at the end of the sting to which the model is attached only measures axial and normal forces relative to the balance centerline. Therefore, when the sting changes angle of attack, the drag force vector keeps in line with the balance and sting center line, and the normal force vector stays perpendicular to the balance axis, which is not in the vertical and horizontal directions of the desired lift and drag.

Removing the zero air speed balance readings- With the model at zero air speed and zero α , click on the “Zero” button on the computer Run Screen. This zeros all six of the balance readings (NF, AF, PM). However, as the α is changed from zero degrees, the balance readings do include the components of the weight of the model plus balance on the Normal force, Axial force, and pitching moment as a function of the sine and cosine of α . These must be removed from each of the measurements made at all test speeds. This is done by first testing the model at zero air speed where you pitch the model at the same α 's that you plan to test at the tunnel test speeds, and record the balance data (NF₀, AF₀, PM₀). Then, when you test at a desired wind speed, you subtract the zero air speed balance readings at the corresponding α 's for the balance measurements of NF, AF, PM, (see the subtractions in Eqns. 3.1.2-1, 3.1.2-2, 1 and 3.1.2-3).

Now, to get Lift and Drag in the velocity reference system, you must convert (or “transform”) the balance normal and axial measurements into the lift and drag directions by the simple geometry and trig equations shown in Figure 3.1.2-1. You will need to add these equations and calculations in your Excel spread sheet that you will obtain from the tunnel test data so you can plot the C_L , C_D , and C_M versus α , and also plot C_L vs. C_D , as discussed in Section 6.6.1.



$$(3.1.2-1) \quad L = (NF - NF_0) \cos a - (AF - AF_0) \sin a$$

$$(3.1.2-2) \quad D = (NF - NF_0) \sin a + (AF - AF_0) \cos a$$

$$(3.1.2-3) \quad M = (PM - PM_0); \text{ at corresponding } a\text{'s}$$

Figure 3.1.2-1 The balance normal (N) and axial (A) force measurements relative to the balance axis must be transformed at an angle of attack (a) into the Lift and Drag directions

The measured balance pitching moment (M) about the center of the balance is in a rotational direction, therefore does not need to be transformed as the angle of attack changes.

3.1.3 Performance Coefficients - Show and describe the equations defining the lift, drag, and pitching moment coefficients. You can easily type equations right into the text using the regular characters, subscripts for things like the “L” in C_L , (format, font, subscript) and superscripts for the exponents like the “2” in V^2 (format, font, superscript). Greek letters may be found in the Symbol font (the Greek letter r may be inserted by typing “r” in the Symbol font). More complex equations may be inserted using Word’s built-in equation editor: “Insert, Object, Microsoft Equation”. There is no excuse for not using proper symbols.

The non-dimensional coefficients are defined as:

$$(3.1.3-1) \text{ Lift coefficient: } C_L = L/(q S)$$

Where L = Lift, in pounds or Newtons

q = dynamic pressure = $\frac{1}{2} \rho V^2$, in lbs/ft² or Newtons/meter²

ρ = air density, in slugs/ft³ or kg/meter³

V = air velocity, in ft/sec. or meters/sec.

S = wing area (top view of wing), in ft² or meters²

$$(3.1.3-2) \text{ Drag coefficient: } C_D = D/(q S)$$

Where D = drag in pounds or Newtons

(3.1.3-3) Pitching moment coefficient about the balance rotation axis:

$$C_M = M / (q S C_{MGC})$$

Where M = pitching moment about the balance rotation axis in foot-pounds or meter-Newtons,

C_{MGC} = chord length of the mean geometric chord, in ft. or meters.

Remember, the C_M or pitching moment coefficient equals the Moment divided by the product of the dynamic pressure times the wing area times the mean aerodynamic chord.

3.2 Experimental Approach

Describe the overall approach for meeting the experiment's objectives. This includes the approach of performing a wind tunnel test (as apposed to doing only theory, etc.), varying certain test variables (angle of attack, trip strips, etc.) recording data, then interpreting the meaning of the data, and documenting the data by writing a team report.

4.0 Test facility description and data acquisition system and procedures

4.1 Wind Tunnel Description

Describe the Cal Poly Low Speed Wind Tunnel and control room. Include a sketch or diagram, in a Figure 4.1-1 (draw your own version with test section dimensions), of the top view of the tunnel with call-outs of the key elements, photographs of the key tunnel elements (Figure 4.1-2, etc.), as well as written descriptions of: what type of wind tunnel (closed or open circuit?, Atmospheric or pressurized?), size of the test section, visibility into the test section, test speed range, how the tunnel speed is controlled, etc.

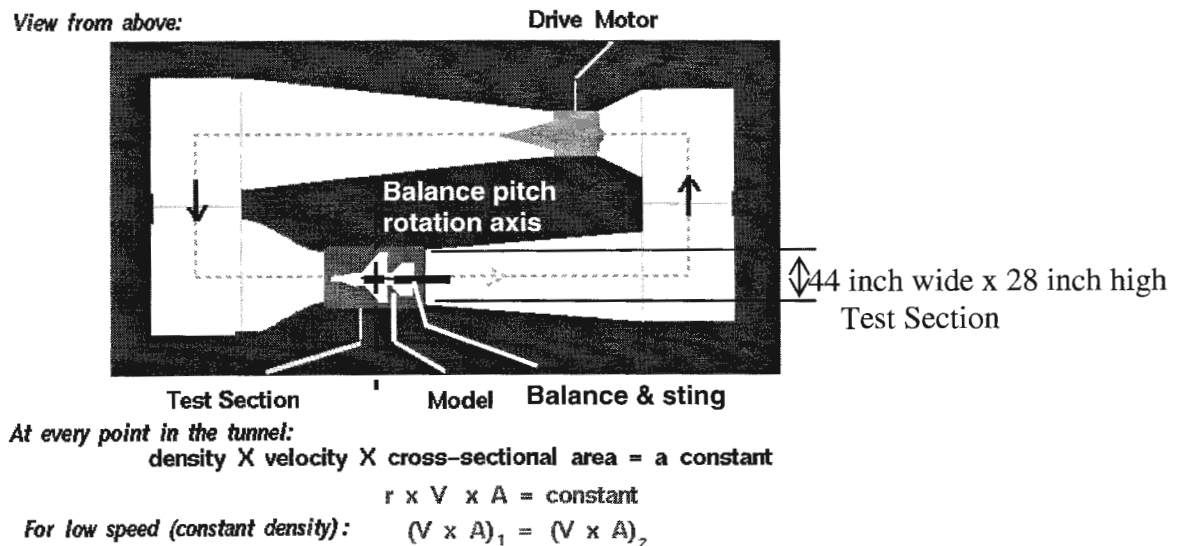


Figure 4.1-1 Cal Poly Pomona Low Speed Closed Circuit Wind Tunnel is capable of velocities up to 200 mph.

4.2 Model balance and Data Acquisition system equipment - Describe the model balance measuring system (its design and how it works), make a diagram in a Figure 4.2-1 and/or up-close photographs (remember each has a figure number and title) of the model mounted to the sting. Describe how the model is fastened to the balance.

Describe what parameters are measured by the balance, describe the data acquisition computers and equipment in the tunnel control room, how the balance sting angle of attack, yaw angle and roll angles are changed and controlled (manual control? automatic control?), etc. What visualization or measurement methods, if any, were used in the test (tufts? Smoke? Pressure rake? Oil flow? Etc.).

4.3 Test Plan and Procedure

4.3.1 Test Plan - Before you start testing, you must make a Test Plan.

A Test Plan defines the model configurations you plan to investigate and the test variables you want to change to give you the data you need to meet the test objectives. It also can indicate the order that you want to change the test variables (AoA) and model configuration variables. You must have a test plan like the sample test plan as shown in Table 4.3.1-1.

To vary the AoA of the wing, you vary the model positioning system's sting AoA, so that becomes a test variable in your test plan. You can vary it for positive AoA (where flow separation stall will occur on the upper surface), or for negative angles of attack (where flow separation stall can occur on the lower surface).

Calculate the model Reynolds Number (Equation 3.1.1-1) based on the test velocity, and the air density and viscosity coefficient at the altitude of the wind tunnel, and include the value in the test plan in your Table 4.3.1-1 discussed below.

Also, as will be discussed in Section 5.2, the model configuration could be changed by adding various devices to the wing. In this test, yarn strips called "tufts" are added to the upper surface of the wing for indicating when flow separation starts to occur at the stall angle of attack. All test runs will have the tufts on the wing.

Now that we have defined the tunnel test variables and the model configuration variables, we are ready to construct our Test Plan like Table 4.3.1-1, below.

Table 4.3.1-1 Wind Tunnel Test Plan for the Complete Wing Model

Run #	Model Config.# and description	Velocity & Re mph & no units	AoA Range Deg.
0.1	Measure model geometry and install & align model in tunnel	0	0
0.2	Measure the Zero speed balance data	0	0 to + 14 to -6
1	A. Tufts on upper wing surface	V1 = 50 Re1=____x 10 ⁵	0 to + 14 to -6
2	A. Tufts on upper wing surface	V2 = 60 Re2=____x 10 ⁵	0 to + 14 to -6
3	A. Tufts on upper wing surface	V3 = 70 Re3=____x 10 ⁵	0 to + 14 to -6
4	A. Tufts on upper wing surface	V4 = 80 Re4=____x 10 ⁵	0 to + 14 to -6
5	A. Tufts on upper wing surface	V5 = 90 Re5=____x 10 ⁵	0 to + 14 to -6
6	A. Tufts on upper wing surface	V6 = 100 Re6=____x 10 ⁵	0 to + 14 to -6

4.3.2 Test Procedure -Now expand you test plan in Table 4.3.1-1, into a detailed test set-up and test procedure in a table such as seen in Table 4.3-2 below, but construct it in your own words. Use the first 4 columns from your test plan, then add column's to describe the steps of how the wind tunnel test is set-up and how the Run # are conducted and the tunnel is controlled, and add any other topic for a column of information that you think will help make the test procedure clear. Remember, your test procedure should be constructed that someone else could follow its instructions to conduct the test with out you there to help.

The wind tunnel test will be run under the guidance of the laboratory technician expert (Jim Cesari) according to the test procedure table.

Table 4.3-2 Test Procedures

Run # & Respo nsible team #	Model Config. # and descriptio n	Velocity Ft/sec Re no units	AoA Range Deg.	Step #	Procedure Title	Procedure
0.1				0.1	Measure wing geometry	Using a linear scale, protractor and calipers, measure and make a 3 view diagram with dimensions of the wing root chord, tip cord, leading and trail edge angles, and root and tip thicknesses. Also, then calculate and indicate in a table on the diagram the wing area, the mean aerodynamic chord, the airfoil section designation, the aspect ratio, taper ratio, and thickness to chord ratio at the root and tip. Also measure and sketch the location tufts on the wing surface(s).
0.1				0.2	Install model on wind tunnel balance and align zero angle of attack with the tunnel wind axis	Align the model mounting hole with the sting balance and slide the model over the cylindrical balance until the screw holesetc. etc.
0.1				0.3	Close-up tunnel	Close all wind tunnel test section access doors

0.2			-6 to +14 to 0	0.4	Record zero balance readings	At zero AoA, click on the "Zero" button on the computer Run screen. Then change the model AoA and record the balance data at each AoA that is planned for the tests at the desired tunnel wind speeds. (This zero airspeed balance data must be later subtracted from the balance data acquired at the tunnel air speeds to obtain the pure aerodynamic data).
0.2				0.5	Start fan motor	Start wind tunnel motor by...Etc.
1	A. Tufts on upper surface only	V1 = _____, Re = _____ x10 ⁵	0	1.1	Set tunnel speed at desired test velocity, Vi	At the command of the test director, increase the tunnel velocity = _____ mph using to speed control knob.
				1.2	Start data acquisition system	On the computer control panel screen, click on the icon...etc.
				1.3	Record and plot data	At the command of the test director, the team manually records the model balance lift, drag, and pitching moment, and notes on tuft activity in a paper data table, and then manually plots the parameters vs. AoA. Take a photograph of the tufts on the top surface (remember to have a photo numbering system so you can relate the photo number with the test angle of attack and velocity). Note if the tufts are steady or oscillating in your data table. Then stop auto data acquisition at the command of the team leader.
				1.4	Increase the angle of attack in the <u>positive</u> direction by 2 degrees (or smaller increment if your manual plots or tufts indicate the AoA is near stall)	At the command of the test director, change the AoA on the control knob until the AoA reading matches the desired value.
			2 to +14	1.5	Record data and plot data then increment AoA up to max AoA	Repeat steps 1.2 through 1.4 until the maximum positive AoA is tested. Test up to AoA= + _____ degrees
			0	1.6	Return the model to AoA = zero degrees	Slowly reduce the AoA control on the computer to zero degrees...etc.
	A. Tufts on upper surface only	V1 = _____, Re = _____ x10 ⁵	0 to -6 (negative)	1.7	Increase AoA in the <u>negative</u> direction by 2 degrees (or smaller increment if your manual plots or tufts indicate the AoA is near stall)	At the command of the test director, change the AoA on the control panel. ...etc.
				1.8	Repeat steps 1.3 and 1.7 until the maximum <u>negative</u> AoA is tested	Test up to AoA = - _____ degrees
				1.9	Return to AoA=zero	Repeat Step 1.6
2	A. Tufts on upper surface only	V2 = _____, Re = _____ x10 ⁵	0	2.1	Increase test velocity to next test velocity	Change test teams. Increase the tunnel speed to the next desired velocity
			0	2.2-2.3	Record data at zero AoA	Repeat steps 1.2 & 1.3
			2 to +14	2.4-2.5	Increase AoA in positive direction, record & plot data up to max AoA	Repeat steps 1.4 and 1.5
			0	2.6	Return to AoA=zero	
			0 to -6 negative	2.7-2.9	Increase AoA in <u>negative</u> direction, record & plot	Repeat steps 1.7 to 1.9

			direction		data to max $-\text{AoA}$, return to $\text{AoA}=\text{zero}$	
3	A. Tufts on upper surface only	$V_3 =$ _____ , $\text{Re} =$ _____ $\times 10^5$	0 to +14 to -6	3.1 to 3.9	Increase test velocity to V_3 , Record and plot data at all desired AoA 's	Change test teams, Repeat steps 1.1 to 1.9
4	A. Tufts on upper surface only	$V_4 =$ _____ , $\text{Re} =$ _____ $\times 10^5$	0 to +14 to -6	4.1 to 4.9	Increase test velocity to V_4 , Record and plot data at all desired AoA 's	Change test teams, Repeat steps 1.1 to 1.9
5	A. Tufts on upper surface only	$V_5 =$ _____ , $\text{Re} =$ _____ $\times 10^5$	0 to +14 to -6	4.1 to 4.9	Increase test velocity to V_4 , Record and plot data at all desired AoA 's	Change test teams, Repeat steps 1.1 to 1.9
6	A. Tufts on upper surface only	$V_6 =$ _____ , $\text{Re} =$ _____ $\times 10^5$	0 to +14 to -6	4.1 to 4.9	Increase test velocity to V_4 , Record and plot data at all desired AoA 's	Change test teams, Repeat steps 1.1 to 1.9
7	A. Tufts on upper surface only	$V=0$	0	5.1	Return tunnel to $V = 0$	Shut down tunnel by etc.

5.0 Test Article

5.1 Model description and wing geometry

Measure the model wing geometry (see Step 1 in Table 4.3.2 above). Then in your team report describe the wing wind tunnel model geometry and construction. What materials have be used to construct the model? Include its airfoil section designation, a diagram of its design in an 3 view drawing (top view, side view, front view) similar to Figure 5.1-1 (remember to reference the figure number in your text!) with dimensions in feet or meters (wing span, root and tip chord length, maximum thickness, leading edge and trailing edge angles, $\frac{1}{4}$ chord angle, model mount attachment dimensions of diameter and length), show the location and width of any span-wise sand "trip strips" added to the upper or lower surfaces to induce a turbulent boundary layer, if it had tuft yarn added to observe separated flow, where the tufts were located on the surface? Etc.

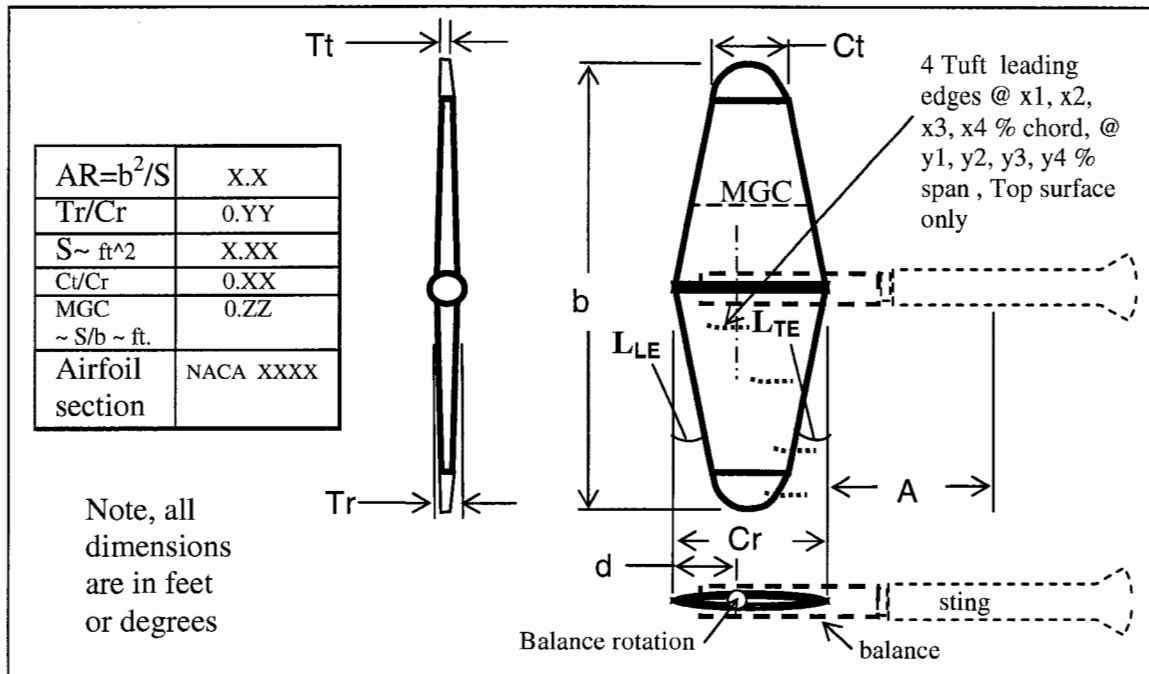


Figure 5.1-1 Wing model geometry

6.0 Test data results and interpretation

This is the most important part of your test and report. The manner in which you show your test data should tell a story of how your test data satisfies your key test objectives. One way to do this is to set up sub sections under topic 6 that group your data by the test objectives, such as “measuring the key performance parameters of the wing for future use for aircraft design and future theoretical correlations”. Under section 6.0, you can write an introductory sentence or two to introduce what will be shown in this section.

6.1 Key wing performance parameters (Lift, drag, pitching moment, stall initiation AoA)

6.1.1 Test Data Plots of key wing performance parameters

In this section, you can present the test data to satisfy the technical objective of providing wing aerodynamic data for future aircraft design studies and to provide data to verify future theoretical predictions. A good way to present wing data for design is by using plots of the data instead of tables of numbers. The plots can often tell a clearer story than lists of numbers in your data table, but the data table from which the plots are made should be included in the report, at least in an Appendix.

Each team will only plot their own data at the run number and tunnel velocity at which they tested.

The plots of the aerodynamic parameters of lift, drag, and pitching moment about the balance rotation axis should be presented in terms of non-dimensional coefficients using

equations 3.1.3-1,-2, and -3, instead of actual units such as pounds and ft-pounds, so the data can be easily scaled for full scale design calculations. *Remember, you must transform the Normal and Axial balance measurements into the model Lift and Drag directions using equations 3.1.2-1, 3.1.2-2, and 3.1.2-3. Also, make sure all units are consistent (feet, ft./second, ft^2 , etc.)!*

In this report section, first write an introductory description of what kinds of data you are showing and in your text reference the figure numbers of the data plots. Typical plot formats of the data you measure according to the Test Plan would include Figure 6.1-1, lift coefficient vs. AoA (the data is not real) at a single tunnel velocity (i.e. a single Reynolds Number), Figure 6.1-2 drag coefficient versus lift coefficient, and Figure 6.1-3 pitching moment coefficient about the balance rotation axis vs. lift coefficient (for a symmetric airfoil section, i.e. zero camber, the moment coefficients are zero; if the airfoil has camber the pitching moments usually are in the negative range).

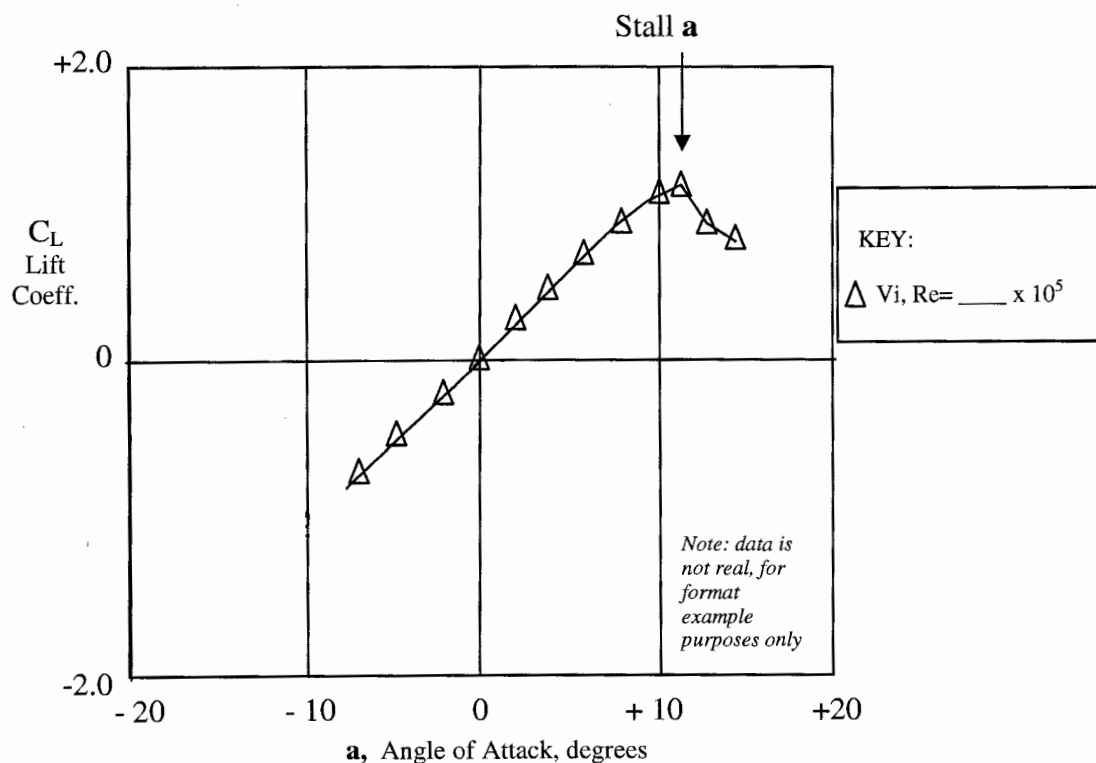


Figure 6.1.1-1 Measured Wing Lift Coefficient vs. Angle of Attack at Velocity $V_i = \text{____}$ mph

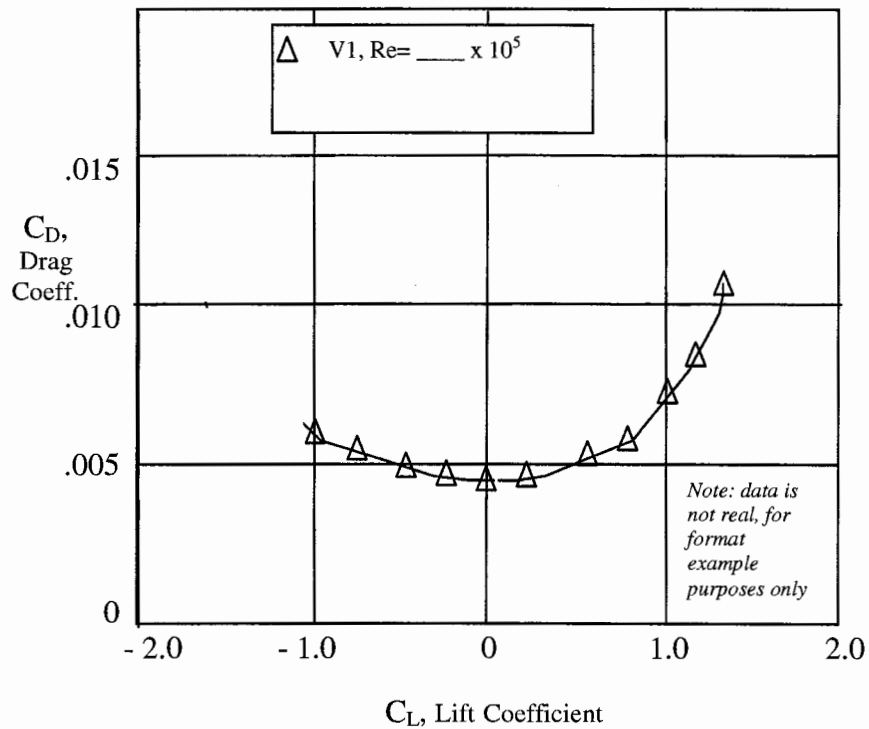


Figure 6.1.1-2 Measured Drag Coefficient versus Lift Coefficient at $V_i = ____ \text{ mph}$

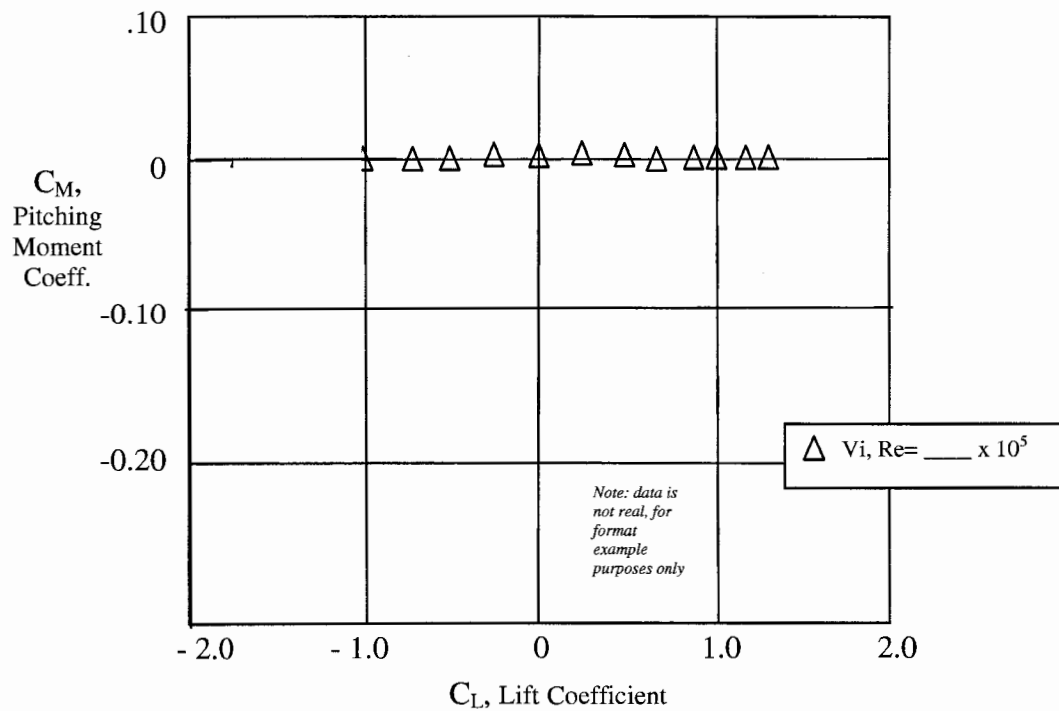


Figure 6.1.1-3 Measured Pitching Moment Coefficient versus Lift Coefficient at $V_i = ____ \text{ mph}$

6.1.2 Data Interpretation

After you show the data plots, write your interpretation of what the data means or reveals about the aerodynamic performance of the wing. When discussing the data, refer to the figure number that you are discussing.

For example, discuss if the data have smooth trends or do some of the data points fall way off of an expected smooth curve (called “wild points”) possibly indicating errors in the data? Does the C_L change as the AoA increases have an abrupt slope reversal at stall instead of a smooth reversal indicating an adverse stall characteristic? What AoA did the tufts start to vibrate? Do the tuft vibrations correlate with the C_L plot slope change at stall? Does the C_D vs. C_L plot show a C_L condition where the drag abruptly increases? Does the C_M pitching moment vs. C_L plot show approximately zero for a symmetric airfoil, or in a negative range for a cambered airfoil, as it should? Include your answers to these questions in your general discussion.

7.0 Conclusions and Recommendations

This section is short and concise. The conclusions are those things that you want the reader to remember after reading your report. Each conclusion is a statement, usually in a single sentence that summarizes the most important results of your experiment, and what was learned or proven. Each conclusion usually relates to an objective that you defined in Section 2. Conclusions are drawn from the discussions already given in the report; new information should not be introduced in this section. You should review each section of the report to extract the most important conclusions. Usually there are between three to five important conclusions, but there is no rule for this.

The key conclusion(s) is also stated in the Executive Summary.

This section also includes recommendations. Recommendations can include (1) your ideas for improving the accuracy, increasing the scope, or changing the procedures of the experiment itself, and (2) recommendations of accepting or improving your wing design based on your test results. Usually there are one or two recommendations, but again there is no rule for how many you give.

8.0 References

The references are the existing books or reports that were used as information sources in your report. References should be referred to by number in the report text. An example of a reference format is:

1. Anderson, John. D., Introduction to Flight, 6th Edition, McGraw-Hill Publishing, New York, N.Y., 2007

Velocity = _____ ft/sec, Re = _____, q = _____ psf, Pinf = _____ psi

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