DEVELOPING A PRACTICAL WIND TUNNEL TEST ENGINEERING COURSE FOR UNDERGRADUATE AEROSPACE ENGINEERING STUDENTS

A Thesis

by

BENJAMIN JEREMIAH RECLA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Edward White
Committee Members,	Christine Ehlig-Economides
	Kristi Shryock
	Thomas Strganac
Head of Department,	Rodney Bowersox

May 2013

Major Subject: Aerospace Engineering

ABSTRACT

This thesis describes the development and assessment of an undergraduate wind tunnel test engineering course utilizing the 7ft by 10ft Oran W. Nicks Low Speed Wind Tunnel (LSWT). Only 5 other universities in the United States have a wind tunnel of similar size and none have an undergraduate wind tunnel test engineering course built around it. Many universities use smaller wind tunnels for laboratory instruction, but these experiments are meant to only demonstrate basic concepts. Students go beyond conceptual learning in this wind tunnel test engineering course and conduct real-world experiments in the LSWT. This course puts knowledge into practice and further prepares students whether continuing on to graduate school or industry.

Course content mainly originates from the chapters in *Low Speed Wind Tunnel Testing* by Barlow, Rae, and Pope. This is the most comprehensive book that addresses the specific requirements of large scale, low speed wind tunnel testing. It is not a textbook for novices. The three experiments used in the course are modeled on actual experiments that were performed at the LSWT. They are exactly what a commercial entity would want performed although the time scale is drastically reduced because of class requirements.

Students complete the course with a working knowledge of the requirements of large scale, low speed wind tunnel tests because they have successfully performed real-world tests and have performed data reduction that is needed for high-quality industrial tests.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Edward White, for his expert guidance and direction throughout the creation of this course. He was instrumental in the success of my time here at Texas A&M. I would also like to thank my committee members, Dr. Christine Ehlig-Economides, Dr. Thomas Strganac, and Dr. Kristi Shryock, for their wisdom and guidance.

Thanks also go to my friends and colleagues for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the staff working at the Oran W. Nicks Low Speed Wind Tunnel. They put in extra hours to make sure that the experiments for my class worked out well.

I want to thank Doug Kutz for sitting in on my class and providing valuable feedback, and also for helping set up the experiments in the LSWT.

Thank you to the 15 students who signed up for my experimental course. Your feedback was invaluable in making this course better for future students.

Finally, I want to thank my lovely and understanding wife for her patience and love, for providing encouragement throughout my years in Grad school, and for helping me to find a path to God. Through God all things are possible.

NOMENCLATURE

Aero	Aerospace Engineering Department at Texas A&M University
AIAA	American Institute of Aeronautics and Astronautics
API	American Petroleum Institute
a	Lift curve slope
B	Wind tunnel test section width
b	Effective span of model
C	Area of test section
$C_{D,0}$	Coefficient of drag at zero lift
C_D	Coefficient of drag
C_L	Coefficient of lift
C_{PM}	Coefficient of pitching moment
C_{RM}	Coefficient of rolling moment
C_{SF}	Coefficient of side force
C_{YM}	Coefficient of yawing moment
CFD	Computational Fluid Dynamics
CRV	Crew recovery vehicle
D	Drag on model
FFT	Fast Fourier Transform
FISF	Fringe Imaging Skin Friction
H	Wind tunnel test section height

HARS	High Attitude Robotic Sting
HW	Homework set
I_u	Turbulence intensity
K_1	Solid blockage boundary correction variable for wing
K_3	Solid blockage boundary correction variable for body
L	Lift on model
LSWT	Oran W. Nicks Low Speed Wind Tunnel
NASA	National Aeronautics and Space Administration
PIV	Particle image velocimetry
PM	Pitching moment
psf	Pounds per square foot
q_{act}	Dynamic pressure – raw measured by wind tunnel
q_{corr}	Dynamic pressure – corrected for boundary corrections
RC	Radio controlled
RM	Rolling moment
S	Planform area
SF	Side force
TAMU	Texas A&M University
t	Time
t_b	Thickness of body
U	1 hour mean wind speed
u	Wind speed

V_b	Volume of body
V_w	Volume of wing
YM	Yawing moment
z	Height
α	Angle of attack
β	Sideslip angle
δ	Boundary correction factor
λ	Streamline curvature variable
$\frac{dp}{dl}$	Change in pressure through test section
l_t	Tail length
ε_{sb_b}	Solid blockage correction for body
ε_{sb_w}	Solid blockage correction for wing
ε_{wb}	Wake blockage boundary correction
λ_3	Horizontal buoyancy boundary correction variable
τ_{1_b}	Solid blockage boundary correction variable for body
τ_{1_w}	Solid blockage boundary correction variable for wing
τ_2	Streamline curvature correction variable
$\Delta C_{L,SC}$	Change in coefficient of lift due to streamline curvature correction
$\Delta C_{PM,SC}$	Change in coefficient of pitching moment - streamline curvature
ΔD_B	Change in drag due to horizontal buoyancy boundary correction
$\Delta \alpha_{SC}$	Change in angle of attack due to streamline curvature correction

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

A wind tunnel is considered “low speed” if the velocity range is less than a Mach number of 0.3, below which it can be assumed that the flow is incompressible. By assuming the flow is incompressible, the primary equations dictating fluid flow are simplified.

Texas A&M University (TAMU) is in a unique position having a large, commercial, low speed wind tunnel located on its campus. There are only six universities in the United States that currently have a low speed wind tunnel with an approximately 7 foot by 10 foot test section. The other universities that have a similar sized wind tunnel are University of Washington, University of Maryland, M.I.T., Wichita State University, and Georgia Tech. The reason that most universities do not own a wind tunnel of this size is because of the significant cost and space needed to build, maintain, and operate it. Additionally, in order to teach just basic concepts to undergraduate students, smaller tunnels are more cost effective. However, commercial entities rarely test in smaller wind tunnels mainly because the data obtained from such tests is usually not accurate enough. The most important aspect when scaling aerodynamic data for low speed testing is the Reynolds number. Matching the Reynolds number between a full size model and a scale model assures that the aerodynamic data can be scaled properly. In the smaller wind tunnels, this Reynolds number matching is impossible for most tests making the aerodynamic data obtained very inaccurate. When a company is developing a multi-million dollar product, it requires wind tunnel data that can be scaled accurately from a smaller model to a full size model. This is usually only achieved in a larger wind tunnel, something on the order of magnitude of the LSWT.

Because most universities only use smaller wind tunnels, most students are not exposed to the nuances of larger scale wind tunnel tests. This puts them at a disadvantage after graduation whether they are continuing their education in graduate school or moving to industry. Most people who fall into these two categories and are faced with doing large scale wind tunnel tests must teach themselves the many facets associated with large scale testing. This presents a unique opportunity for TAMU. The wind tunnel test engineering class developed in this thesis is a bridge between the basic wind tunnel testing techniques taught in TAMU’s Aerospace Engineering Lab I and the wind tunnel testing requirements that a major corporation might require for a commercial venture.

The course goal is to present senior-level undergraduate students a practical wind tunnel test engineering course that outlines the specific requirements of large scale testing. These requirements include wind tunnel wall boundary corrections, tare and interference, internal and external balance use, instrumentation, flow visualizations, and uncertainty analysis. “Practical” in this context means to teach the students how to actually perform the test and get accurate data. It is not so much about the theory behind a testing technique, but more about the how and why of a testing technique. Students will get the tools to perform large scale wind tunnel testing by working through representative examples. There is some theory content, but it is not the focus of the class.

In order to show students practical applications of wind tunnel testing, students execute three experiments modeled after commercial tests performed at the LSWT. These three tests are typical of the primary different types of tests performed at the LSWT. They include testing an offshore oil rig for stability criteria, testing a space re-entry vehicle while performing a tare and interference calculation and applying boundary corrections, and doing a real-world test for a NASA microgravity RC jet project using an internal strain-gauge balance. All of these tests are further explained in the *Experiments* chapter.

The focus of this course is on course content and not on developing a new teaching technique. This material is not currently taught at any major university in the United States, at least not at the undergraduate level. There are a few graduate courses in experimental aerodynamics that teach some of the topics of this class, but none that is as comprehensive and none that actually perform tests in a large scale, wind tunnel. So it is a unique course and one that will benefit TAMU students greatly. Once the course content is better established, new teaching approaches can then be developed in future semesters.

An important part of teaching this course is assessing the new course content and evaluating how well that content meets the overall course goals. These course goals are further developed in the next chapter and found in Appendix E.

2. COURSE DEVELOPMENT AND DESCRIPTION

The objective of this thesis is to outline the development and execution of a practical wind tunnel test engineering course for aerospace engineering students using a commercial low speed wind tunnel for all experiments. This course is mainly built on another course at TAMU, Aero 302: Aerospace Engineering Lab I.

Aero 302 is a junior level lab class that uses small scale wind tunnels and instruments typical of basic aerodynamics experiments. It reinforces and demonstrates concepts taught in Aero 212, 301, and 303 and sets the stage for more sophisticated experimental efforts later. It is a required class and one that students thoroughly enjoy since they actually get hands-on experience during the labs.

The focus of this thesis is to develop and assess a formal class that covers the specific requirements involved in large scale, low speed wind tunnel testing. It does this by performing real-world lab experiments so students can put in to practice all of the concepts that they are learning.

The main reference book used for this course is *Low Speed Wind Tunnel Testing* by Barlow, Rae, and Pope [1]. This book is not written as a textbook, but more of a reference guide for wind tunnel engineers. In its Third Edition, the book covers low speed wind tunnel testing quite well, but does so above the novice level. However, it is one of the only books available that covers low speed wind tunnel testing in any great detail.

The first step in structuring this course was to link program goals of aerospace engineering to course educational objectives. Beginning with the end in mind and executing a reverse planning process in order to meet the desired goals, the course objectives were developed in order to drive the course content. There were lots of factors that played into choosing the goals and objectives for this course. These included: time available for class and lab work, facility availability, anticipated level of knowledge of students in the class, instructor knowledge and teaching ability, and complexity of material. Taking all of these factors into account, Table 1 shows the overall goals for the course.

Aero 489: Program Goals for Fall 2012	
1	Provide students with an opportunity to perform real world tests in a commercial low speed wind tunnel in order to reinforce aerodynamic concepts introduced in previous courses;
2	Increase knowledge of the practical elements of experimental aerodynamics and to develop an appreciation for how aerodynamic data is acquired;
3	Apply modern instrumentation and measurement techniques to the acquisition of aerodynamic data and understand the inherent limitations of each technique;
4	Gain proficiency in estimating experimental uncertainty;
5	Introduce and apply boundary corrections to wind tunnel test data
6	Teach students to critically analyze the results of their experiments and present them in a concise and logical fashion, both in written and oral forms;

Table 1: Program Goals

Using the overall program goals, 33 educational objectives were developed for the course. Each of these objectives is evaluated at the end of the course. Those results can be seen in the *Results and Recommendations* chapter, as well as in Appendix E. The 33 educational objectives for the course are further divided into subcategories. The first subcategory deals with introductory objectives as seen in Table 2 below.

	Educational Objectives:
	Introductory Objectives
1	Apply Bernoulli's equation and conservation of mass to solve a steady, incompressible flow problem
2	Identify the components of a wind tunnel and describe the function of each component
3	Describe the advantages and disadvantages of an Eiffel type wind tunnel
4	Describe the advantages and disadvantages of a Gottingen type wind tunnel
5	Explain in your own words why we need to conduct uncertainty analysis of our experimental results
6	Distinguish between accuracy and precision in reported results
7	Calculate the absolute uncertainty and/or relative uncertainty for measured aerodynamic forces/moments found in experimentation
8	Calculate the linear regression best fit line using the equations from the Numerical Recipes book
9	Explain "Goodness of fit" measure and apply it to your linear regression results
10	Determine when it is better to use a hot wire anemometer instead of a pitot tube for velocity measurement and explain your reasoning
11	Calculate the Fast Fourier Transform (FFT) for a given set of data and identify the dominant frequency

Table 2. Introductory Educational Objectives

These objectives were critical building blocks for continued work in a laboratory experimentation class on wind tunnel testing. Most of the topics covered in these objectives were touched upon in earlier courses at TAMU, so this course went more in depth with some of the concepts so that the students had a very good understanding of the material prior to moving on to advanced concepts.

Pressure, Flow, and Shear Stress Objectives	
12	Identify the different types of pressure measurement devices for wind tunnel experiments
13	Identify the different ways of attaining the flow velocity measurement during a wind tunnel test and describe the principle behind each way
14	Identify the different techniques of measuring skin friction during a wind tunnel experiment and describe the principle behind each technique
15	Describe the purpose and operation of Fringe Imaging Skin Friction (FISF) interferometry
16	Calculate the API standard boundary layer profile given one hour mean wind speed at the reference height, averaging time period, and model scale

Table 3. Pressure, Flow, and Shear Stress Objectives

The next subcategory dealt with pressure, flow, and shear stress measurements as seen in Table 3 above. Admittedly the purpose and operation of Fringe Imaging Skin Friction (FISF) interferometry is quite advanced for undergraduate work. However, it is a technique that another graduate student was actively involved in so there was a wealth of firsthand knowledge that could be used. The last objective for this subcategory directly related to the first experiment conducted in the course as can be seen in the *Experiments* chapter.

The subcategory on wind tunnel reference frames and scaling considerations is very important for getting accurate data from the wind tunnel tests. Two of the five homework sets (see Appendix C) in the class included scaling problems. These educational objectives can be seen in Table 4 below.

Reference Frames and Scaling Objectives	
17	Transform forces and moments from the wind axis reference frame to the body axis reference frame and vice versa
18	Optimize the scaling of a model for a wind tunnel test given the full scale parameters and constraints
19	List the factors that affect scaling determination for a low speed wind tunnel test

Table 4. Reference Frame and Scaling Objectives

The next subcategory dealt with external and internal balances and was crucial for the second and third experiments, respectively. These objectives are seen in Table 5.

External/Internal Balance Objectives	
20	Describe the four main types of external balances
21	List the advantages and disadvantages for each type of external balance
22	List the three quantities that any strut connecting a model to the external balance adds to the balance output
23	Explain how an internal force balance works
24	Describe the two general sources of error for internal balance measurements
25	Apply misalignment and elastic deformation corrections to the forces and moments measured from an internal balance

Table 5. External and Internal Balance Objectives

Information on internal balances is scarce. They are highly complex measuring devices that are still relatively new to wind tunnel testing. AIAA published the best practices for internal balance use only 10 years ago, with a revision 5 years ago [2].

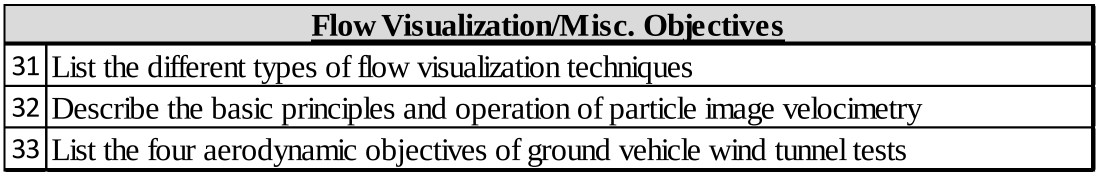
The objectives relating to boundary corrections are the most important objectives of the course. Understanding how and when to apply boundary corrections is critical to large scale, low speed wind tunnel testing. Since a wind tunnel has walls, the raw force and moment data read by an internal or external balance is not completely representative of what the same model would produce in free flight. This data must be corrected for the inclusion of these boundaries. This is a concept that gets little or no exposure in earlier undergraduate classes, but is crucial to the success of a large scale wind tunnel test. The educational objectives in Table 6 were used to determine how well the students received the material.

Boundary Correction Objectives	
26	Calculate the free air loads on an aerodynamic body in the low speed wind tunnel by removing the tare and interference of the strut
27	Determine the up-flow angle in the low speed wind tunnel during an experiment given the upright and inverted configurations of a model
28	Describe the four main boundary corrections used in low speed wind tunnel testing
29	Identify what boundary corrections to apply during an experiment and apply those boundary corrections to the calculated free air loads
30	Distinguish between Maskell’s boundary correction method and Shindo’s simplified boundary correction method

Table 6. Boundary Correction Objectives

These objectives were tested in the last two laboratory experiments and on two of the five homework sets.

The last subcategory dealt with concepts that were covered in the class and are important, but did not fit into another subcategory. It included topics in flow visualization, particle image velocimetry, and ground vehicle testing as seen in Table 7.



	Flow Visualization/Misc. Objectives
31	List the different types of flow visualization techniques
32	Describe the basic principles and operation of particle image velocimetry
33	List the four aerodynamic objectives of ground vehicle wind tunnel tests

Table 7. Flow Visualization and Misc. Objectives

Only in-class lectures were conducted on the above objectives. To further address each objective, a mini-lab exercise could be performed in one of the smaller wind tunnels in the H.R. Bright Building at TAMU. This concept is further explored in the *Results and Recommendations* chapter.

This course was taught in the fall of 2012 to 15 TAMU seniors in the aerospace engineering department as *Aero 489: Wind Tunnel Test Engineering* (see Syllabus in Appendix A). It counted as a technical elective and was worth 3.0 credit hours. The course consisted of 36 lectures, each 50 minutes long and 3 all day labs (8 hours each) at the LSWT. Course notes for each lecture can be found in Appendix B. Every student knew that this was the first time that this course was being taught and everyone was very receptive to giving feedback in order to make the course better for the future.

The format for presenting lectures followed McKeachie’s *Teaching Tips* [3]. Lectures started with an introduction to the material being covered or a summary of material previously learned that was being built upon. For PowerPoint presentations, a notes packet was distributed to the students so they could take notes. The notes packet did not include all of the information that was in the presentation so that students had to pay attention to write down accompanying information to the main points of the lecture. Notes were not handed out if the lecture did not include multimedia. This was so students stayed engaged throughout the lecture by taking notes on what was written on the board. Pictures and videos were used extensively throughout the course to aid in the student’s understanding of the material and to keep them interested. The conclusion of the lecture included the main points of the lecture and gave students a chance to ask questions.

The course was structured so that most work was done in groups. The 15 students were randomly grouped into 3 groups of 5 students each. Each group was responsible for one of the three experiments in the LSWT. Every group had to turn in a lab report at the conclusion of the lab experiment at the LSWT, but for each experiment one of the groups was responsible for also giving an oral briefing to the class on the lab and their results. The lab report format and grading criteria is the same standard used for Aero 302. The oral briefing grading sheet uses a lot of the same criteria as the lab report grading sheet, but also takes into account the quality of the presentation and how well the team gives the presentation. The grading sheets for the lab report and the oral presentation can be found in Appendix F.

Grading for the course consisted of group grades and individual grades. 75% of a student's grade came from the 3 group lab experiments at 25% each, while the remaining 25% came from 5 individual homework sets that were worth 5% each. When a group had to give an oral presentation for a specific lab, the oral presentation was worth 75% of that specific lab group grade and the group's written report was worth 25%. This was done so that the group presenting focused more on the presentation than the lab report. Since most of the coursework was completed in groups, I wanted a way for students to be fairly recognized for their group contributions and graded accordingly. At the conclusion of each lab report/presentation, students submitted an individual assessment of the amount of work that each individual contributed to that particular lab report/presentation. These assessments were used to make minor adjustments to a student's lab grade based on the amount of work that he/she did on the lab [4]. If a student did more work than his/her team members, then it is only fair to give that student a slightly higher grade. If he/she did less work, then to be fair, he/she should get a slightly lower grade.

The course development really centered on the program goals and educational objectives previously discussed. But there would not be a course without the use of the Oran W. Nicks LSWT, so the experiments are equally important to the development of the course since each of the three experiments was chosen to highlight and complement the objectives. Each of the three experiments is discussed in detail in the next chapter.

3. EXPERIMENTS

Each of the three large experiments was chosen to represent the major tests performed in the Texas A&M LSWT. They also were meant to give the students a feel for the different types of experiments typically performed in a large scale wind tunnel. All of the student lab handouts for each experiment can be found in Appendix D.

3.1 Experiment 1

The first experiment used a 1:190 scale model of a semi-submersible offshore oil platform (Fig 1). Since Texas A&M has one of the closest large scale wind tunnels in relation to the Gulf Coast, the LSWT does numerous tests for the offshore oil industry. A laboratory experiment that replicates one of these tests was the natural choice for the first experiment in the class since it is easily set up and provides a good overview of instrumentation and procedures at the LSWT.

Figure 1. Representation of Semi-Submersible Platform

The main objectives for the first lab experiment are for the students to: get an introduction to the LSWT, perform a boundary layer measurement with a hot wire probe, and perform coordinate transformations. There was no key question that was asked of the students for this lab. From experience and from reviewing past offshore oil rig tests that the LSWT conducted, it was concluded that having the students answer a key question on the stability of the platform would have been too time consuming as considerably more time teaching them about hydrodynamics would be needed. Focusing on the wind tunnel test procedures was more important than the specific hydrodynamics and stability of the platform.

Background information provided to the students was helpful in determining the requirements for the test and why we are conducting the test. The background is as follows:

> *Offshore oil platforms are often subjected to harsh marine environments e.g. strong wind and currents. This makes the platform's dynamic positioning, mooring requirements, and stability of utmost importance. Tests of offshore oil platforms are routinely conducted in the Oran W. Nicks Low Speed Wind Tunnel (LSWT) for this reason.*
>
> *Semi-submersible platforms with a small water plane area are very sensitive to weight changes. An over- dimensioned and very heavy mooring system is therefore unfavorable since it limits the payload capacity. Determining the wind and current loads by wind tunnel tests can reduce the dimensions of the moorings thus increasing the allowable weight for payload and increasing the overall cost effectiveness of the offshore oil platform.*
>
> *To determine the wind induced effects with regard to stability, the above-water part of the platform is tested for even keel as well as inclined conditions. Based on the even keel load tests a critical axis is defined as the axis around which, the overturning (pitching) moment is the largest. Inclination tests are*

then made about the critical axis to determine the wind forces and overturning moments [5].

Given the time constraints of the lab, the even keel tests were already conducted. Based on these even keel tests, the critical axis was determined for three different draft heights. Each group was given a different draft height so that no group was replicating the work of another group. At each draft height the semi-submersible oil platform is inclined at two different heel angles, 5° and 30°. At each heel angle, the platform will be rotated ± 40° while force and moment data is read by the LSWT's external balance. This raw data was given to the students to manipulate for their reports.

Students were asked to convert the model scale forces to full scale forces. They then needed to be transferred to the model since the center of the semi-submersible model was not located at the external balance center (Fig. 2).

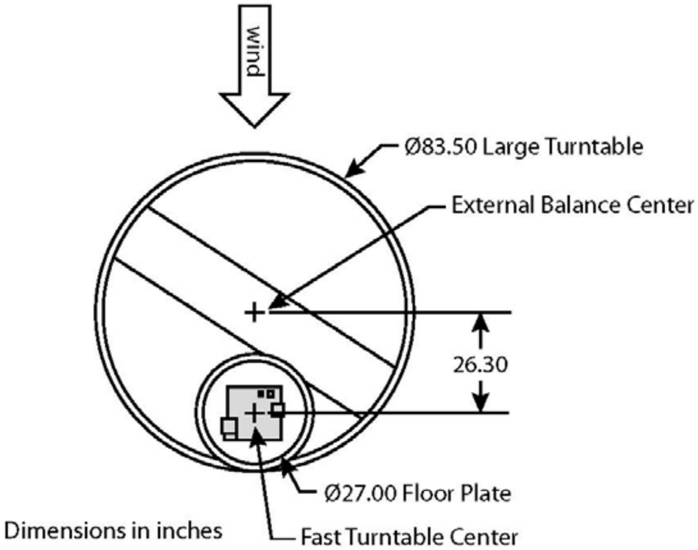


Figure 2. Center of Model in Relation to Balance Center

Students then needed to transfer the forces and moments from the wind axis coordinate system to the body axis coordinate system. Finally they plotted these forces and moments versus the yaw angle.

Another key part of this first experiment was to experimentally determine the boundary layer profile in the wind tunnel and match it to a standard American Petroleum Institute (API) boundary layer profile at 70 knots. This profile is found using the following equations [6]. The first equation for wind speed u(z,t) in ft/s at height (z) in ft above sea level is:

$$u(z,t) = U(z) * [1 - 0.41 * I_u(z) * \ln(\frac{t}{t_0})] \tag{3.1}$$

where the 1 hour mean wind speed U(z) in ft/s at a height (z) in ft is given by:

$$U(z) = U_0 * \left[1 + C * \ln\left(\frac{z}{32.8}\right)\right] \tag{3.2}$$

$$C = 0.0573 * (1 + 0.0457 * U_0)^{\frac{1}{2}} \tag{3.3}$$

and where the turbulence intensity $I_u(z)$ at level z is given by:

$$I_u(z) = 0.06 * [1 + 0.0131 * U_0] * (\frac{z}{32.8})^{-0.22} \tag{3.4}$$

U_0 (ft/s) is the 1 hour mean wind speed at the reference height of 32.8 ft. (10m), and t(s) is an averaging time period (where t $\leq t_0$; t_0 = 3600 seconds). Shorter times correspond to higher potential worst case averages.

Students were asked to plot what the boundary layer should look like based on the API standards. Curves for ±4% uncertainty were also plotted to give the actual boundary layer a left and right limit. We assumed that U_0 = 188 ft/s and t = 1800 seconds. Based on the 1:190 scale model, the API reference height of 32.8 ft corresponds to 2.07 inches in the wind tunnel. Students were asked to plot the height vs. velocity in the tunnel from 1 inch to 35 inches. Based on time constraints, we did not adjust the boundary layer profile in the tunnel, but instead we used the boundary layer fence from the last test that the LSWT conducted (Fig. 3). Setting the boundary layer in the wind tunnel can take anywhere from 5 to 15 hours of wind tunnel time.

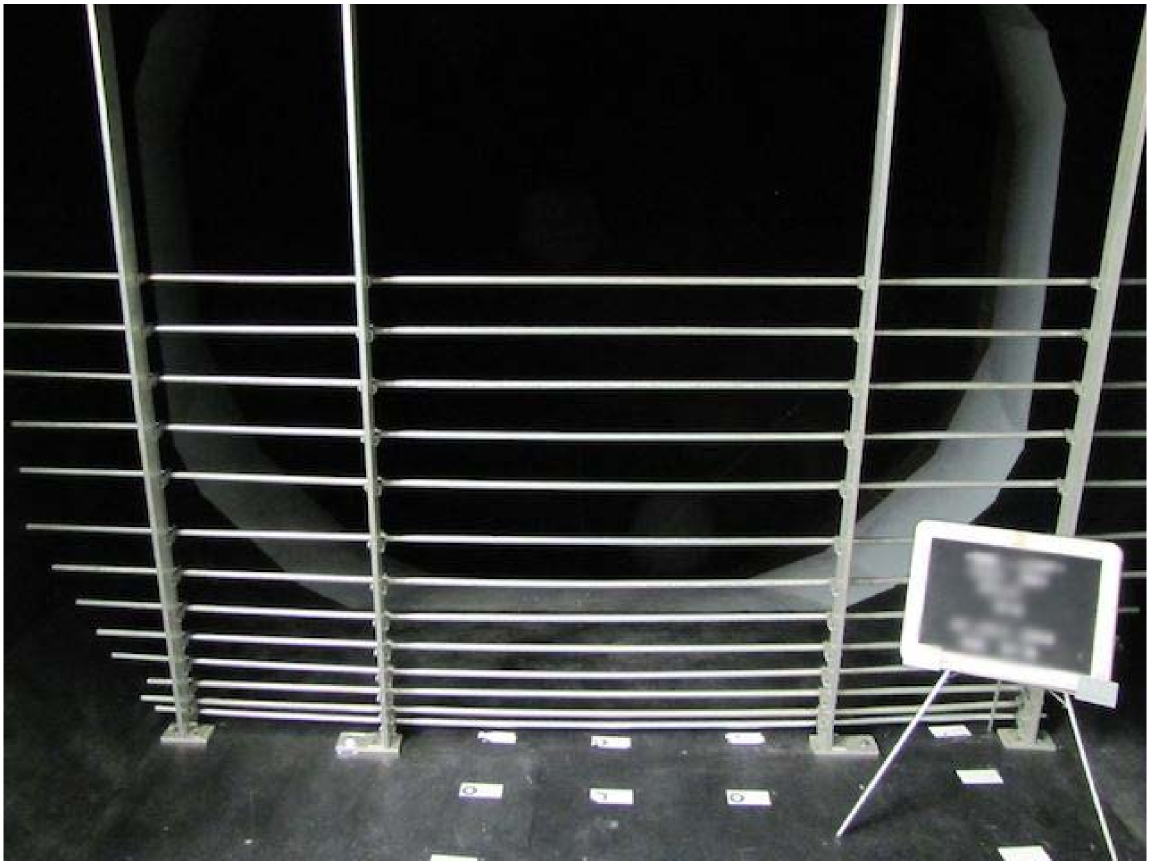


Figure 3. Boundary Layer Fence in LSWT

As a demonstration, on lab day a hot wire probe was installed in the tunnel and took measurements from 1 inch to 35 inches at 1 inch increments at a dynamic pressure value of 48.5 psf. This was then plotted in real time against the API standard boundary layer profile to see how accurate the boundary layer fence was configured. It was important for the students to see how this is accomplished since it is an integral part of the testing for this type of model. However, all of the objectives for the lab could still be met without using precious wind tunnel time to set up the boundary layer profile perfectly.

The students had two weeks to work on their lab reports/presentation. This first lab report was limited to six pages, and the presentation needed to be less than 30 minutes in length. The results of the lab can be seen in the *Results and Recommendations* chapter.

3.2 Experiment 2

The second lab experiment utilized a 1:10 scale model of NASA's X-38 space re-entry vehicle (see Fig 4). The key question during this lab was: is the X-38 a directionally stable platform after re-entry into the Earth's atmosphere?

Figure 4. NASA’s X-38 Crew Recovery Vehicle (CRV)

The main objectives for this lab are: perform tare and interference calculations, utilize the pyramidal external balance system of the LSWT, apply boundary corrections and upflow angle corrections to the data, and calculate uncertainty in the results.

The background information given to the students for this lab is as follows:

> *NASA’s X-38 CRV is an example of a wingless lifting body. Wingless lifting bodies generate aerodynamic lift - essential to flight in the atmosphere - from the shape of their bodies.*
>
> *When operational, the CRV will be an emergency vehicle to return up to seven International Space Station (ISS) crewmembers to Earth. It will be carried*

> *to the space station in the cargo bay of a space shuttle and attached to a docking port. If an emergency arose that forced the ISS crew to leave the space station, the CRV would be undocked and - after a deorbit engine burn - the vehicle would return to Earth much like a space shuttle. A steerable parafoil parachute would be deployed at an altitude of about 40,000 feet to carry it through the final descent and the landing. The CRV is being designed to fly automatically from orbit to landing using onboard navigation and flight control systems. Backup systems will allow the crew to pick a landing site and steer the parafoil to a landing, if necessary* [7].

The LSWT did some testing for NASA for this project before it was cancelled due to budget constraints. One of the scale models of the X-38 is still on loan to Texas A&M and provided a great test vehicle for the class since it is an excellent platform to show the tare and interference correction and allowed the students to recreate an actual test performed on a space re-entry vehicle that NASA spent millions of dollars on to create.

The model was placed in the test section of the LSWT at two different angles of attack, 0° and 10°. At each angle of attack, a yaw sweep of ±35° was performed. The dynamic pressure in the tunnel was 85 psf, which equates to a wind velocity of approximately 180 mph.

In order to get accurate loads on the model, first the students had to remove the effects of the strut that was used to hold the model in the wind tunnel. Any strut connecting a model to the balance can be considered to add three quantities to the balance output: direct aerodynamic force of the strut (tare), effect strut has on airflow on model (interference), and effect model has on airflow of the strut (interference) [1]. Performing this tare and interference calculation involves using image struts in the wind tunnel and testing the model upright and inverted (see Fig 5).

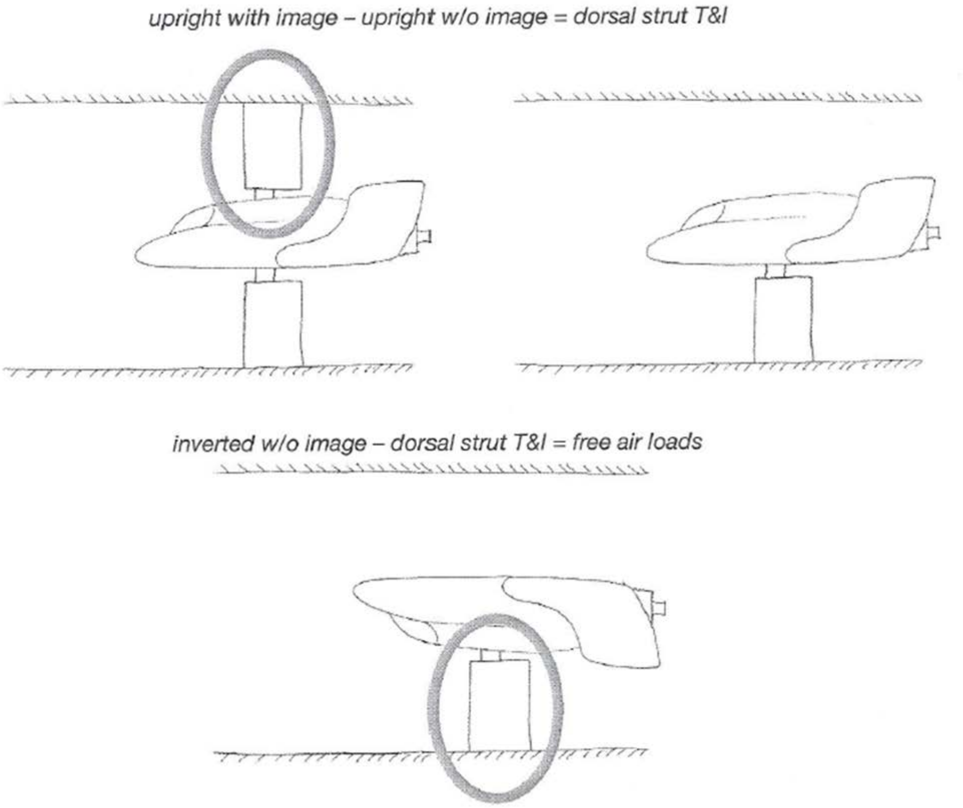


Figure 5. Tare and Interference Calculation Diagram

Due to time constraints with the lab each group only got to see one configuration of the model, i.e. upright with image strut, upright without image strut, inverted without image strut. All of the data was given to the students so that they could find the free air loads on the X-38 model.

The students also needed to find the up-flow angle in the wind tunnel. Especially when a model is installed, the air flowing through the test section is not perfectly horizontal. In the LSWT there is a slight up-flow of approximately 0.5° to 1°. In order to find this angle, students need data for a model that is upright with image strut attached and for a model that is inverted with image strut attached. After plotting the coefficient of lift versus the angle of attack, the students can see that there is indeed an up-flow angle in the tunnel. If these two plots were the same, then there would be no up-flow angle. In order to find the up-flow angle, the lines are extended to where they both cross the x-axis (angle of attack). Half the distance between where each line crosses the x-axis is equal to the up-flow angle.

Other corrections that need to be applied to this data are boundary corrections for wake blockage and solid blockage. Wake blockage is attributed to the model drag creating a decelerated wake that decreases effective flow cross sectional area and increases the velocity seen by the model. Solid blockage from the model decreases the effective area for the flow around the model resulting in the model seeing a higher velocity than measured in the test section [1]. Both of these corrections are due to the walls of the wind tunnel. There is a finite area that the air flows through in a test section and because of conservation of mass and Bernoulli’s equation, reducing the area increases the velocity. So in order to get accurate results, boundary corrections for solid blockage and wake blockage must be applied.

In wind tunnel tests, engineers are more concerned with the dynamic pressure, q, of the flow which includes the velocity of the flow and the air density instead of just the velocity of the flow by itself. For this reason we are concerned with finding the corrected dynamic pressure value, q_{corr}, after applying the solid blockage and wake blockage corrections. The formula [1] to find the corrected dynamic pressure is:

$$q_{corr} = q_{act}(1 + \varepsilon_{wb} + \varepsilon_{sb_w} + \varepsilon_{sb_b})^2 \tag{3.5}$$

where q_{act} is the raw dynamic pressure measured during the wind tunnel test, ε_{wb} is the correction [1] due to wake blockage which equals:

$$\varepsilon_{wb} = \frac{SD}{2Cq_{act}} \tag{3.6}$$

The solid blockage can be broken down into two equations [1] that deal with the wing and the body, respectively.

$$\varepsilon_{sb_w} = \frac{K_1 \tau_{1_w} V_w}{C^{\frac{3}{2}}} \tag{3.7}$$

$$\varepsilon_{sb_b} = \frac{K_3 \tau_{1_b} V_b}{C^{\frac{3}{2}}} \tag{3.8}$$

$\tau_{1_w}, \tau_{1_b}, K_1$, and K_3 are solid blockage variables that can be found in the charts in Fig. 6 below. B/H for the LSWT is equal to 1.43.

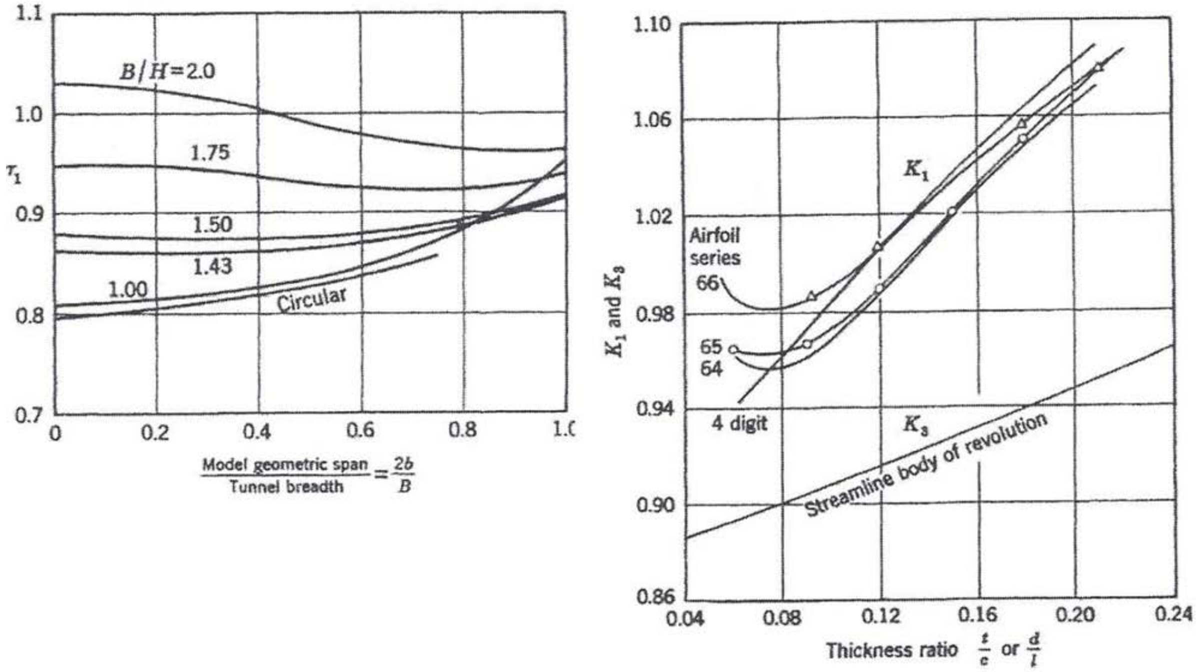


Figure 6. Charts to Find Variables for Solid Blockage Corrections [1]

The key graph for the second lab report dealt with the coefficient of yawing moment versus the yaw angle. Based on the sign convention, if there was a positive slope on this graph it meant that the space re-entry vehicle was directionally stable. If you look at the graph in Fig. 7, you can see that the X-38 has a negative slope for this comparison meaning that it is not a stable platform.

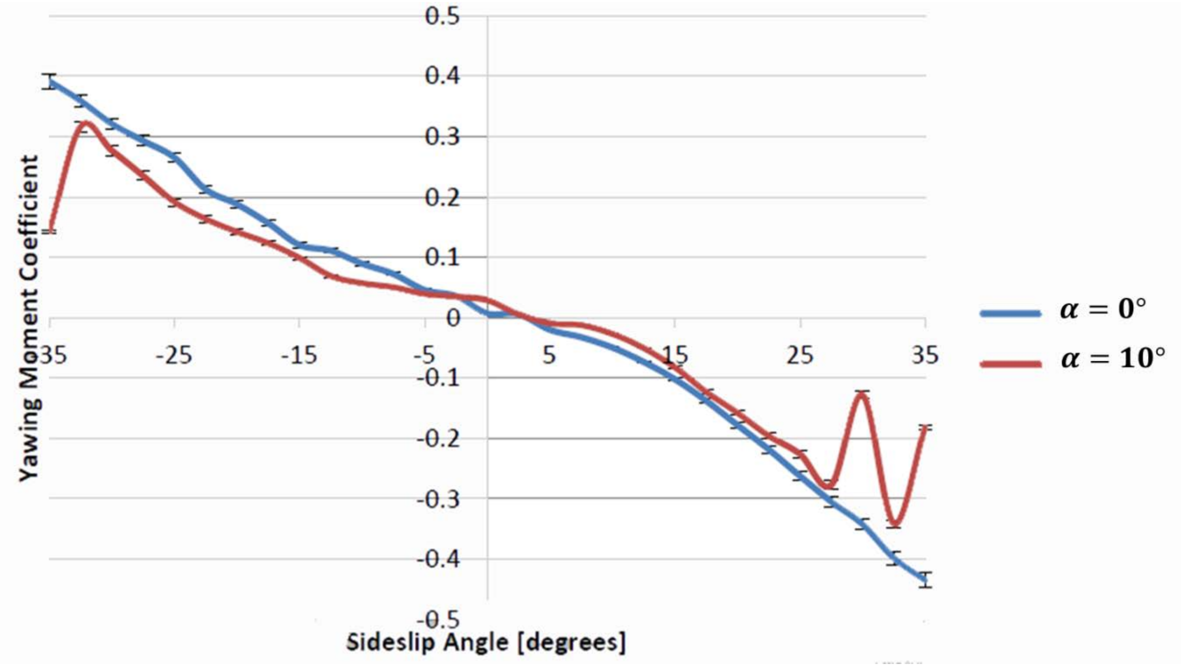


Figure 7. Coefficient of Yawing Moment versus Sideslip Angle for X-38

The X-38 is not a directionally stable platform in the subsonic flight regime. This is probably why NASA chose to deploy a parafoil parachute at 40,000 feet after the X-38's re-entry into Earth's atmosphere. Prior to this flight level, the X-38 is supersonic and is actually quite stable. This was a good experiment and one that showed the students how wind tunnel tests can aid in the design and testing of a vehicle.

3.3 Experiment 3

The third experiment allowed us to conduct a real-world experiment for NASA's Unmanned Microgravity Flight Program using the DV8R commercial RC jet (Fig 8).

NASA microgravity facilities include drop towers (limited to 3-4 seconds) and the expensive manned 727 aircraft. The NASA Unmanned Microgravity Flight Program aims to develop a small, unmanned, turbine-powered aircraft capable of carrying 8-10 lb. payloads in a shoe-box size compartment on microgravity parabolas up to 12 seconds in length. A phased approach to testing will take place once flight clearance is granted. Phase I will see the aircraft flown manually by a pilot in a virtual cockpit. The autopilot will downlink telemetry to populate virtual ground displays. During phase II the aircraft roll and yaw axes will be stabilized by the autopilot; off-loading the human pilot to concentrate solely on pitch and throttle. During phase III the autopilot software will be modified to fly the entire parabola automatically while the vehicle is taken off and landed manually. [8]

Figure 8. DV8R Unmanned Microgravity Flight Platform

Since this program is still in the initial phase of testing, wind tunnel test data is required to help develop the autopilot function and take this program to the next phase. NASA agreed to allow my wind tunnel test engineering class to perform some of the tests for this program. It was a great opportunity for the class to do some real-world testing that had the potential for real growth in NASA's program.

NASA really just wanted the forces and moments from the wind tunnel tests, so creativity was needed to come up with a key question that the students could answer. The key question for this lab: Is there aerodynamic hysteresis after stall and why is this important? The main objectives for the lab are: utilize an internal balance, apply boundary corrections, use a flow visualization technique, and conduct uncertainty analysis and linear regression.

NASA's DV8R is a commercial, off the shelf RC jet that they have modified with a more powerful gas engine. It has a wingspan of 83 inches and a body length of 87 inches. We mounted it (see Fig 9) on the LSWT's High Attitude Robotic Sting (HARS) and used a Task Mark XIII internal balance to gather our force and moment data.

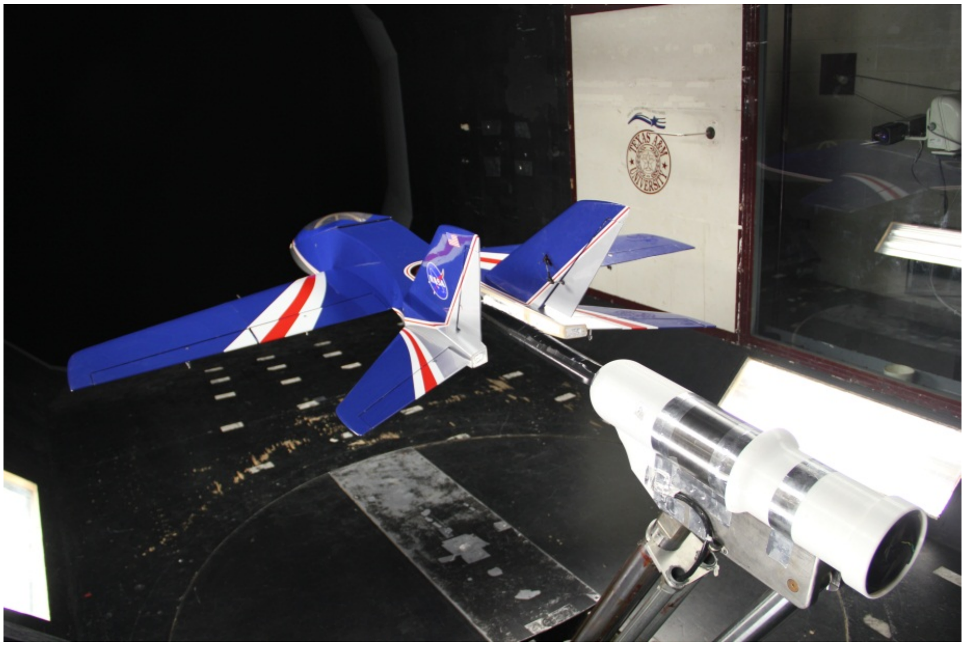


Figure 9. DV8R Mounted on HARS inside LSWT

Internal balance use on this experiment was important because it gave the students exposure to the nuances of using an internal balance. The main one being sting deflection corrections that must be applied to the data. Sting deflections are measured prior to the experiment by hanging weights with a known value and measuring deflections. This gives a chart to use for sting deflections after the actual forces are measured.

The RC Jet was placed in the LSWT and measurements were taken for angles of attack ranging from -15° to +20°. Inverted measurements were also taken in order to find the up-flow angle. Servos were mounted inside NASA's RC Jet in order to control the ailerons, rudder, and elevators. These were controlled through a radio control transmitter operated by one of the LSWT technicians. The plan was to make small control inputs and take force and moment data through a set angle of attack range.

Smoke was also used in this experiment to see one of the many flow visualization techniques taught in the course. Figure 10 shows a great example of wing tip vortices on the model.

Figure 10. Wing Tip Vortices from DV8R

Students were asked to apply boundary corrections to the data that was obtained in the test. They applied wake blockage and solid blockage corrections in the same way that they had to apply them from the second experiment. They also needed to apply horizontal buoyancy and streamline curvature boundary corrections to the data.

Horizontal Buoyancy is a variation of static pressure along the test section that produces a drag force analogous to the hydrostatic force on objects in a stationary fluid in a uniform gravitational field [1]. This variation in static pressure results from the thickening of the boundary layer as it progresses toward the exit cone. Pressure is progressively more negative as the exit cone is approached, so there is a tendency for the model to be “drawn” downstream. This results in additional drag on a model in a wind tunnel. The following equation is used to correct for this [1]:

$$\Delta D_B = -\frac{\pi}{4}\lambda_3 {t_b}^3 \frac{dp}{dl} \tag{3.9}$$

The chart in figure 11 is used to find λ_3, which is approximately 5 for this experiment. However since the wind tunnel walls in the LSWT are canted slightly outward to account for the growth of the boundary layer in the test section, the change in drag due to horizontal buoyancy is negligible for this experiment. Students were expected to realize this fact and make a comment about it in their lab report.

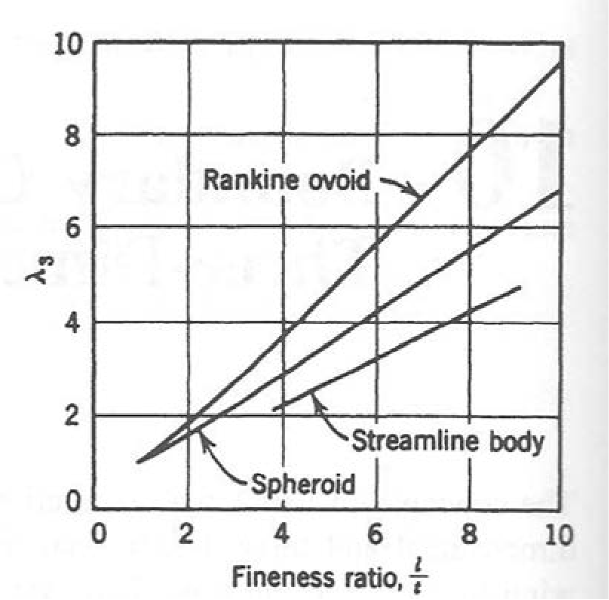


Figure 11. Chart to Find λ_3 for Horizontal Buoyancy [1]

The last boundary correction that needs to be applied is streamline curvature. Streamline Curvature is only applied to bodies that generate lift. The presence of the walls prevents the normal curvature of the free air that occurs over lifting bodies resulting in the body appearing to have more camber than it actually has. This affects the accuracy of the lift force, the pitching moment, and changes in angle of attack. The equations that govern streamline curvature corrections from are [1]:

$$\triangle \alpha_{SC} = \tau_2 \delta \left(\frac{S}{C}\right) C_L \tag{3.10}$$

$$\Delta C_{L,SC} = -\Delta \alpha_{SC} \cdot \mathrm{a} \tag{3.11}$$

$$\Delta C_{PM,SC} = -0.25\ \Delta C_{L,SC} \tag{3.12}$$

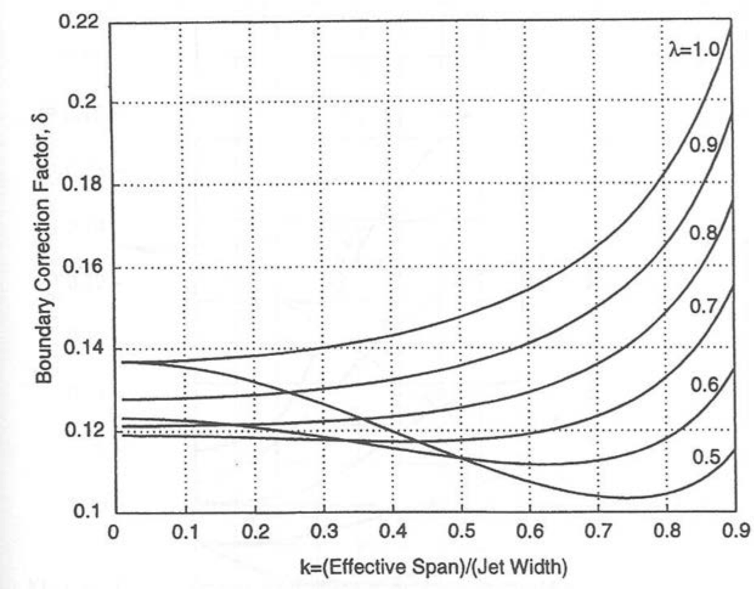


Figure 12. Chart to Find Boundary Correction Factor [1]

For this experiment the effective span of our model divided by the jet width is equal to approximately 0.7. For streamline curvature λ is the tunnel aspect ratio, so for the LSWT this equals 0.7. Using the chart in figure 12, our boundary correction factor is 0.122.

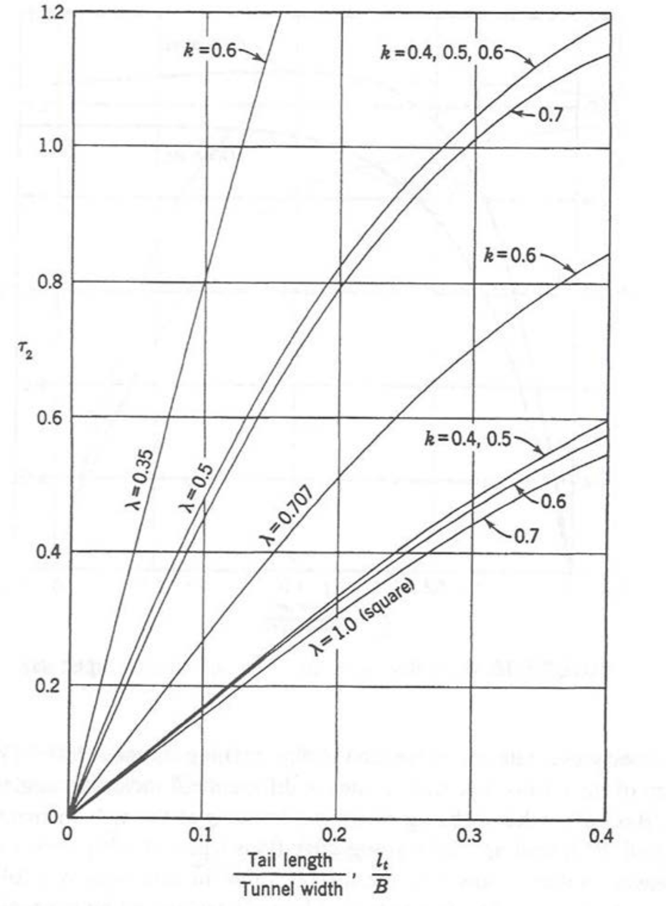


Figure 13. Chart to Find τ_2[1]

Tail length is equal to ¼ of the wing chord length. Using the chart in figure 13, τ_2 is equal to 0.1.

Another deliverable for the lab was to find $C_{D,0}$ and perform a linear regression in order to find a C_D-fit line for the drag polar (C_D vs. C_L) plot. In order to do this, the students were given the following equation which is applicable within some limits before stall onset [9]:

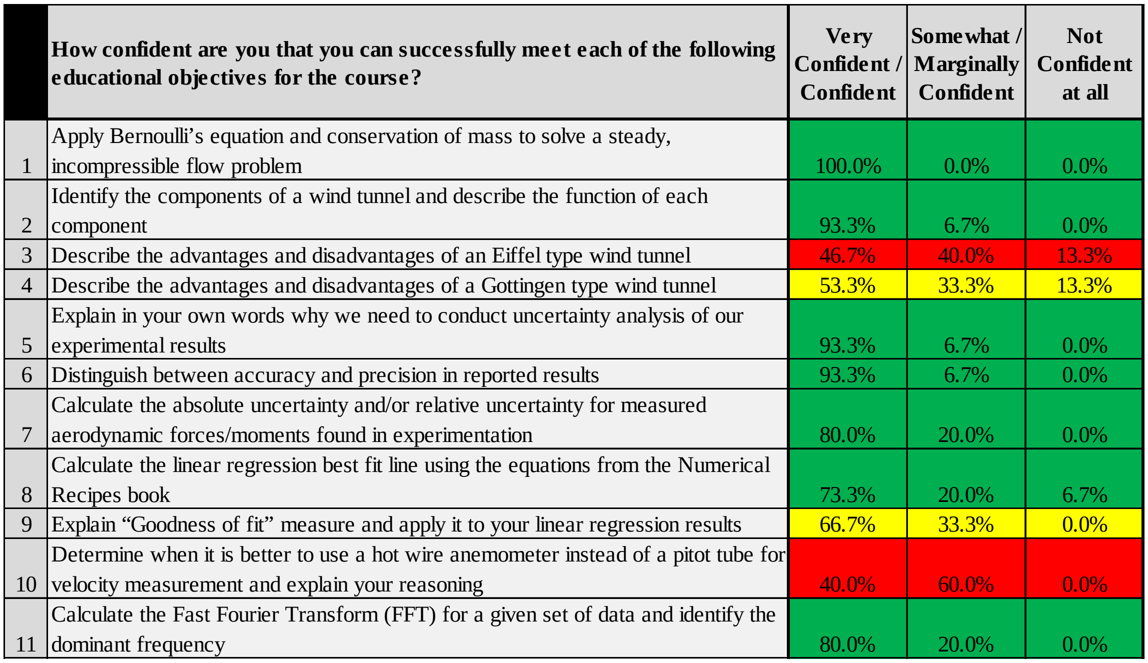
$$C_D = C_{D,0} + \kappa C_L^2 \tag{3.12}$$

Then they needed to use the equations from Press's *Numerical Recipes* [10] in order to find the variables and their uncertainties. Those equations can be found in the class notes in Appendix B as well as in the lab experiment handout in Appendix D. Students were then asked to quantify how well their C_D-fit line matched the actual data. By using the formula for χ^2, the students were able to give a numerical estimate of how well the uncertainty was estimated or a "Goodness of Fit" measure.

This was a long lab and one that was a culmination of the learning expected of the students throughout the class. The lab report was limited to 10 pages, but each group included all of their calculations as appendices, which did not count against their 10 page limit. The quality of work on this last lab was quite impressive despite the challenges of actually conducting it.

4. RESULTS AND RECOMMENDATIONS

The end of course survey was used to gauge how confident the students were in meeting the course educational objectives. Homework 5 listed all of the educational objectives and had the students circle whether they were extremely confident, confident, somewhat confident, marginally confident, or not confident at all. The extremely confident and confident answers were grouped together and the somewhat and marginally confident answers were grouped together. These can be seen in the following chart (Table 8) for the introductory objectives.

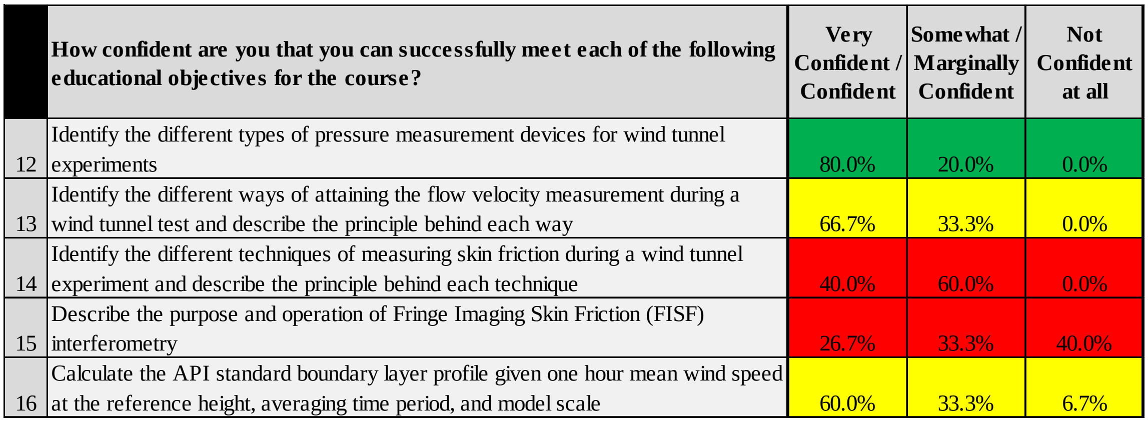


	How confident are you that you can successfully meet each of the following educational objectives for the course?	**Very Confident / Confident**	**Somewhat / Marginally Confident**	**Not Confident at all**
1	Apply Bernoulli’s equation and conservation of mass to solve a steady, incompressible flow problem	100.0%	0.0%	0.0%
2	Identify the components of a wind tunnel and describe the function of each component	93.3%	6.7%	0.0%
3	Describe the advantages and disadvantages of an Eiffel type wind tunnel	46.7%	40.0%	13.3%
4	Describe the advantages and disadvantages of a Gottingen type wind tunnel	53.3%	33.3%	13.3%
5	Explain in your own words why we need to conduct uncertainty analysis of our experimental results	93.3%	6.7%	0.0%
6	Distinguish between accuracy and precision in reported results	93.3%	6.7%	0.0%
7	Calculate the absolute uncertainty and/or relative uncertainty for measured aerodynamic forces/moments found in experimentation	80.0%	20.0%	0.0%
8	Calculate the linear regression best fit line using the equations from the Numerical Recipes book	73.3%	20.0%	6.7%
9	Explain “Goodness of fit” measure and apply it to your linear regression results	66.7%	33.3%	0.0%
10	Determine when it is better to use a hot wire anemometer instead of a pitot tube for velocity measurement and explain your reasoning	40.0%	60.0%	0.0%
11	Calculate the Fast Fourier Transform (FFT) for a given set of data and identify the dominant frequency	80.0%	20.0%	0.0%

Table 8. Results of Survey on Introductory Objectives

Green means that at least 70% of the students were confident in meeting that objective, yellow means that between 50% to 70% of the students were confident in meeting that objective, and red means that less than 50% of the students were confident that they could meet that objective.

When looking at the results of the survey for the introductory objectives, the first thing that jumps out is that only about half the students can name the advantages and disadvantages of using a Gottingen or Eiffel type wind tunnel. This is a concept that was covered on the second day of class and one that the students were not tested on, so it is no surprise that it scored low. However after talking with several of the students, the thing that threw them off on the question was that the wind tunnels were referred to as "Gottingen" and "Eiffel" instead of "closed" and "open" type, respectively. As soon as I said closed and open, they knew immediately and would have put down that they were a lot more confident on the survey. Knowing when to use a hot wire anemometer versus a pitot tube for velocity measurements again was something that was covered toward the beginning of the class and one that I did not test them on. The results of "Goodness of Fit" measure and application to linear regression results are a little concerning. This is a topic that is covered in Aero 302, but it is something that they do in groups in that class. HW#2 required that they do this individually and then in groups on lab report #3. Most people did not do very well when asked to apply it on HW#2, so I went over the solution in class. There were issues with it on Lab Report #3 as well. My recommendation is to spend another 0.5 hours teaching this subject while going over more examples with the students.



	How confident are you that you can successfully meet each of the following educational objectives for the course?	**Very Confident / Confident**	**Somewhat / Marginally Confident**	**Not Confident at all**
12	Identify the different types of pressure measurement devices for wind tunnel experiments	80.0%	20.0%	0.0%
13	Identify the different ways of attaining the flow velocity measurement during a wind tunnel test and describe the principle behind each way	66.7%	33.3%	0.0%
14	Identify the different techniques of measuring skin friction during a wind tunnel experiment and describe the principle behind each technique	40.0%	60.0%	0.0%
15	Describe the purpose and operation of Fringe Imaging Skin Friction (FISF) interferometry	26.7%	33.3%	40.0%
16	Calculate the API standard boundary layer profile given one hour mean wind speed at the reference height, averaging time period, and model scale	60.0%	33.3%	6.7%

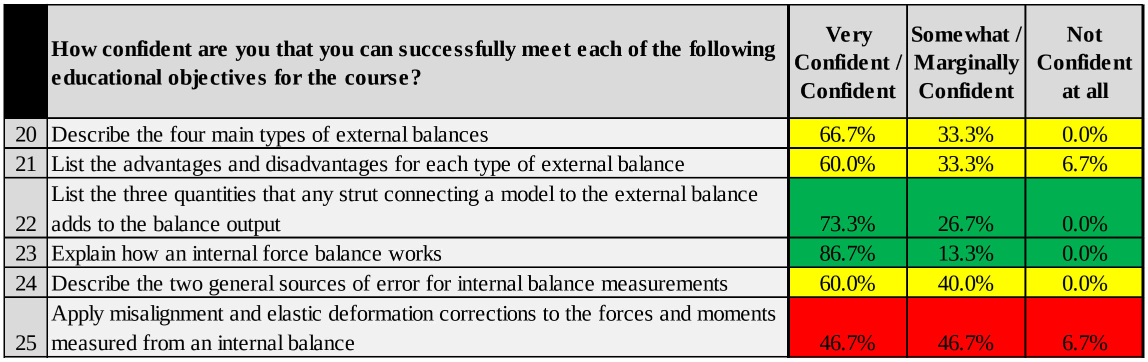
Table 9. Results of Survey on Pressure, Flow, and Shear Stress Objectives

Table 9 outlines the results of the end of course survey when dealing with the pressure, flow, and shear stress educational objectives. Very few people were confident in describing the purpose and operation of Fringe Imaging Skin Friction (FISF) Interferometry. This is very advanced for the undergraduate level. However, giving undergraduates exposure to techniques like this is a way to really make the students stand out when applying for graduate schools or getting a job in the aerospace industry. Most aerospace engineering undergraduates are not going to be exposed to this technique. My recommendation is that a mini-lab be performed in the 3 foot by 4 foot wind tunnel in the basement of the H.R. Bright Building. Allowing the students to witness and participate in an experiment that uses this technique will greatly improve their understanding of it. Running this mini-experiment would also help with the student’s understanding of identifying the different types of skin friction measurement.

	How confident are you that you can successfully meet each of the following educational objectives for the course?	**Very Confident / Confident**	**Somewhat / Marginally Confident**	**Not Confident at all**
17	Transform forces and moments from the wind axis reference frame to the body axis reference frame and vice versa	93.3%	6.7%	0.0%
18	Optimize the scaling of a model for a wind tunnel test given the full scale parameters and constraints	100.0%	0.0%	0.0%
19	List the factors that affect scaling determination for a low speed wind tunnel test	100.0%	0.0%	0.0%

Table 10. Results of Survey on Reference Frame and Scaling Objectives

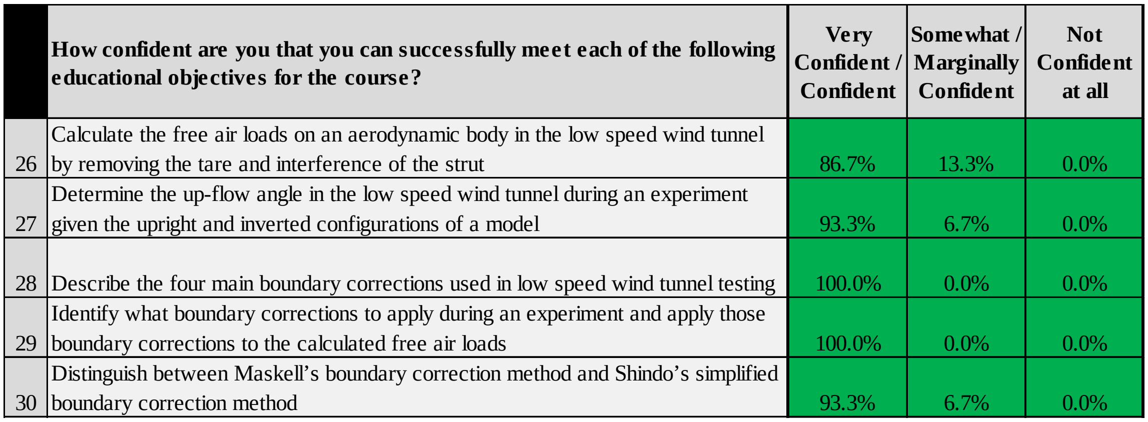
Table 10 highlights the results of survey with regards to the reference frame and scaling objectives and shows that the students understood some of the concepts that were really emphasized. When the class did not do very well on the scaling problem on HW#3, I decided to include more scaling problems on HW#4. This last minute change really helped drive home the concept of scaling and the difficulties associated with scaling when conducting wind tunnel tests.



	How confident are you that you can successfully meet each of the following educational objectives for the course?	**Very Confident / Confident**	**Somewhat / Marginally Confident**	**Not Confident at all**
20	Describe the four main types of external balances	66.7%	33.3%	0.0%
21	List the advantages and disadvantages for each type of external balance	60.0%	33.3%	6.7%
22	List the three quantities that any strut connecting a model to the external balance adds to the balance output	73.3%	26.7%	0.0%
23	Explain how an internal force balance works	86.7%	13.3%	0.0%
24	Describe the two general sources of error for internal balance measurements	60.0%	40.0%	0.0%
25	Apply misalignment and elastic deformation corrections to the forces and moments measured from an internal balance	46.7%	46.7%	6.7%

Table 11. Results of Survey for External and Internal Balance Objectives

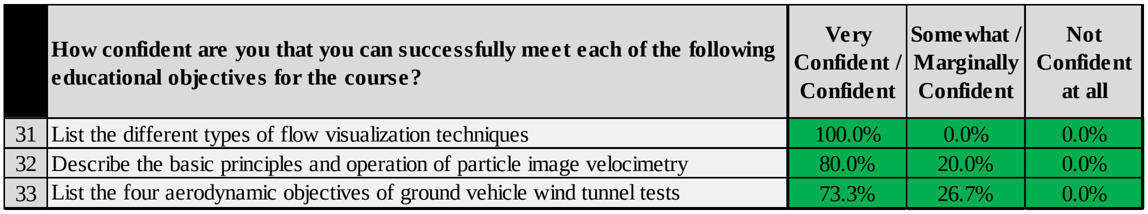
The educational objectives dealing with external and internal balances (Table 11) really highlight that the students were not tested on these objectives. Class content covered all of the objectives, but there were no homework questions related to the objectives. Lab #3 really went in-depth on how an internal balance works, so it is good to see that objective having such a high confidence percentage as it is a difficult subject to understand. My recommendation is to include a question on one of the homework assignments about internal balance misalignment and elastic deformation corrections that will really emphasize this educational objective.



	How confident are you that you can successfully meet each of the following educational objectives for the course?	Very Confident / Confident	Somewhat / Marginally Confident	Not Confident at all
26	Calculate the free air loads on an aerodynamic body in the low speed wind tunnel by removing the tare and interference of the strut	86.7%	13.3%	0.0%
27	Determine the up-flow angle in the low speed wind tunnel during an experiment given the upright and inverted configurations of a model	93.3%	6.7%	0.0%
28	Describe the four main boundary corrections used in low speed wind tunnel testing	100.0%	0.0%	0.0%
29	Identify what boundary corrections to apply during an experiment and apply those boundary corrections to the calculated free air loads	100.0%	0.0%	0.0%
30	Distinguish between Maskell’s boundary correction method and Shindo’s simplified boundary correction method	93.3%	6.7%	0.0%

Table 12. Results of Survey Related to Boundary Correction Objectives

The boundary correction objectives seen in Table 12 are all green meaning that very few people in the class did not feel confident meeting those objectives. These objectives were the most important objectives in the course and their content comprised a good portion of class time as well as homework and lab reports. The time spent on these objectives should remain the same.

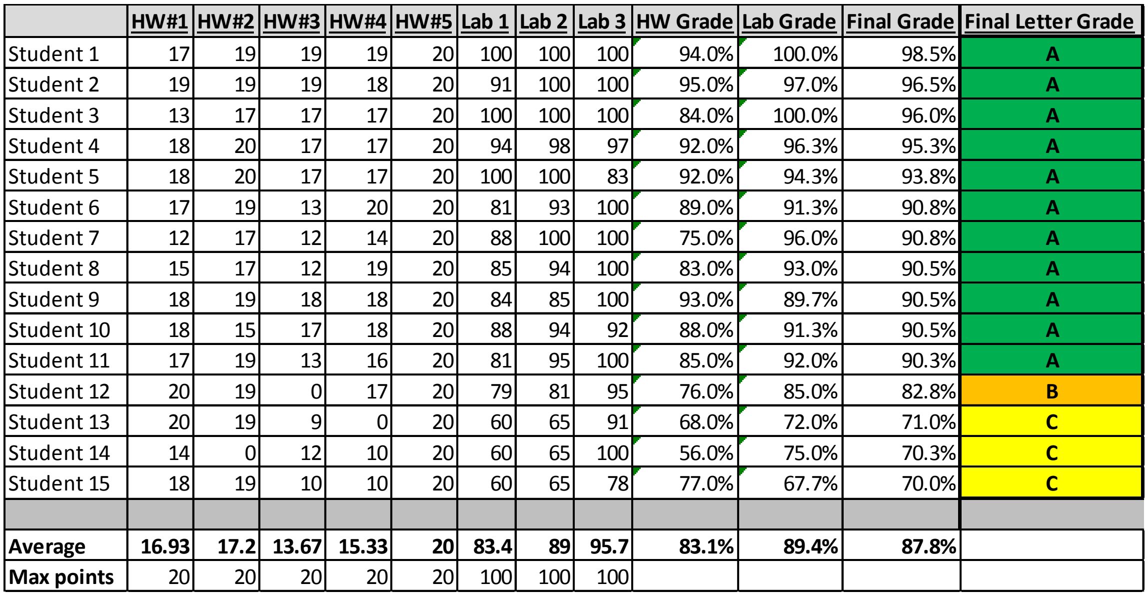


	How confident are you that you can successfully meet each of the following educational objectives for the course?	Very Confident / Confident	Somewhat / Marginally Confident	Not Confident at all
31	List the different types of flow visualization techniques	100.0%	0.0%	0.0%
32	Describe the basic principles and operation of particle image velocimetry	80.0%	20.0%	0.0%
33	List the four aerodynamic objectives of ground vehicle wind tunnel tests	73.3%	26.7%	0.0%

Table 13. Results of Survey for Flow Visualization/Miscellaneous Objectives

The objective above that relates to particle image velocimetry (Table 13) was one of the harder objectives to cover in the class. An entire class period was devoted to PIV.

This included going in depth on how to set up this procedure and why we would use this particular technique. This is another technique that the students would really benefit from by having a mini-lab experiment built around it. PIV is going to be set up in the LSWT over the next few years based on research funding that was just attained. This is a great opportunity to expose undergraduates to a technique that very few graduate students even know about.



	HW#1	HW#2	HW#3	HW#4	HW#5	Lab 1	Lab 2	Lab 3	HW Grade	Lab Grade	Final Grade	Final Letter Grade
Student 1	17	19	19	19	20	100	100	100	94.0%	100.0%	98.5%	A
Student 2	19	19	19	18	20	91	100	100	95.0%	97.0%	96.5%	A
Student 3	13	17	17	17	20	100	100	100	84.0%	100.0%	96.0%	A
Student 4	18	20	17	17	20	94	98	97	92.0%	96.3%	95.3%	A
Student 5	18	20	17	17	20	100	100	83	92.0%	94.3%	93.8%	A
Student 6	17	19	13	20	20	81	93	100	89.0%	91.3%	90.8%	A
Student 7	12	17	12	14	20	88	100	100	75.0%	96.0%	90.8%	A
Student 8	15	17	12	19	20	85	94	100	83.0%	93.0%	90.5%	A
Student 9	18	19	18	18	20	84	85	100	93.0%	89.7%	90.5%	A
Student 10	18	15	17	18	20	88	94	92	88.0%	91.3%	90.5%	A
Student 11	17	19	13	16	20	81	95	100	85.0%	92.0%	90.3%	A
Student 12	20	19	0	17	20	79	81	95	76.0%	85.0%	82.8%	B
Student 13	20	19	9	0	20	60	65	91	68.0%	72.0%	71.0%	C
Student 14	14	0	12	10	20	60	65	100	56.0%	75.0%	70.3%	C
Student 15	18	19	10	10	20	60	65	78	77.0%	67.7%	70.0%	C
Average	**16.93**	**17.2**	**13.67**	**15.33**	**20**	**83.4**	**89**	**95.7**	**83.1%**	**89.4%**	**87.8%**	
Max points	20	20	20	20	20	100	100	100				

Table 14. Final Grade Distribution

Besides feedback forms from the students, grades were also used to determine the relative success of the course. Student grades can be seen above in Table 14. The average percentage in the class was 87.8%. The only students that did not get an A in the class either did not turn in one of the homework sets, or participated minimally in one or more of their group lab reports. Since this was a new course, I did not want to make it so challenging that everyone failed, nor did I want to make it too easy so that everyone got an A. The homework sets that were developed (seen in Appendix C) proved to be just about the correct level of difficulty with an 83.1% average.

The lab report quality definitely got better throughout the semester. I graded lab reports for Aero 302 in a previous semester so knew exactly what standard was set by that course. The standard in this course was the same, if not a little higher since all of the students were now seniors. It showed a good trend that lab report grades went from an average of 83.4% on lab 1 to 95.7% on lab 3, which was arguably the hardest lab. Overall I am very happy with the level of work that the students turned in and their grades are a direct reflection of that satisfaction.

Throughout the semester after action reviews were conducted after each lab and then a final comprehensive after action review was conducted for the class. These reviews yielded many recommendations for improvement, but also let me know that I was generally on the correct path with respect to the class content and delivery. Most recommendations were minor tweaks to the content instead of recommendations for drastic change to the course material. I took this feedback from the students, evaluated it, and came up with recommendations to improve the course. These recommendations can be broken down into two categories: implement immediately and implement sometime in the future, if possible.

There are several recommendations for improvement to the course content that should be implemented immediately. The most common comment on the feedback form was that students wanted to be more involved in the experiment set-up. Since I already have one group designated to give a presentation on a certain experiment, **I recommend that group elect a leader who would act as a liaison to the LSWT. This leader would coordinate with the LSWT, and the group would participate with all aspects of the experiment to include installation and procedures, such as sting deflection calibrations.** This would also aid in giving a more in-depth presentation to the class by the group that helped set-up the experiment.

Another recommendation that should be implemented immediately is to conduct a mini-lab on flow visualization in the 3 foot by 4 foot wind tunnel in the basement of the H.R. Bright building. It would be very easy to show the use of tufts, china clay, and oil flow. The china clay and oil flow would be very messy, but I feel the value gained by such an experiment would outweigh the costs. In addition, it would give the students a lot more hands-on time in the laboratory. The students could apply tufts with little guidance, but a member of the LSWT staff would probably need to help with the china clay solution and the oil flow visualization. It would be straightforward to observe the boundary layer transition point on a cambered airfoil using oil flow visualization. All that would be needed is a mixture of titanium dioxide suspended in linseed oil and a cambered airfoil. Smoothly adjust the angle of attack of the airfoil from 0° to 30° in order to see the transition point move on the airfoil's surface. It is an experiment that would offer a great deal of value to the flow visualization techniques learned in class and would be easy to implement.

Some other recommendations that should be implemented immediately are to:

- **Decrease the size of the groups to 3 or 4 students instead of 5 students**
- **Frontload the individual homework sets for the course in order to give more time for the time intensive lab reports at the end of the course**
- **Increase the amount of time spent going over linear regression**
- **Decrease the amount of time spent on uncertainty analysis**
- **Add a homework problem on internal balance misalignment and elastic deformation corrections**
- **Set hard dates each semester that the labs will be conducted out at the LSWT.**

There are a couple of recommendations that should be implemented in the future, but not necessarily right away. These include two more mini-labs in the 3 foot by 4 foot wind tunnel in the basement of the H.R. Bright building. The first mini-lab would go over FISF interferometry. This is a powerful, non-intrusive technique for evaluating skin friction levels. This lab would take a lot of set-up work, and I wouldn't necessarily want the students to help set it up, as that would probably take longer than a normal lab period. So a grad student would probably be needed who is familiar with FISF interferometry to set up all of the equipment and run the lab for the students. It would be a great addition to this class, but I do not have enough knowledge on the subject to forecast the potential pitfalls that one might encounter when setting up this lab. Another mini-lab that would be a great experience for the students would include setting up a PIV experiment. Again this experiment would take a long time to set up, and I don’t have the required knowledge to forecast possible pitfalls. Exposing students to FISF interferometry and PIV would greatly elevate the value of this class. This should be a goal for the class in the next five years or so.

5. CONCLUSION

This Wind Tunnel Test Engineering course was taught in the fall of 2012 to 15 seniors in the Texas A&M Aerospace Engineering department. Covered topics included wind tunnel anatomy and design, uncertainty analysis, boundary corrections, scaling, internal and external balance use, PIV, and flow visualizations. Students completed five individual homework sets, turned in three group lab reports, and gave one group presentation. The average score in the class was 87.8% and final grades included 11 A’s, 1 B, and 3 C’s.

The three lab experiments in the LSWT included tests on a semi-submersible offshore oil platform, a space re-entry vehicle, and an RC jet. The first experiment using the semi-submersible offshore oil platform introduced the students to testing in a large scale, low speed wind tunnel and gave them an appreciation for the amount of work required for such tests. The second experiment on NASA’s X-38 space re-entry vehicle highlighted external balance use, tare and interference, and boundary corrections. The final experiment helped NASA’s unmanned microgravity flight program by providing force and moment data for their RC jet. This experiment really highlighted internal strain gage balance use and application of boundary corrections. All of the experiments successfully reinforced concepts taught in the class and gave the students valuable experience conducting tests in a large scale wind tunnel.

It was a very successful course overall, but was not perfect. Based on student feedback and my self-evaluation, increasing the interaction between the groups and experiment set-up in the LSWT and adding a flow visualization lab in one of the smaller wind tunnels at TAMU can be implemented immediately to make the course better. Since this class has only been taught one time, there will probably need to be four or five more iterations of the class before it is actually in a semi-finalized state. It was a lot of work to set up the course content for this unique class, but was still a lot of fun to teach. My hope is that, in the future, this class becomes a permanent technical elective in the aerospace engineering department.

REFERENCES

[1] Barlow, J.B., W.H. Rae, and A. Pope. *Low-Speed Wind Tunnel Testing*. New York: Wiley, 1999.

[2] American Institute of Aeronautics and Astronautics Staff. *Recommended Practice: Calibration and Use of Internal Strain Gage Balances with Application to Wind Tunnel Testing*. Reston: American Institute of Aeronautics & Astronautics, 2003.

[3] McKeachie, W.J. *Mckeachie's Teaching Tips: Strategies, Research, and Theory for College and University Teachers*. Boston: Houghton Mifflin Company, 1999.

[4] Felder, R.M., J.E. Stice, and R. Brent. *National Effective Teaching Institute Seminar.* ASEE Conference, 2001.

[5] Force Technology Staff. "Wind and Current Loads on Offshore Platforms." URL: http://www.forcetechnology.com/NR/rdonlyres/78FA5994-8DEE-4B2C-81CF-20642E710483/4964/24942en_web.pdf Cited: 08/07/2012.

[6] American Petroleum Institute Staff. "Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Working Stress Design." American Petroleum Institute, 2005.

[7] National Aeronautics and Space Administration Staff. "NASA Dryden Flight Research Center X-38 fact sheet." URL:

http://www.nasa.gov/centers/dryden/news/FactSheets/FS-038-DFRC.html Cited: 08/21/2012

[8] Hart, M., M. Liable, J. Fox, D. Bacque, L. Morin, and D. Del Rosso. “Unmmanned Microgravity Flight Program.” URL: http://research.jsc.nasa.gov/BiennialResearchReport/2011/197-2011-Biennial.pdf Cited: 09/05/2012

[9] Anderson, J. *Fundamentals of Aerodynamics.* New York: McGraw-Hill Education, 2010.

[10] Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery. *Numerical Recipes: the Art of Scientific Computing.* New York: Cambridge University Press, 2007.

Supplemental References for Course Notes

- Tropea, C., A.L. Yarin, and J.F. Foss. *Handbook of Experimental Fluid Mechanics*. New York: Springer, 2007.
- Rathakrishnan, E. *Instrumentation, Measurements, and Experiments in Fluids*. New Delhi: CRC Press, 2007.
- Mehta, R.D. and P. Bradshaw. “Design Rules for Small Low Speed Wind Tunnels.” *Aeronautical Journal (Royal Aeronautical Society).* Volume 73, p443, 1979.

- Dimitriadis, G. “Experimental Aerodynamics.” University of Liege, Belgium. URL: http://www.ltas-aea.ulg.ac.be/cms/index.php?page=dimitriadis Cited 08/01/2012
- Kurtulus, D.F. “Particle Image Velocimetry.” Middle East Technical University Open Courseware. URL: http://ocw.metu.edu.tr/ Cited 010/07/2012
- Klingenberg, L. “Frequency Domain Using Excel.” San Francisco State University, 2005. URL: http://online.sfsu.edu/jtai/downloads/ENGR%20302/Excel.FFT.pdf Cited 08/12/2012
- Neu, Wayne L. “Hot Wire and Hot Film Anemometry.” Virginia Tech AOE4154 course notes. URL: http://www.dept.aoe.vt.edu/~simpson/aoe4154/ Cited 08/05/2012
- Ziliac, G.G. “Further Developments of the Fringe Imaging Skin Friction Technique.” NASA TM110425. Ames Research Center, 1996.
- Alexander, M.G. “Sub Sonic Wind Tunnel Testing Handbook.” WL-TR-91-3073. Wright-Patterson AFB Laboratory, 1991.
- Garner, H.C., E.W.E. Rogers, W.E.A. Acum, and E.C. Maskell. “Subsonic Wind Tunnel Wall Corrections.” Advisory Group for Aerospace Research and Development, 1966.

- Shindo, S. “Simplified Tunnel Correction Method.” Journal of Aircraft, Vol. 32, p210, 1995.

APPENDIX A

Syllabus – (Prerequisite Aero 302)

Student Lecturer	Ben Recla - Office Hours: Tuesday and Friday: 0930 - 1100 in HRBB 032
Faculty	Dr. Edward White – HRBB 604A
Meeting Times	Lectures: Tuesdays and Thursdays 2:20 – 3:10 in HRBB **122** (or at LSWT depending on instructor guidance) Lab Sessions: Thursdays 3:30 to 5:30 (These times will be combined into three 8 hour lab sessions based on the availability of the LSWT. Each of the 8 hour labs will be considered a university approved absence in case you have to miss another class on the respective lab day.) Labs will be conducted at the LSWT located near the intersection of George Bush Dr. and FM 2818 in College Station, TX next to Easterwood Airport *Lab Session attendance is mandatory*
Safety	*Safety in the laboratory is our primary concern at all times* Labs are dangerous places. Everyone must exercise great care to avoid injuries to themselves and others as well as to avoid damaging equipment. Detailed safety instructions will be distributed before the first lab and during the first lab session we will be conducting a safety orientation. Following this, you will be required to sign a safety contract before undertaking any laboratory work.
Text	*No text will be required for this course.* I will be distributing notes in class and via e-mail. For reference I suggest: • Barlow, J.B., W.H. Rae, Jr., and A. Pope. 1999. *Low-Speed Wind Tunnel Testing*, 3rd. ed. John Wiley & Sons: New York.
Grading	Grades will be based 25% on homework assignments and 75% on three group presentations and/or group lab reports. Group activities will receive *group grades* with small adjustments for individual contributions to the group. Written assignments are due at 4:00pm on the due date and are to be submitted via email in .pdf format to benjamin.recla@neo.tamu.edu. Homework assignments are due in class on the due date. Extensions will only be granted with at least 48 hours notice. Your MINIMUM grade will be A, B, C, or D, for averages of 90%, 80%, 70%, or 60%, respectively.

Course Content

	Hours
Introduction	0.5
Wind Tunnel Anatomy and Design	1
Pressure, Flow, and Shear Stress Measurements	2
Flow Visualization	2
Forces and Moments from External Balance Measurements	4
Forces and Moments from Internal Balance Measurements	4
Scaling Effects/Testing Design	4
Boundary Corrections	7
Lab/Project Introductions	1.5
Lab/Project presentations	4
3 Labs (8 hours per lab)	24
Total Hours: Lecture	30
Total Hours: Lab	24

Academic Integrity

The Code of Honor is stated simply as: *An Aggie does not lie, cheat, or steal or tolerate those who do.* The Code of Honor is an effort to unify the aims of all Texas A&M men and women toward a high code of ethics and personal dignity. For most, living under this code will be no problem, as it asks nothing of a person that is beyond reason. It only calls for honesty and integrity, characteristics that Aggies have always exemplified. For additional information, please visit: http://aggiehonor.tamu.edu.

Copyrights

The handouts used in this course are copyrighted. By “handouts” we mean all materials generated for this class, which include but are not limited to syllabi, lab problems, in-class materials, review sheets, and additional problem sets. Handouts may be distributed in class or electronically. Because these materials are copyrighted, you do not have the right to copy the handouts, unless the author expressly grants permission.

Americans with Disabilities Act (ADA) Policy Statement

The Americans with Disabilities Act (ADA) is a federal anti-discrimination statute that provides comprehensive civil rights protection for persons with disabilities. Among other things, this legislation requires that all students with disabilities be guaranteed a learning environment that provides for reasonable accommodation of their disabilities. If you believe you have a disability requiring an accommodation, please contact Disability Services, in Cain Hall, Room B118, or call 845-1637. For additional information visit: http://disability.tamu.edu.

Group Dynamics and Assessment

Much of the work in this class will be conducted in groups. Groups will be selected at random and will stay together throughout the semester. There are a number of reasons that this is a good arrangement for effective learning and retention. Working in groups is also useful training for your eventual professional careers.

An overall group grade will be given for each of the group activities. At the conclusion of each activity, each of you will also submit a confidential individual assessment of the contribution by each of your group members and yourself. Small adjustments to each member's grade on that lab will be made based on these assessments. Because the adjustments are small, it is more effective for groups with a weak member to get that person to contribute more rather than slam that member with bad evaluations.

Assessments will consist of a single word that indicates the extent to which each member {including you} fulfilled his/her/your responsibilities. The possible ratings are:

- **Excellent**
    - Consistently went above and beyond, tutored group members, carried more than his/her fair share of the load
- **Very Good**
    - Consistently did what (s)he was supposed to do, well prepared and cooperative
- **Satisfactory**
    - Usually did what (s)he was supposed to do, acceptably prepared and cooperative
- **Marginal**
    - Sometimes failed to show up or complete assignments, minimally prepared and cooperative
- **Deficient**
    - Often failed to show up or complete assignments, rarely prepared
- **Unsatisfactory**
    - Consistently failed to show up or complete assignments, unprepared
- **No Show**
    - No participation at all

Ratings are not your opinion of the grade that is appropriate for each group member.

Ratings are used to adjust the group grade to reflect individual contributions. If a group grade is an `A' and the group members all receive equal ratings, all will receive an `A', regardless of whether their ratings were `excellent' or `satisfactory'. If the same hypothetical group had a group grade of `C' and decided to all rate each other as `excellent', everyone would still receive a `C'. Please use the guidelines above to select your ratings so that I can have a correct understanding of the dynamics of each group. It is my intention that `satisfactory' is a typical and honorable rating.

Course Purpose and Objectives

Catalog Demonstrates and complements material in courses on aerodynamics, structures, and dynamics; advanced testing techniques utilizing the Oran W. Nicks Low-Speed Wind Tunnel. (Prerequisite: Aero 302)

This description is too general for you to know what you will be expected to learn during this class. This page gives more information about the skills I intend this course to develop. These fall into seven major categories summarized below:

- **Wind Tunnel Anatomy and Design**
    - What is the overall aerodynamic objective of most wind tunnels? What is the central issue when sizing a low-speed wind tunnel? What other considerations are there when building a wind tunnel?
- **Pressure, Flow, and Shear Stress Measurements**
    - What do we measure in a wind tunnel test? What instruments are used for these measurements?
- **Flow Visualization**
    - What is the value in using flow visualization techniques? What are the different types of flow visualization?
- **Forces and Moments from External Balance Measurements**
    - What is the purpose of load measurements on the model? How do we measure these loads? What are the types of external balances?
- **Forces and Moments from Internal Balance Measurements**
    - What are the basic aspects of internal balances? Why would we use an internal balance versus an external balance?
- **Scaling Effects / Testing Design**
    - What are scale effects? Why are they important?
- **Boundary Corrections**
    - What are the different types of boundary corrections? How do we apply those boundary corrections?

Additional Notes

This is an experimental course that is still in its initial stages of development. Feedback forms will be handed out throughout the semester to help gauge the effectiveness of the course.

The three mandatory labs will be all day labs and are based on the availability of the LSWT. You will probably have to miss other classes on the respective lab day in order to attend. This will count as an excused absence but must be coordinated prior to the lab.

APPENDIX B

Aero 489 Course Notes

Lesson 1: Syllabus and Expectations

- Primary Instructor
- Meeting Times
- Labs (tentatively scheduled)
- Safety
- Text Book
    - "Low Speed Wind Tunnel Testing" by Barlow, Rae, and Pope – Primary
    - Springer Handbook of Experimental Fluid Mechanics
    - Instrumentation, Measurements, and Experiments in Fluids
- Grading Scheme
- Academic Integrity
- Copyrights
- ADA policy
- Groupwork
    - Groups selected at random
    - Group Assessment sheet for labs
    - Lab grading policy
- Course Purpose and Objectives
    - Only 5 other universities in U.S. have a wind tunnel of similar size

Seven Major Categories for Topics

- Wind Tunnel Anatomy and Design
  - Types of wind tunnels, parts of wind tunnel
- Pressure, Flow, and Shear Stress Measurements
  - ESP, multihole probes, hot wire anemometry, boundary layer measurement, hot films
- Flow Visualization
  - Tufts, Oil, China Clay, Smoke, PIV
- External Balance Measurements – Lab 1 & 2
- Internal Balance Measurements – Lab 3
- Optimization of Scaling
- Boundary Corrections – 2-D and 3-D
  - Wake blockage
  - Solid Blockage
  - Streamline Curvature
  - Horizontal Buoyancy
  - Maskell's method vs. Shindo's method

Notes

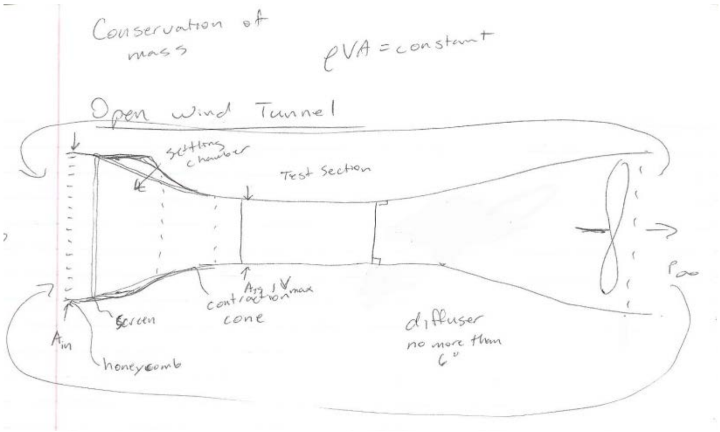
- A lot of this stuff, especially internal balance use is not written in stone. There are recommended practices out there, but it is not the only way to do something.

- This is an experimental course – Feedback forms will be handed out periodically and we will conduct after action reviews for each of the labs and at the end of the course. This helps make the course better for next time in hopes of keeping it as a permanent class at this school.

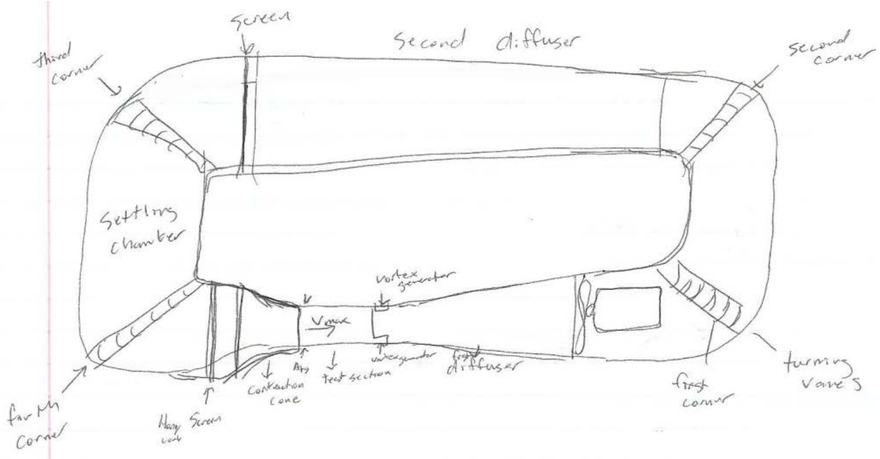
Lesson 2

- History of Wind Tunnels
    - Whirling Arm – mid-1700s to mid-1800s
        - Most famous was Otto Lilienthal’s whirling arm tests before his glider experiments
        - Limitations – imprecise results – the arm stirred up air with its motion so that the arm itself and air it went through were moving
        - Could not determine true relative velocity of object
        - Also difficult to mount instruments on the arm to measure forces while it was spinning at high speed.
    - Frank Wenham – first individual to design a tunnel in 1871
        - 12 feet long and 18 inches square, steam powered fan drove air through a duct to the test section where the model was mounted
    - Most famous early wind tunnel was that of the Wright Brothers
        - 6 feet long, 16 inches square test section
        - Aerodynamic measuring device made from an old hacksaw blade and bicycle spoke wire
        - Tested over 200 models of different types of wings, different aspect ratios
        - Accumulated tables of aerodynamic data and used them to build an accurate and reliable wing seen on the Wright Flyer

- In an age of high speed computers and CFD, why do we still have wind tunnels?
    - Validate numerical solutions
    - Calibrate numerical solutions
    - In fact, numerical solutions are only good when we already know the solution
- Wind Tunnel Principles
    - Loads exerted by static air on a moving body equal the loads exerted by moving air on a static body.
    - Scaling laws necessary, which we will get into in another class
        - Assume incompressible flow – for this class the Mach number will always be less than 0.3
        - Reynolds number matching is the primary scaling law that we will try to follow
- Open Type (Eiffel) Wind Tunnel



    - Advantages – Cheaper to build; pollutants are purged
    - Disadvantages – Room is the return path for the air, so size of the tunnel has to correspond to the size of the room; Noisy; More expensive to run than closed type
  - Closed Type (Gottingen) Wind Tunnel

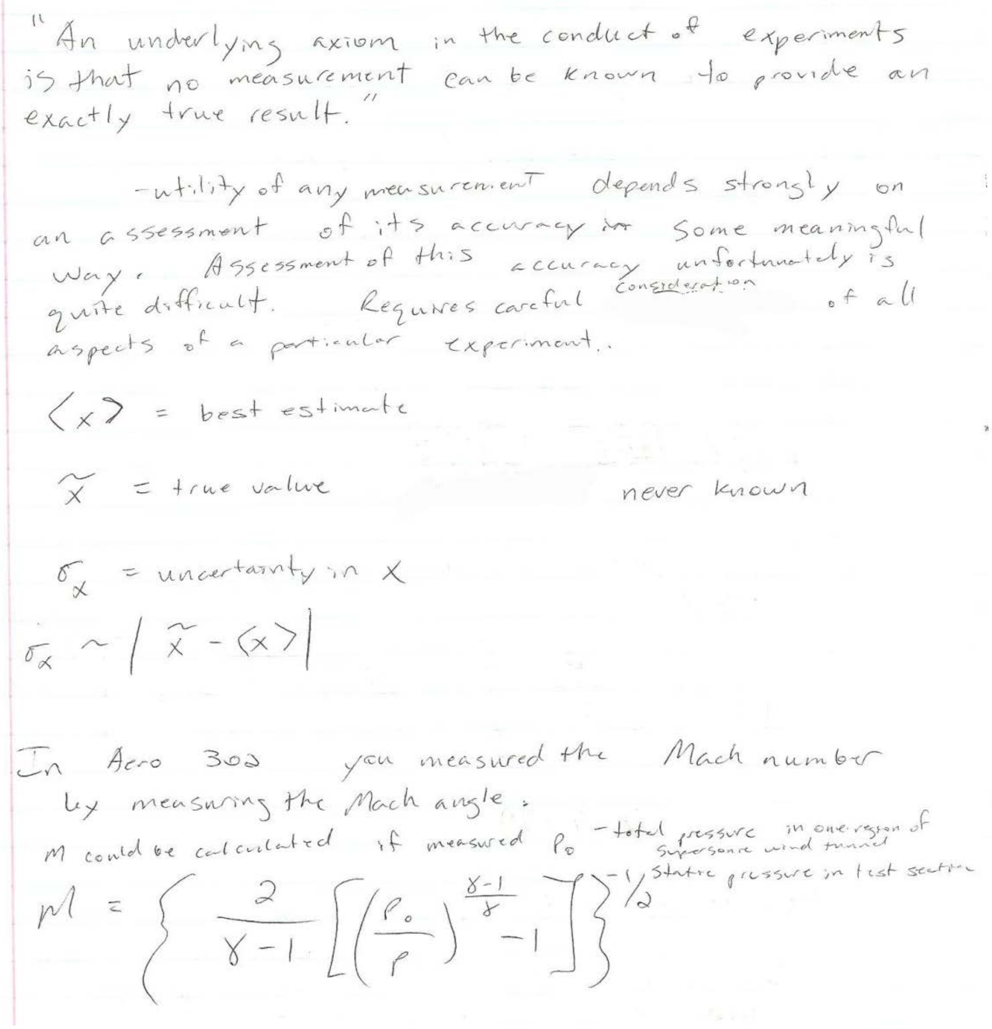


    - Advantages – Cheaper to operate, energy is only required to overcome losses in the tunnel; less noisy than open type; quality of flow can be easily controlled
    - Disadvantages – Expensive to build versus open type; cannot be purged of pollutants very easily; Continuous loss of energy in the tunnel can heat up the air requiring a cooling method, especially in the summer
  - Wind Tunnel Dimensions – can have a test section that measures only a few inches square up to the 80 foot by 120 foot wind tunnel at NASA Ames Research Center

- Typical Low Speed Wind Tunnels
    - Must have a Reynolds number of greater than 1.5 to 2 million in order for flow to be fully turbulent and simulate real world conditions
    - Most have a test section similar in size to the LSWT of 7 feet by 10 feet to achieve this Reynolds number
- Closed Typed Wind Tunnel Sections
    - Test Section
    - Diffuser (First and Second Stage)
    - Fan Section
    - Settling Chamber
    - Contraction Cone
    - Corners – Turning Vanes

Lesson 3

- Uncertainty Analysis



"An underlying axiom in the conduct of experiments is that no measurement can be known to provide an exactly true result."

-utility of any measurement depends strongly on an assessment of its accuracy in some meaningful way. Assessment of this accuracy unfortunately is quite difficult. Requires careful consideration of all aspects of a particular experiment..

$\langle x \rangle$ = best estimate

$\tilde{x}$ = true value never known

σ_x = uncertainty in x

$$\sigma_x \sim \left| \tilde{x} - \langle x \rangle \right|$$

In Aero 302 you measured the Mach number by measuring the Mach angle.

M could be calculated if measured p_0 - total pressure in one region of supersonic wind tunnel

p - static pressure in test section

$$M = \left\{ \frac{2}{\gamma - 1} \left[\left(\frac{p_0}{p} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\}^{1/2}$$

$$M = \left\{ \frac{2}{\gamma - 1} \left[\left(\left(\frac{p_o}{p} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\}^{1/2}$$

Imagine $p_o = 65 \pm 3$ psia

$p = 6.1 \pm 0.9$ psia

$\gamma = 1.4$ Known exactly

What is $M \pm \sigma_m \leftarrow$ uncertainty in M

$\uparrow$ best estimate of M

Best estimate of M uses best estimate of input values

$$M = \left\{ \frac{2}{1.4 - 1} \left[\left(\frac{65}{6.1} \right)^{\frac{1.4-1}{1.4}} - 1 \right] \right\}^{1/2}$$

$$= 2.19779$$

How do we find σ_m?

In order to do this we must propogate errors
better term propagate uncertainties

We know $\tilde{m} \neq \langle m \rangle$ and $\tilde{m}$ is unknowable

Interested in representing potential differences in uncertainty $\sigma_m \sim |\tilde{m} - \langle m \rangle|$

Imagin $\sigma_{P_0} = 3\,psi$ but every other quantity is known exactly

The difference between $\tilde{P}_0$ & $\langle P_0 \rangle$ is small so we can use a Taylor Series expansion to represent how σ_{P_0} propagates int σ_m

$$\tilde{m} \approx \langle m \rangle + \frac{\partial m}{\partial P_0} \underbrace{(\tilde{P}_0 - \langle P_0 \rangle)}_{\sigma_{P_0}} + \ldots\ldots$$

But since we don't know the true values this turns into

$$\sigma_m^2 \sim |\tilde{m} - \langle m \rangle| = \left(\frac{\partial m}{\partial P_0}\right)^2 \sigma_{P_0}^2$$

σ_m = absolute uncertainty has quantity's units

$\frac{\sigma_m}{m}$ = relative uncertainty unitless, expressed as a percentage

What if ρ and ρ_0 have uncertainties

$$\tilde{m} \simeq \langle m \rangle + \frac{\partial m}{\partial \rho} \underbrace{(\tilde{\rho} - \langle \rho \rangle)}_{\sigma_\rho} + \frac{\partial m}{\partial \rho_0} \underbrace{(\tilde{\rho}_0 - \langle \rho_0 \rangle}_{\sigma_{\rho_0}}$$

uncertainty squared is called variance

always positive

$$\boxed{\sigma_m^2} = \left[\frac{\partial m}{\partial \rho} (\sigma_\rho) + \frac{\partial m}{\partial \rho_0} \sigma_{\rho_0} \right]^2$$

$$\sigma_m^2 = \left(\frac{\partial m}{\partial \rho} \right)^2 \sigma_\rho^2 + 2 \left(\frac{\partial m}{\partial \rho} \right) \left(\frac{\partial m}{\partial \rho_0} \right) \underbrace{\sigma_{\rho\rho_0}^2}_{\text{covariance of } \rho \text{ \& } \rho_0} + \left(\frac{\partial m}{\partial \rho_0} \right)^2$$

Shows

how uncertainties in ρ & ρ_0 are related

- not really a squared term - so never take square root of it

Most pairs of measurements of different quantities are uncorrelated - errors in measuring something with one sensor have nothing to do with errors in measuring a different pressure with another sensor. Many covariances are zero, just like in this example.

Covariance - doesn't matter what order ρ & ρ_0 appear $\sigma_{\rho\rho_0}^2 = \sigma_{\rho_0\rho}^2$

- can be positive, negative, or zero

Covariance of two quantities x & y always fall into the range

$$-\sigma_x \sigma_y \leq \sigma_{xy}^2 \leq \sigma_x \sigma_y$$

$$\boxed{-1 \leq \frac{\sigma_{xy}^2}{\sigma_x \sigma_y} \leq 1}$$

So what if $\rho, \rho_0, \; \& \; \gamma$ have uncertainties?

$$\sigma_m^2 = \left(\frac{\partial m}{\partial \rho_0} \sigma_{\rho_0} + \frac{\partial m}{\partial \rho} \sigma_\rho + \frac{\partial m}{\partial \gamma} \sigma_\gamma \right)^2$$

Expand out

a lot of the covariances do away

So if wanted to work it out

$$\frac{\partial m}{\partial \rho_0} = \frac{1}{\gamma m_\rho} \left(\frac{\rho}{\rho_0} \right)^{1/\gamma}$$

$$\frac{\partial m}{\partial \rho} = -\left[\frac{1}{\gamma m_\rho} \left(\frac{\rho}{\rho_0} \right)^{\frac{1}{\gamma}} \right] \left(\frac{\rho_0}{\rho} \right)$$

Let's work a simpler example

$C_L = \frac{L}{qS}$

$q = \frac{1}{2}\rho V^2$ = dynamic pressure
S = planform area
L = lift
C_L = coefficient of lift

- Assume covariance term is zero
- $L = 165 \pm 1$ lbf
  $q = 75.1 \pm 0.1$ psf
  $S = 22.2 \pm 0.1$ ft^2

Find $C_L \pm \sigma_{C_L}$

First find C_L using best estimates

$$\frac{165}{(75.1)(22.2)} = 0.98967324 \text{ unitless since } C_L$$

Find $\sigma_{C_L} = \sqrt{\left(\left(\frac{\partial C_L}{\partial L}\right)^2 \sigma_L^2\right) + \left(\left(\frac{\partial C_L}{\partial q}\right)^2 \sigma_q^2 + \left(\left(\frac{\partial C_L}{\partial S}\right)^2 \sigma_S^2\right)}$

$\frac{\partial C_L}{\partial L} = \frac{1}{qS}$ $\quad \sigma_L = 1$

$\frac{\partial C_L}{\partial q} = -\frac{L}{q^2 S}$ $\quad \sigma_q = 0.1$

$\frac{\partial C_L}{\partial S} = -\frac{L}{qS^2}$ $\quad \sigma_S = 0.1$

$$\frac{q^{-1}L}{S} \qquad -\frac{L}{q^2 S}$$

$$\sigma_{C_L} = \sqrt{\left(\left(\frac{1}{qS}\right)^2 \sigma_L^2\right) + \left(\left(\frac{-L}{q^2S}\right)^2 \sigma_q^2\right) + \left(\left(\frac{-L}{qS^2}\right)^2 \sigma_S^2\right)}$$

$$= \sqrt{\left(\frac{1}{(75.1)(22.2)}\right)^2 (1)^2 + \left(\left(\frac{-165}{(75.1)^2 22.2}\right)^2 (0.1)^2\right) + \left(\left(\frac{-165}{75.1(22.2)^2}\right)^2 (0.1)^2}$$

$$= \sqrt{\underbrace{3.59761 \times 10^{-7}}_{Lift} + 1.73661 \times 10^{-8} + 1.98736 \times 10^{-7}}$$

What variable has largest effect on uncertainty in C_L ?

.0000003597 .0000000173661 .000000198736

$$\sigma_{C_L} = .00075{}^{88}563$$

$C \pm \sigma_{C_L}$

0.98967324± .0007588563 ↙ not an exact number why it is called uncertainty should one, maybe two digits

0.98967 ± .00076 units

$(989.67 \pm 0.76) \times 10^{-3}$ units

$$C_L = \underset{C_L}{(989.7} \underset{\pm}{\pm} \underset{\sigma_{C_L}}{0.8)} \times 10^{-3}$$

How many digits of precision should it have?

number of reported digits (precision) should not exceed the accuracy of the value when reporting results.

uncertainty value tells you how many digits to use in your best estimate.

$\sigma_x = 400$ N

best estimate $X = 32\underline{4}58.34$ N

If certain only up to the hundreds digit, then that is what we report

32400 ± 400 N

32.4 ± 0.4 KN

Same goes

$y = 3.987654321$ ft $\sigma_y = .0\underline{2}1345$ ft

3.99 ± 0.02 ft

Accuracy vs. precision

3 accurate estmate of π

2.123456789 is precise estmate, not accurate

When doing calculations, keep all digits of precision you have as you perform calculations

Only round answers at last stage when reporting results.

Another way we could have worked this problem is with relative uncertainty

Relative uncertainty in percentages

$$\left(\frac{\sigma_{C_L}}{C_L}\right)^2 = \left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_q}{q}\right)^2 + \left(\frac{\sigma_s}{s}\right)^2$$

$$\sigma_{C_L} = C_L \left(\left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_q}{q}\right)^2 + \left(\frac{\sigma_s}{s}\right)^2\right)^{1/2}$$

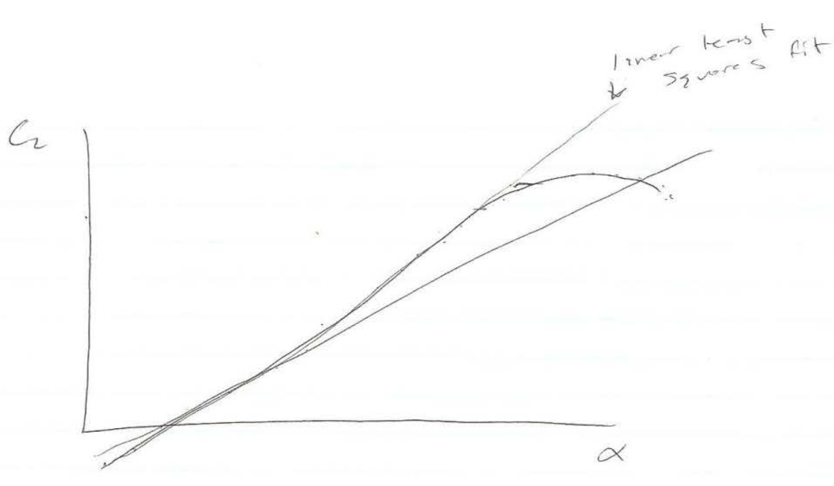
$$= 0.98967\,(.07785 + .000002 + .0002)^{1/2}$$

$$.007668$$

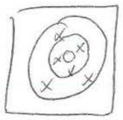
$$= 0.98967 \,/$$

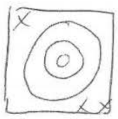
$$\underline{\underline{= .007589}}$$

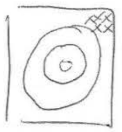
Can only use relative uncertainty if multiplying and dividing only any addition/subtraction does not work.

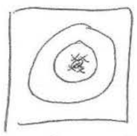


Accuracy vs. Precision


Accurate
Not Precise


Not Accurate
Not Precise


Not Accurate
Precise


Accurate
Precise

3 is Accurate Value for π, but not precise

2.1372439 is Precise, not accurate

3.14159 is precise & accurate

27 is neither

Uncertainty term tells you accuracy & precision info

Random errors -

If we repeat an experiment 10 times do we expect to get the same number 10 times, NO

well they can't all be the best estimate

So we take the mean of all sampled data for our best estimate.

How do we find the uncertainty in this mean?

$\langle c_i \rangle$ mean

$$\sigma_{\langle c_2 \rangle} = \frac{S_p}{\sqrt{N}}$$

N = number of samples

S_p = sample standard deviation

$$= \left[\frac{1}{N-1} \sum_{n=1}^{N} \left(\underset{\overset{\uparrow}{\text{Single Sample}}}{c_{2_N}} - \underset{\overset{\uparrow}{\text{Sample mean}}}{\langle c_2 \rangle} \right)^2 \right]^{1/2}$$

How much single samples vary from sample mean

Bias errors - Systematic errors

Bias errors are constant sample to sample
- make true value truly unknowable

- can be caused by

- Inherent instrumentation issues (self heating of thermistor
- calibration nonlinearity
- manufacturing variations - imperfect quality control
- Imperfect experimental setups & procedures
- etc.

Note we can measure $\sigma_{\langle x \rangle}$ but we can only estimate bias errors from instrumentation specs and our own assessment of experimental setup and model form errors.

Linear regression

A common data analysis task is to provide the best fit between the line $y = ax + b$ with a set of N measured data points $(x_i, y_i \pm \sigma_{y_i})$

In doing this we need to calculate

a & b as well as σ_a σ_b & σ_{ab}^2 and

some means of knowing whether we have a good fit between the data and the assumed functional form of how y varies with x

To approach this problem, imagine that we have preliminary guesses for a & b

we calculate N differences

$$d_i = \frac{y_i - (a x_i + b)}{\sigma_{y_i}} \leftarrow \text{weighted with uncertainty}$$

We say the best fit line is the one that minimizes the sum of d_i^2 for the N measured data points

The sum of the squared differences is called χ^2 (chi squared)

$$\chi^2 = \sum_{i=1}^{N} \left[\frac{y_i - (\quad a x_i + b}{\sigma_{y_i}} \right]^2$$

With the help of the Numerical Recipes Book we have ways of finding a & b

$$a = \frac{S S_{xy} - S_x S_y}{S S_{xx} - S_x S_x}$$

$$b = \frac{S_{xx} S_y - S_x S_{xy}}{S S_{xx} - S_x S_x}$$

$$S = \sum_{i=1}^{N} \frac{1}{\sigma^2_{y_i}} \qquad S_x = \sum_{i=1}^{N} \frac{x_i}{\sigma^2_{y_i}}$$

$$S_y = \sum_{i=1}^{N} \frac{y_i}{\sigma^2_{y_i}} \qquad S_{xx} = \sum_{i=1}^{N} \frac{x_i^2}{\sigma^2_{y_i}}$$

$$S_{xy} = \sum_{i=1}^{N} \frac{x_i y_i}{\sigma^2_{y_i}}$$

Goodness of fit" measure

$\frac{\chi^2}{N-2}$ ← line   N-3 for quadratic, etc.

= 1   as good a fit as our uncertainties permit

>> 1   then perhaps our model function is not apropriate

<< 1   sign we have overestimated our uncertainties or faked our data

Next thing we need is our parameter uncertainty for a & b From Numerical Recipes book

$$\sigma_a^2 = \frac{S}{SS_{xx} - S_x S_x} \qquad \sigma_b^2 = \frac{S_{xx}}{SS_{xx} - S_x S_x}$$

Covariance

$$\sigma_{ab}^2 = \frac{-S_x}{SS_{xx} - S_x S_x}$$

So one thing I will ask you to do is find a linear least squares fit for

$$C_L = \overset{\text{- lift curve slope}}{a}(\alpha - \overset{\text{- zero lift angle of attack}}{\alpha_{L=0}})$$

$y = ax + b$

$y = C_L$ in this case

$x = \alpha$

$a = a$

$b = -a\alpha_{L=0}$

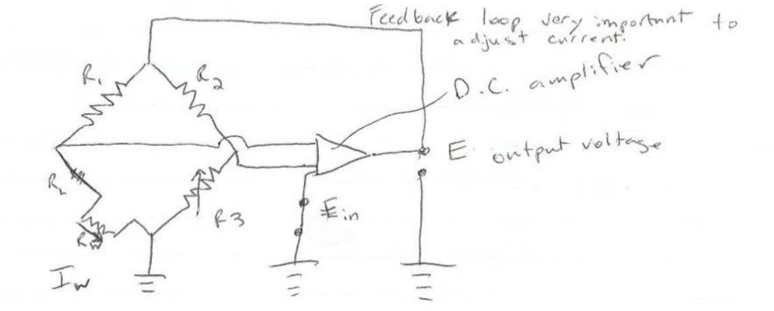
so I will tell you to find a & $\alpha_{L=0}$

and plot on a graph of C_L vs α

Use goodness of fit measure to get best values for a & $\alpha_{L=0}$ based on N samples

Lesson 4

- Hot Wire Anemometry
    - Hot wire anemometers measure fluid velocity by sensing the changes in heat transfer from a small, electrically heated element exposed to the fluid
    - Key feature of the hot wire anemometer is its ability to measure very rapid changes in velocity
        - Accomplished by coupling a very fine sensing element (typically a wire four to six microns in diameter) with a fast feedback circuit which compensates for the drop in natural sensor response. Time response to flow fluctuations as short as a few microseconds can be achieved.



        - Standard for studying turbulent flow
        - Small sensor size (normally only a millimeter in length) also makes this technique valuable in applications where access is difficult or large sensors obstruct the flow
    - Hot Wire Calibration

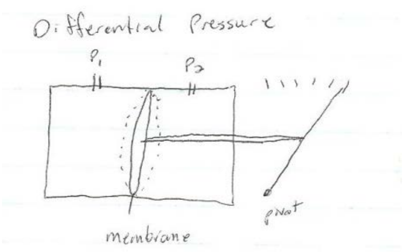
        - Follows King's Law $E^2 = A + Bu^n$
            - Where E is the voltage across the wire, u is the velocity of the flow normal to the wire, A, B, and n are constants. You can assume that n = 0.45 or 0.5. This is common for hot wire probes. However in a research setting you should determine n along with A and B.
            - A and B can be found by measuring the voltage, E, at known velocities in a flow. A least squares fit can then be applied to find A and B.
            - The values of A and B depend on the anemometer circuitry, the temperature of the air, the relative humidity in the air, and the resistance of the wire that you are using.
- Fast Fourier Transform
    - Significantly faster than a Fourier Transform
        - For example, sampling at 20000 Hz for 0.8 seconds, can do an FFT in 0.8 seconds. If you tried to do the same calculation using a Fourier Transform instead of a Fast Fourier Transform, one calculation could take days to perform.
    - Important things to remember about FFT
        - # of data samples must be a power of 2 (2^n) e.g. 128, 256, 512, 1024, etc.

- Only graph half of sample data – second half mirrors the first half of data
- Must have rough idea of frequency you are trying to determine and sample at least 4 times faster than that
- Use the IMABS function in Excel

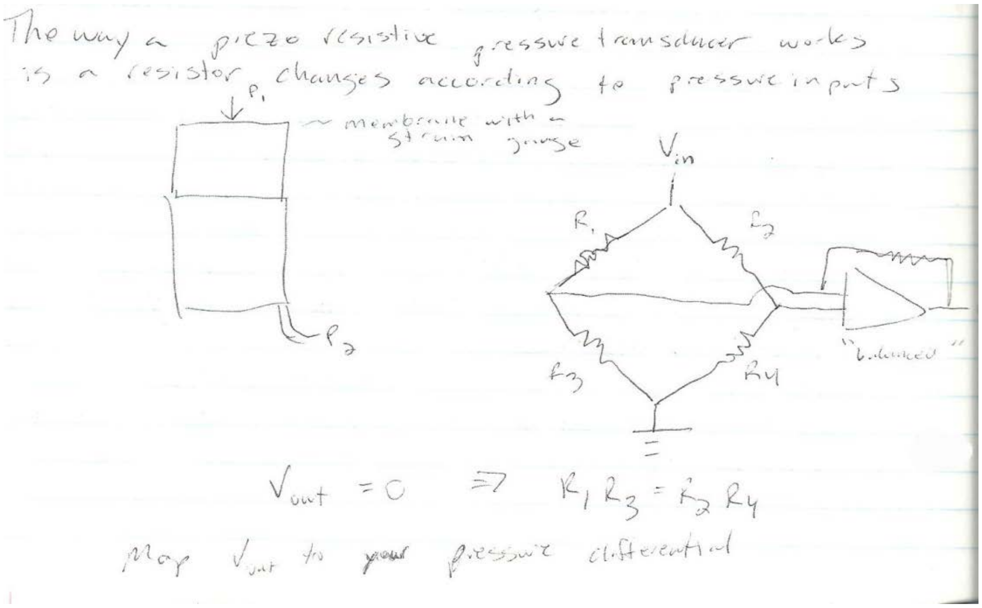
Lesson 5

- Pressure Measurement and Instrumentation
  - U tube manometer – one of the oldest devices for measuring pressure and one of the easiest to build
    - Manometers are used (at least they used to be used) for calibrating and checking other devices, since it is difficult to obtain a more accurate or precise result in the range of differential pressures commonly of interest in subsonic aerodynamic testing.
    - Factors limiting the accuracy of manometer
      - Accuracy in measurement of the height of the fluid in the manometer
      - Accuracy of liquid density and uniformity of liquid density
      - Presence of forces other than the weight of the liquid – specifically surface tension, which can lead to a pressure jump across the liquid
    - Most commonly used fluids are silicon oil or water with dye.
    - Older wind tunnels would have a bank of 50 to 200 manometers mounted on the wall in order to take pressure readings
  - Pressure Transducers
    - Term usually applied to a device that provides an electrical response to a pressure or change in pressure

- Most commonly used pressure transducers are of the diaphragm type. This means that the basic sensing mechanism is a thin sheet of material that deforms as pressure across it changes



- Diaphragm type can sometimes be too large for our needs
- Piezo Resistive Pressure Transducer – smaller
    - Resistor changes according to pressure inputs

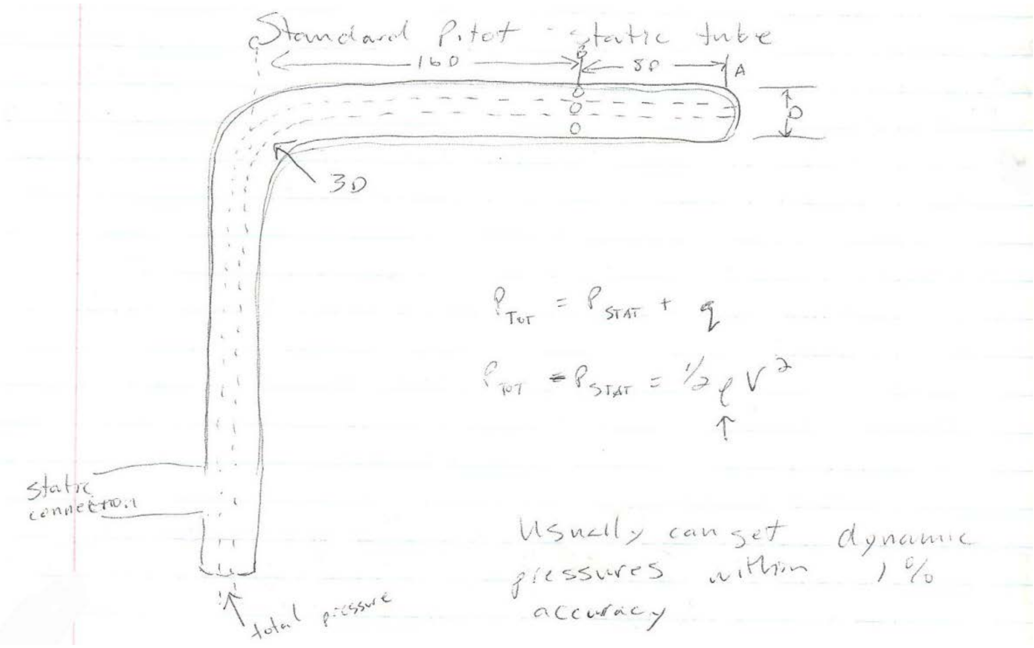

The way a piezo resistive pressure transducer works is a resistor changes according to pressure inputs

$$V_{out} = 0 \Rightarrow R_1 R_3 = R_2 R_4$$

Map V_{out} to your pressure differential

- ESP Pressure Scanner

            - Useful for taking multiple pressure readings, like pressure taps on an airfoil.
            - Consist of an array of silicon piezoresistive pressure sensors
            - Usually come with 16, 32, or 64 pressure ports
            - Seen used for unsteady pressure measurements
- Flow Measurements
    - Pitot Static Tube
        - Most common device for measuring total pressure and static pressure of a stream

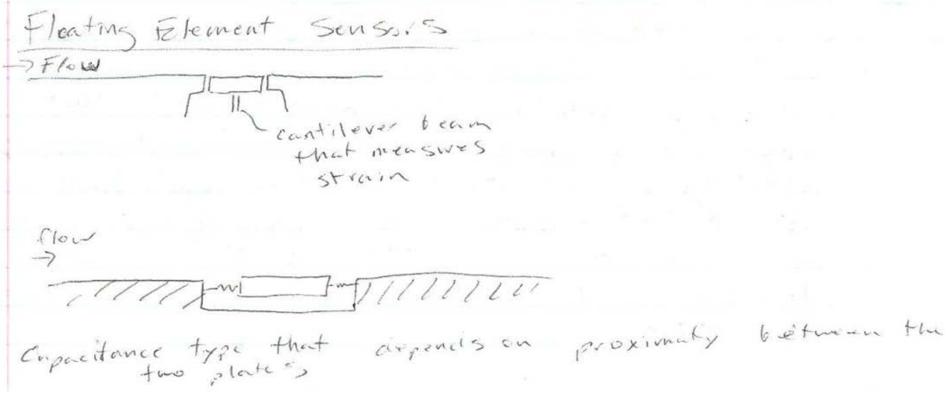


        - Usually can get dynamic pressures to within 1% accuracy
        - Shape of the head and yaw in the tube affect uncertainty

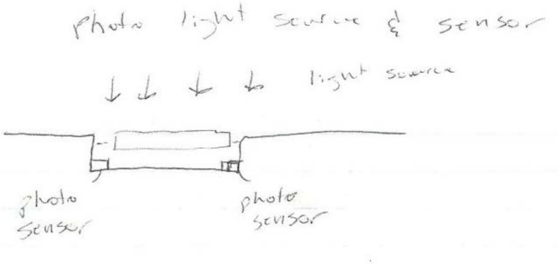
        - Static pressure port location is critical
        - Only good for 1-D flow
    - Multi hole probes
        - Good for 3-D velocity measurement
        - Most common are the 5 hole and 7 hole probes
        - Steady flow measurement is quite simple
        - Calibration and data reduction algorithms can be difficult
    - Hot Wire Anemometry
        - Talked about previously
        - Used when there are rapid changes in velocity
    - Particle Image Velocimetry
        - Will talk about in its own class in the future
        - PIV works by seeding a known test area with particles and lighting them up with a laser. Take two pictures with a high speed camera at a known time interval between exposures and measure the distance traveled by each particle to determine the velocity.
- Skin Friction Measurement
    - Skin friction on a wing plays a significant role in the total drag of the wing
    - When there is a laminar boundary layer, this skin friction is minimal. Once that boundary layer transitions to a turbulent boundary layer skin friction drag increases dramatically. Naturally one of the main goals in

today's aerodynamic research is to delay this transition from laminar to turbulent flow in order to reduce the total drag thus improving performance and fuel economy.

- This class will not cover ways to delay this transition; we will cover ways to measure this skin friction.
- Ways to measure (not all inclusive)
    - Boundary layer rake
    - Boundary layer hot wire anemometer
    - Floating element sensor – Cantilever beam; Capacitance Type

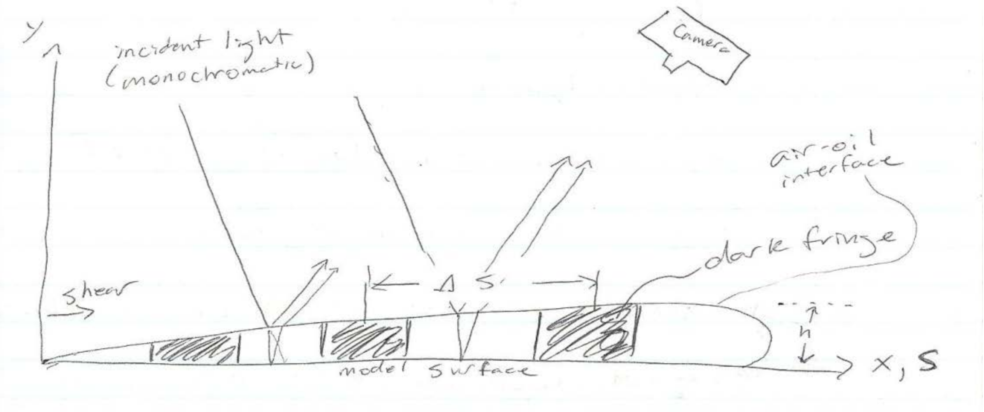


    - Photo light source and sensor



    - Fringe Imaging Skin Friction (FISF) interferometry

- Technique is widely used in large scale wind tunnel tests and is useful for validating CFD turbulence models
- Non-intrusive, easy to implement, and relatively accurate
- It has been shown that oil flowing due to shear would thin at a rate proportional to the level of applied shear. Tanner and Blows also showed that “fringes” would develop due to interference between light reflecting off the air-oil interface and light reflecting off the surface under the oil. These fringes marked contours of constant oil thickness that could be used to assess the local thickness of the oil and consequently the shear
- Silicone oil is the oil of choice since its viscosity is relatively insensitive to temperature



This is actually a nasty partial differential equation but is reduced to this when we assume that τ_w is constant in x and t and ~~at~~ $t = 0$ $h = \infty$

using

$$\tau_w = \frac{s \mu_o}{h t}$$

$$\frac{\partial h}{\partial t} = -\frac{1}{\mu_o} \frac{\partial}{\partial x} \left[\frac{h^2}{2} \tau_w \right. =$$

where

τ_w = shear stress at wall

μ_o = oil's viscosity

s = distance perpendicular to fringe bands ($s = 0$ at oil leading edge)

t = time

h = height.

Monson, Mateer, and Menter developed a form of the equation that only relies on knowing the end state of the oil's thickness distribution.

$$C_f = \frac{\tau_w}{q_\infty} = \frac{\left(\frac{2 n_o}{\lambda}\right)\cos\left(\theta_r\right)\left(\Delta s\right)}{\int_{t_o}^{t_{n+1}} \left(\frac{q_\infty}{\mu_o}\right) dt}$$

Skin friction

where n_o = is the oil's index of refraction

λ = is the illumination wavelength

θ_r = refracted light angle through the oil

Δs = fringe spacing (distance between peaks of dark fringes)

μ_o = oil viscosity

q_∞ = dynamic pressure

t_o = time before tunnel is started = 0

t_{n+1} = total run time of tunnel

Light refraction angle through the oil is related to the angle of incidence of the light source by

$$\sin \theta_r = \left(\sin \frac{\theta_i}{n_o}\right)$$

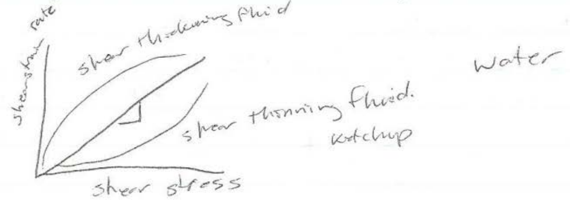
Uncertainty in C_f measurements range between 1 and 10% depending on the resolution of the imaging system and the accuracy of measuring tunnel conditions

Skin Friction is proportional to fringe spacing

ΔS

Newtonian Fluids

a fluid whose stress versus strain rate curve is linear and passes through the origin



$$\tau_w = \mu \frac{du}{dy}$$

↑ ↑ viscosity is constant ↖ strain rate

velocity gradient perpendicular to the shear

ss

only dependent on temp & pressure not on forces acting on it.

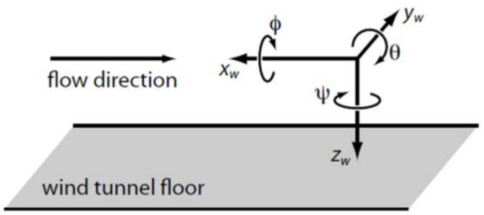
Non Newtonian fluids – Ketchup, toothpaste, paint, blood, shampoo

Lesson 6

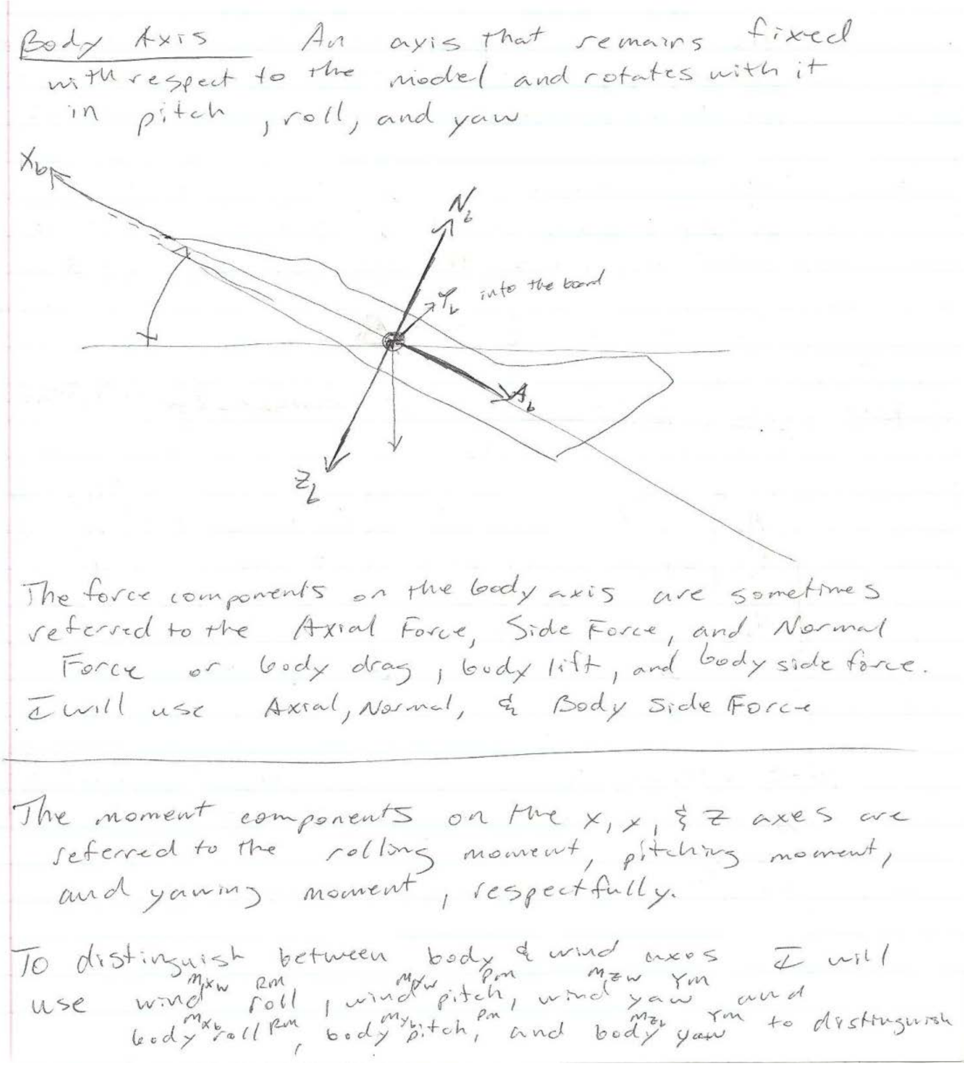
- Reference Frames
    - AIAA agreed upon reference frames
        - Any reference frame is determined by its orientation relative to some other frame or basic physical reference and the location of the origin. A reference frame is a set of three orthogonal axes, by convention always labeled right hand sequence
    - Two most agreed upon reference frames are the body axis frames and the wind axis frames. Third reference frame out there is the stability axis frame, but we will not use that one in this course.
        - Wind Axis Reference Frame
            - Positive X axis pointing into the wind, Positive Z pointing down, and Positive Y pointing into the board
            - Drag is in the negative x direction, Lift is in the negative Z direction, and Side Force is in the positive y direction

$$D = -F_{x_w} \qquad S = F_{y_w} \qquad L = -F_{z_w}$$

$$RM = +M_{x_w} \qquad PM = +M_{y_w} \qquad YM = +M_{z_w}$$



    - In LSWT, we assume that the tunnel walls are parallel to the x axis of the wind axis coordinate system.
- Body Axis Reference Frame
    - This axis remains fixed with respect to the model and rotates with it in pitch, roll, and yaw
    - Force components are referred to Axial Force, Normal Force, and Side Force



Body Axis An axis that remains fixed with respect to the model and rotates with it in pitch, roll, and yaw

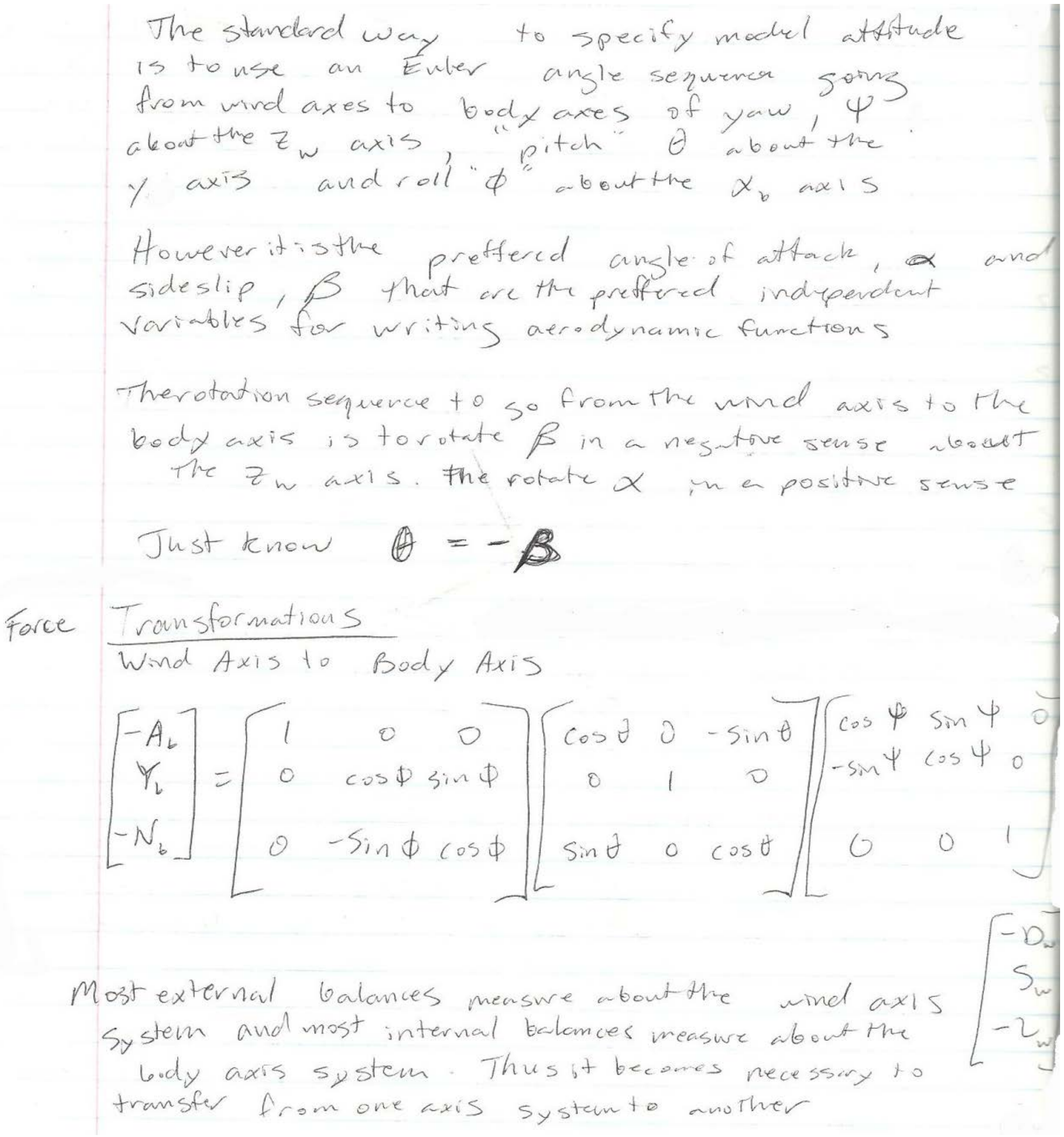
The force components on the body axis are sometimes referred to the Axial Force, Side Force, and Normal Force or body drag, body lift, and body side force. I will use Axial, Normal, & Body Side Force

---

The moment components on the x, x, & z axes are referred to the rolling moment, pitching moment, and yawing moment, respectfully.

To distinguish between body & wind axes I will use wind$^{M_{xw}}$ roll^{Rm}, wind$^{M_{yw}}$ pitch^{Pm}, wind$^{M_{zw}}$ yaw^{Ym} and body$^{M_{xb}}$ roll^{Rm}, body$^{M_{yb}}$ pitch^{Pm}, and body$^{M_{zb}}$ yaw^{Ym} to distinguish

- Reference Frame Transformations



The standard way to specify model attitude is to use an Euler angle sequence going from wind axes to body axes of yaw, ψ about the z_w axis, "pitch" θ about the y axis and roll "ϕ" about the x_b axis

However it is the preffered angle of attack, α and sideslip, β that are the preffered independent variables for writing aerodynamic functions

Therotation sequence to go from the wind axis to the body axis is to rotate β in a negative sense about the z_w axis. the rotate α in a positive sense

Just know $\theta = -\beta$

Force Transformations

Wind Axis to Body Axis

$$\begin{bmatrix} -A_b \\ Y_b \\ -N_b \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -D_w \\ S_w \\ -L_w \end{bmatrix}$$

Most external balances measure about the wind axis system and most internal balances measure about the body axis system. Thus it becomes necessary to transfer from one axis system to another

Most commonly roll ϕ is zero which gives us

$$\begin{bmatrix} -A_b \\ Y_b \\ -N_b \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\psi & \sin\psi\cos\theta & -\sin\theta \\ -\sin\psi & \cos\psi & 0 \\ \sin\theta\cos\psi & \sin\theta\sin\psi & \cos\theta \end{bmatrix} \begin{bmatrix} -D_w \\ S_w \\ -L_w \end{bmatrix}$$

or

$$\begin{bmatrix} A_b \\ Y_b \\ N_b \end{bmatrix} = \begin{bmatrix} D_w\cos\theta\cos\psi - S_w\sin\psi\cos\theta - L_w\sin\theta \\ D_w\sin\psi + S_w\cos\psi \\ D_w\sin\theta\cos\psi - S_w\sin\theta\sin\psi + L_w\cos\theta \end{bmatrix}$$

or Body Axis to Wind Axis

$$\begin{bmatrix} D_w \\ S_w \\ L_w \end{bmatrix} = \begin{bmatrix} A_b\cos\theta\cos\psi + Y_b\sin\psi + N_b\sin\theta\cos\psi \\ -A_b\sin\psi\cos\theta + Y_b\cos\psi - N_b\sin\theta\sin\psi \\ -A_b\sin\theta + N_b\cos\theta \end{bmatrix}$$

Moment transformations similar

$$\begin{array}{l} RM \rightarrow \\ PM \rightarrow \\ YM \rightarrow \end{array} \begin{bmatrix} M_{x_b} \\ M_{y_b} \\ M_{z_b} \end{bmatrix} = \begin{bmatrix} M_{x_w}\cos\theta\cos\psi + M_{y_w}\sin\psi\cos\theta - M_{z_w}\sin\theta \\ -M_{x_w}\sin\psi + M_{y_w}\cos\psi \\ M_{x_w}\sin\theta\cos\psi + M_{y_w}\sin\theta\sin\psi + M_{z_w}\cos\theta \end{bmatrix}$$

$$\begin{bmatrix} M_{x_w} \\ M_{y_w} \\ M_{z_w} \end{bmatrix} = \begin{bmatrix} M_{x_b} \cos\theta \cos\psi - M_{y_b} \sin\psi + M_{z_b} \sin\theta \cos\psi \\ M_{x_b} \sin\psi \cos\theta + M_{y_b} \cos\psi + M_{z_b} \sin\theta \sin\psi \\ -M_{x_b} \sin\theta + M_{z_b} \cos\theta \end{bmatrix}$$

Other common terms to use in these equations is substituting $\theta = \alpha$ and or $\psi = -\beta$

Moment Transfers

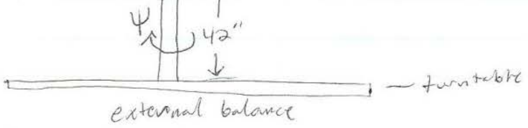
Transferring forces and moments from one reference point to another. If a system of Forces produces a resultant Force $\underline{F}_1$ and a resultant moment $\underline{M}_1$ relative to point 1, then an equivalent system acting at another point, point 2, is

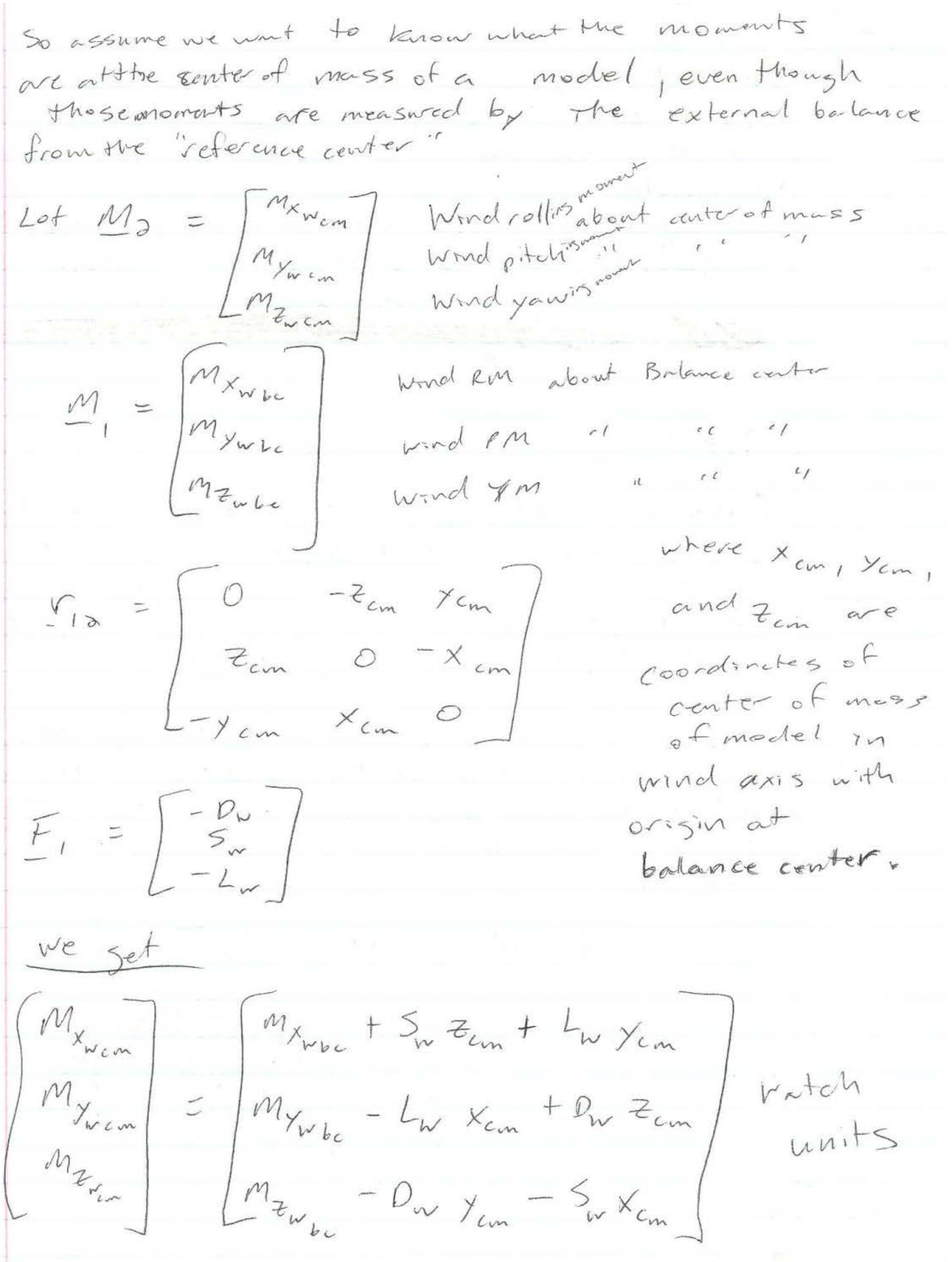
$$\underline{F}_2 = \underline{F}_1$$ Force is a force

$$\underline{M}_2 = \underline{M}_1 - \underset{\substack{\uparrow \\ \text{vector} \\ \text{from point 1 to point 2}}}{\underline{r}_{12}}\, \underline{F}_1$$

The common use of this expression is to transferr moments from a "balance center" to a reference of choice for a particular model.

In the LSWT this "balance center" or reference center is located





So assume we want to know what the moments are at the center of mass of a model, even though those moments are measured by the external balance from the "reference center"

Let $\underline{M}_2 = \begin{bmatrix} M_{x_{w_{cm}}} \\ M_{y_{w_{cm}}} \\ M_{z_{w_{cm}}} \end{bmatrix}$

Wind rolling moment about center of mass

Wind pitching moment " " "

Wind yawing moment

$\underline{M}_1 = \begin{bmatrix} M_{x_{wbc}} \\ M_{y_{wbc}} \\ M_{z_{wbc}} \end{bmatrix}$

Wind RM about Balance center

wind PM " " "

Wind YM " " "

$\underline{r}_{12} = \begin{bmatrix} 0 & -z_{cm} & y_{cm} \\ z_{cm} & 0 & -x_{cm} \\ -y_{cm} & x_{cm} & 0 \end{bmatrix}$

where x_{cm}, y_{cm}, and z_{cm} are coordinates of center of mass of model in wind axis with origin at balance center.

$\underline{F}_1 = \begin{bmatrix} -D_w \\ S_w \\ -L_w \end{bmatrix}$

we set

$$\begin{bmatrix} M_{x_{w_{cm}}} \\ M_{y_{w_{cm}}} \\ M_{z_{w_{cm}}} \end{bmatrix} = \begin{bmatrix} M_{x_{wbc}} + S_w z_{cm} + L_w y_{cm} \\ M_{y_{wbc}} - L_w x_{cm} + D_w z_{cm} \\ M_{z_{wbc}} - D_w y_{cm} - S_w x_{cm} \end{bmatrix}$$

watch units

- Scaling and Similarity
  - Since conducting experiments using scale models is the primary activity of most major wind tunnels, we must consider aspects of

experiments using scale models, the results of which may effectively be used to predict full scale behavior

- From the non-dimensional Navier-Stokes equation and non-dimensional energy equation there are three coefficients that we use for similarity in wind tunnel testing: Reynolds number, Mach number, and Froude number

$$\text{Reynolds number} = \frac{\text{inertia force}}{\text{viscous force}} = \frac{\rho V l}{\mu}$$

$$\text{Mach number} = \frac{\text{inertia force}}{\text{elasticity force}} = \frac{V}{a} \text{ - speed}$$

$$\text{Froude number} = \sqrt{\frac{\text{inertia force}}{\text{gravity force}}} = \sqrt{\frac{V^2}{lg}}$$

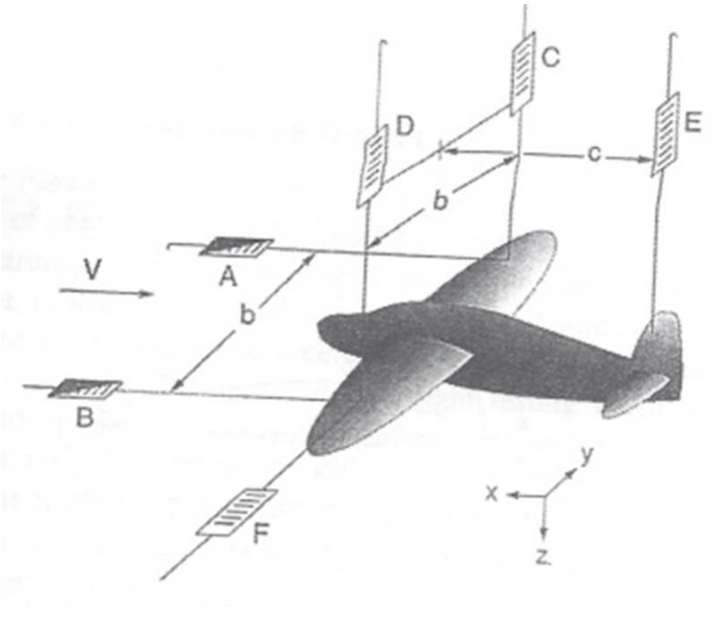
    - Froude number is only important as a similarity parameter for dynamic tests in which model motions as well as aerodynamic forces are involved. This is not the case for this class so we will disregard it.
    - In practice it is seldom possible to match both the Mach number and the Reynolds number to full scale in a model experiment. In fact it is frequently the case that neither the Reynolds number nor the Mach number can be matched. Choices must then be made on the basis of which parameter is known to be most important for the type of flow situation under consideration. Since we are doing

low speed wind tunnel testing with a Mach number less than 0.3, we can assume the change in the Mach number is negligible in our testing regime. This leaves us with the Reynolds number as the primary scaling factor.

- Factors that affect scaling in the LSWT
  - Reynolds number matching – get as close as possible
  - Blockage of tunnel – no more than 15% of 68 square foot tunnel area
  - Manufacturing considerations – ease of manufacturing (1/4 scale versus 8/33 scale)
  - Other parameters set forth in the test
  - Expected force loading vs. limits of external or internal balance

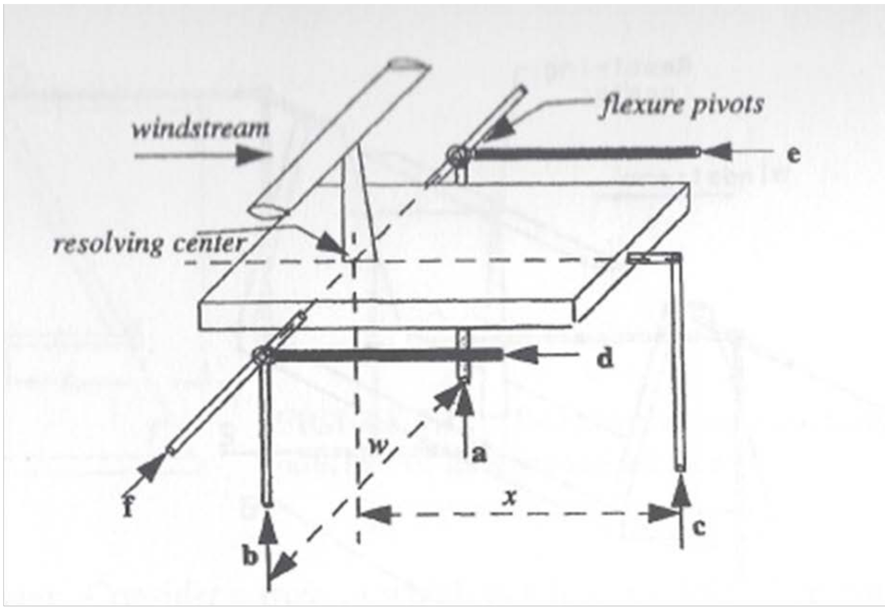
Lesson 7

- External Balances
    - One of the most important functions of wind tunnels is to provide estimates of aerodynamic loads of bodies moving through the air – accomplished by using balances
    - Many different degrees of complexity – maximum of 6 (3 forces and 3 moments)
    - 4 main types – wire, platform, yoke, and pyramidal – named for their main load carrying members



-
    - Wire external balance
        - Model usually mounted inverted to prevent unloading of the wires
        - Large drag on wires that is difficult to assess

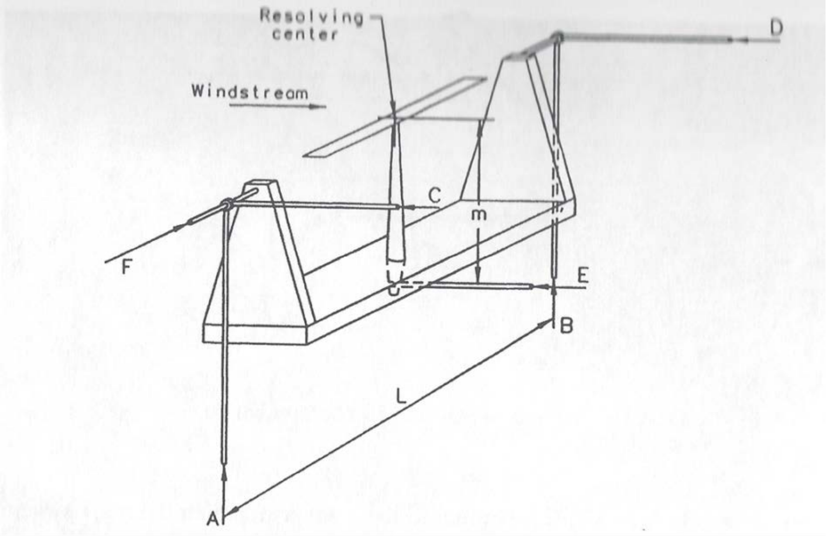
    - Not used extensively



$$L = -(\mathbf{a} + \mathbf{b} + \mathbf{c}) \qquad D = \mathbf{d} + \mathbf{e} \qquad S = -\mathbf{f}$$

$$l = (\mathbf{a} - \mathbf{b})(\tfrac{1}{2}w) \qquad n = (\mathbf{e} - \mathbf{d})(\tfrac{1}{2}w) \qquad m = \mathbf{c}x$$

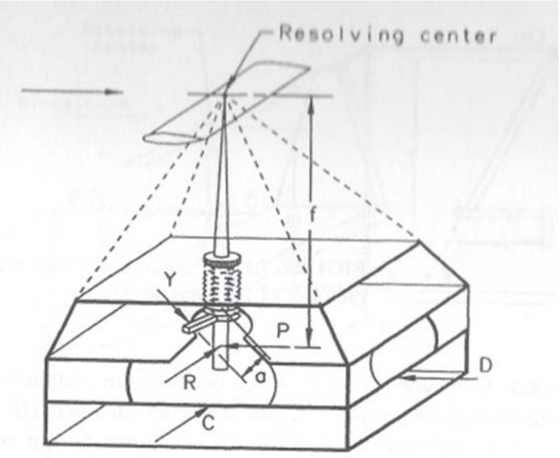
- Platform external balance
    - Widely used, easy to build
    - Disadvantages
        - Moments appear as small differences in large forces
        - The balance resolving center is not at the center of the tunnel and the pitching moments must be transferred
        - Drag and Side Force loads put pitching and rolling moments on the model



$$L = (\mathbf{a} + \mathbf{b}) \qquad D = \mathbf{c} + \mathbf{d} + \mathbf{e} \qquad S = \mathbf{f}$$

$$l = (\mathbf{b} - \mathbf{a})(\tfrac{1}{2}w) \qquad m = -\mathbf{e}x \qquad n = (\mathbf{d} - \mathbf{c})(\tfrac{1}{2}w)$$

- Yoke External Balance
    - Moment Resolving Center is near the center of the tunnel
    - Design leads to larger deflections than the platform balance – particularly in pitch and side force
    - Balance frame must span test section
    - Pitching moment in the drag section instead of lift



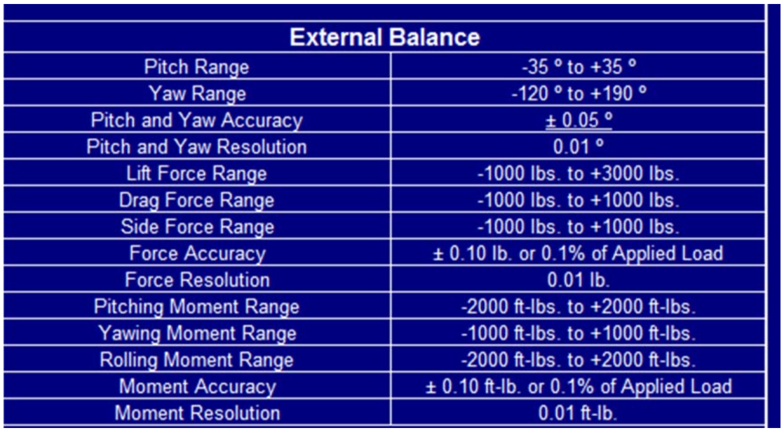
Lift = total weight on lowest table Drag = D Side force = $-C$

Pitching moment = $-P \times f$ Rolling moment = $R \times f$

Yawing moment = $Y \times a$

- Pyramidal External Balance (used in LSWT)
  - Advantages
    - Six components are inherently separated and read by six measuring units
    - No components need to be added, subtracted, or multiplied
  - Disadvantages
    - Calibration and construction is incredibly difficult

- LSWT Pyramidal External Balance
    - 6 component external balance
    - Reference Balance Center corresponds to the geometric center of the wind tunnel test section
        - 42” from the floor, 60” from the sidewall, centered on the large turntable
    - Very accurate



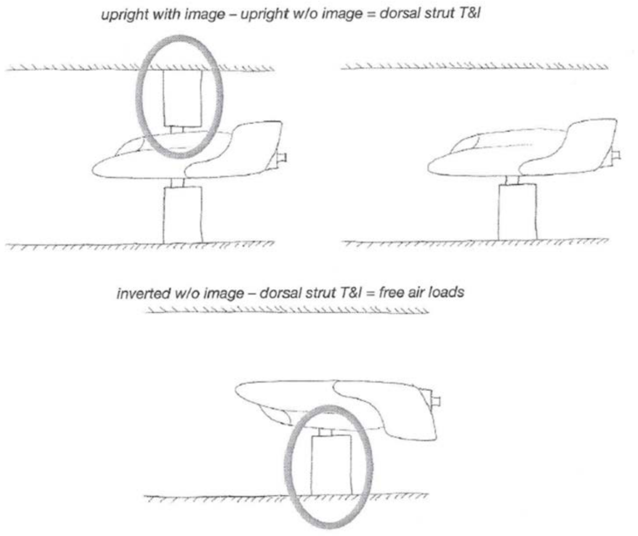
External Balance

Pitch Range	-35 ° to +35 °
Yaw Range	-120 ° to +190 °
Pitch and Yaw Accuracy	± 0.05 °
Pitch and Yaw Resolution	0.01 °
Lift Force Range	-1000 lbs. to +3000 lbs.
Drag Force Range	-1000 lbs. to +1000 lbs.
Side Force Range	-1000 lbs. to +1000 lbs.
Force Accuracy	± 0.10 lb. or 0.1% of Applied Load
Force Resolution	0.01 lb.
Pitching Moment Range	-2000 ft-lbs. to +2000 ft-lbs.
Yawing Moment Range	-1000 ft-lbs. to +1000 ft-lbs.
Rolling Moment Range	-2000 ft-lbs. to +2000 ft-lbs.
Moment Accuracy	± 0.10 ft-lb. or 0.1% of Applied Load
Moment Resolution	0.01 ft-lb.

- External Balance Calibration
    - Extremely complex – involves a 6x21 to 6x33 calibration matrix that is usually nonlinear

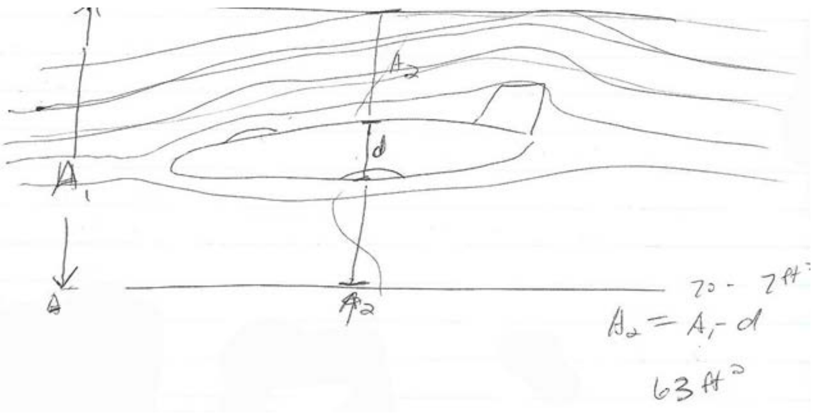
Lesson 8

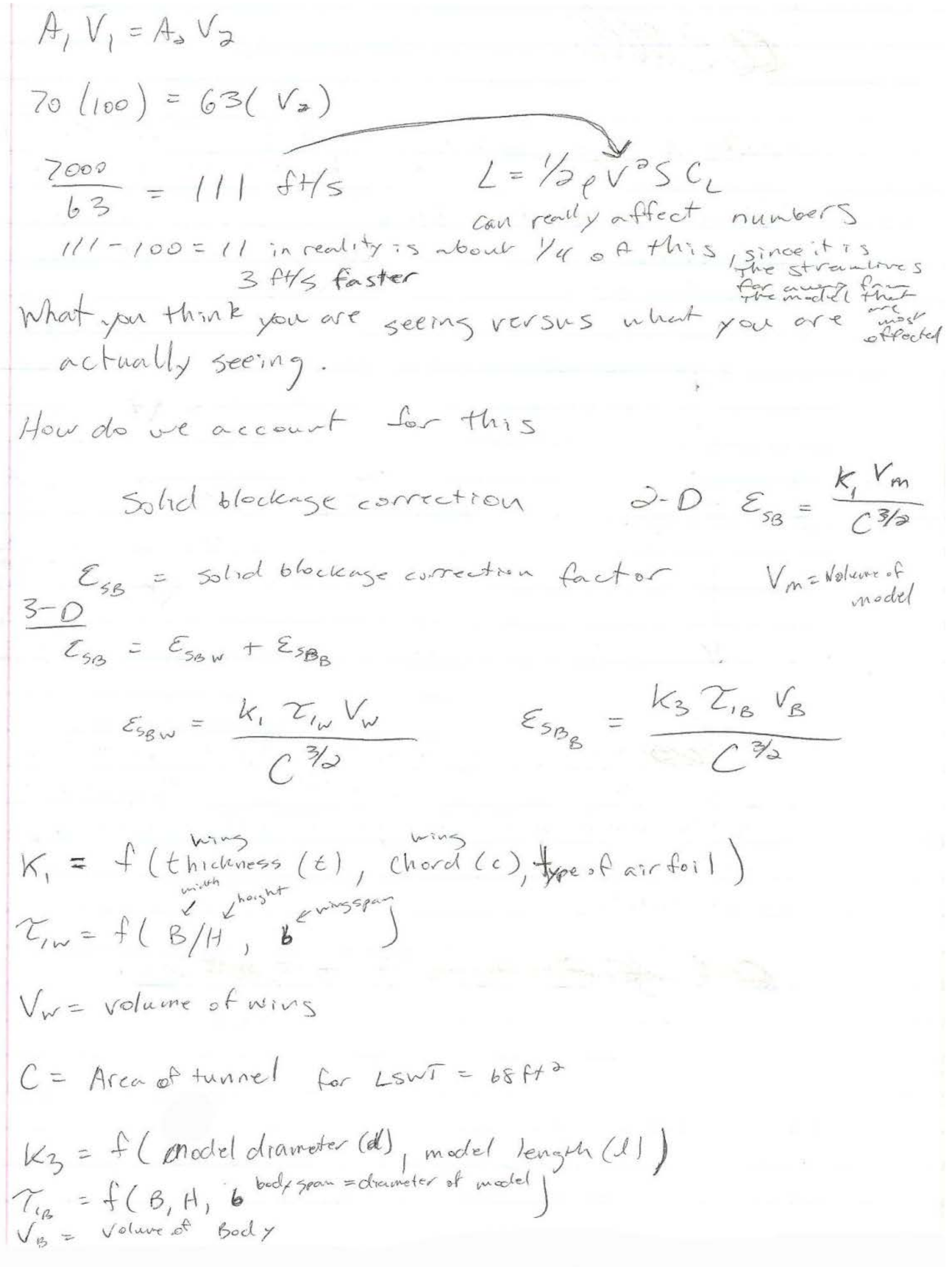
- Tare and Interference
    - Any strut connecting a model to the balance can be considered to add 3 quantities to the balance output
        - 1. Direct aerodynamic force of the strut
        - 2. Effect strut has on airflow on model
        - 3. Effect model has on airflow of strut
    - Because of this we cannot just measure forces on strut alone and subtract from model/strut configuration
    - Tare – direct drag of the support strut
    - Interference – effect of support strut on free air flow
    - Need three runs to do this for every configuration
    - Can be very time consuming



Lesson 9

- Boundary Corrections – Wind tunnels are constrained by walls (boundaries)
  - We are interested in the forces that an aircraft or vehicle would experience in free flight with only maybe a ground plane for a boundary so must apply boundary corrections to the data we gather in a wind tunnel
  - Solid Blockage Boundary Correction
    - The presence of the tunnel walls confining the flow around a model in the test section reduces the area through which air must flow as compared to free air conditions
    - By Conservation of mass and Bernoulli's equation – reduced area increases velocity and we do not get accurate data. Our model is seeing higher velocities than what the wind tunnel is set at.
    - This increase in velocity, which is approximated as constant over a model, is called solid blockage. It is a function of model thickness, thickness distribution, and model size.





$A_1 V_1 = A_2 V_2$

$70(100) = 63(V_2)$

$\frac{7000}{63} = 111$ ft/s $\qquad L = \frac{1}{2}\rho V^2 S C_L$

can really affect numbers

111 − 100 = 11 in reality is about 1/4 of this, since it is the streamlines far away from the model that are most affected

3 ft/s faster

What you think you are seeing versus what you are actually seeing.

How do we account for this

Solid blockage correction $\qquad$ 2-D $\quad \varepsilon_{SB} = \frac{K_1 V_m}{C^{3/2}}$

ε_{SB} = solid blockage correction factor $\qquad V_m$ = Volume of model

3-D

$\varepsilon_{SB} = \varepsilon_{SB_W} + \varepsilon_{SB_B}$

$$\varepsilon_{SB_W} = \frac{K_1 \tau_{1W} V_W}{C^{3/2}} \qquad \varepsilon_{SB_B} = \frac{K_3 \tau_{1B} V_B}{C^{3/2}}$$

$K_1 = f(\overset{\text{wing}}{\text{thickness}}\ (t),\ \overset{\text{wing}}{\text{chord}}\ (c),$ type of airfoil$)$

$\tau_{1W} = f(\overset{\text{width}}{B}/\overset{\text{height}}{H},\ b \leftarrow \text{wingspan})$

V_W = volume of wing

C = Area of tunnel for LSWT = 68 ft²

$K_3 = f($model diameter (d), model length $(l))$

$\tau_{1B} = f(B, H, b$ body span = diameter of model$)$

V_B = Volume of Body

- Wake Blockage Boundary Correction
  - Body will generate a wake with a lower mean velocity than the free stream

- Wake blockage and solid blockage go together and they are frequently the only corrections we actually apply based on tests in the LSWT.
- Higher velocity in wake of object creates a lowered pressure, by Bernoulli, and this lowered pressure arising as the boundary layer grows on the model, puts the model in a pressure gradient and results in a higher velocity on the model

2-D

$$\varepsilon_{wB} = \frac{c}{2H} C_{du}$$

c = chord
H = height of tunnel
Cd_u = 2-D drag coefficient uncorrected

3-D

$$\varepsilon_{wB} = \frac{S}{2C} C_{D_u}$$

S = area of model
C = area of test section
C_{D_u} = 3-D drag coefficient uncorrected

Whole point of this is to come up with the velocity that the model sees corrected for boundary conditions.
For windtunnel testing we talk in terms of q instead of velocity

$$q_{corr} = q_{act} (1 + \varepsilon_{wB} + \varepsilon_{sBw} + \varepsilon_{sBB})^2$$

$$\frac{D \text{ force}}{q_{act} (1 + \varepsilon_{wB} + \varepsilon_{sBw} + \varepsilon_{sBB})^2} = C_{D_{corrected}}$$

Example

Drag read by our external balance = 56 lbf

q_{act} − q we told tunnel to run at = 75 psf

$S = 1\ ft^2$

So C_{D_u} = .7467

t_w = 2 in = 1/6 ft

c = 13.5 in = 1.125 ft

l = 54 in = 4.5 ft

d = model diameter = 20 in = 1 2/3 ft

b = 44 in = 3 2/3 ft

V_b = 5 ft^3

V_w = 0.2 ft^3

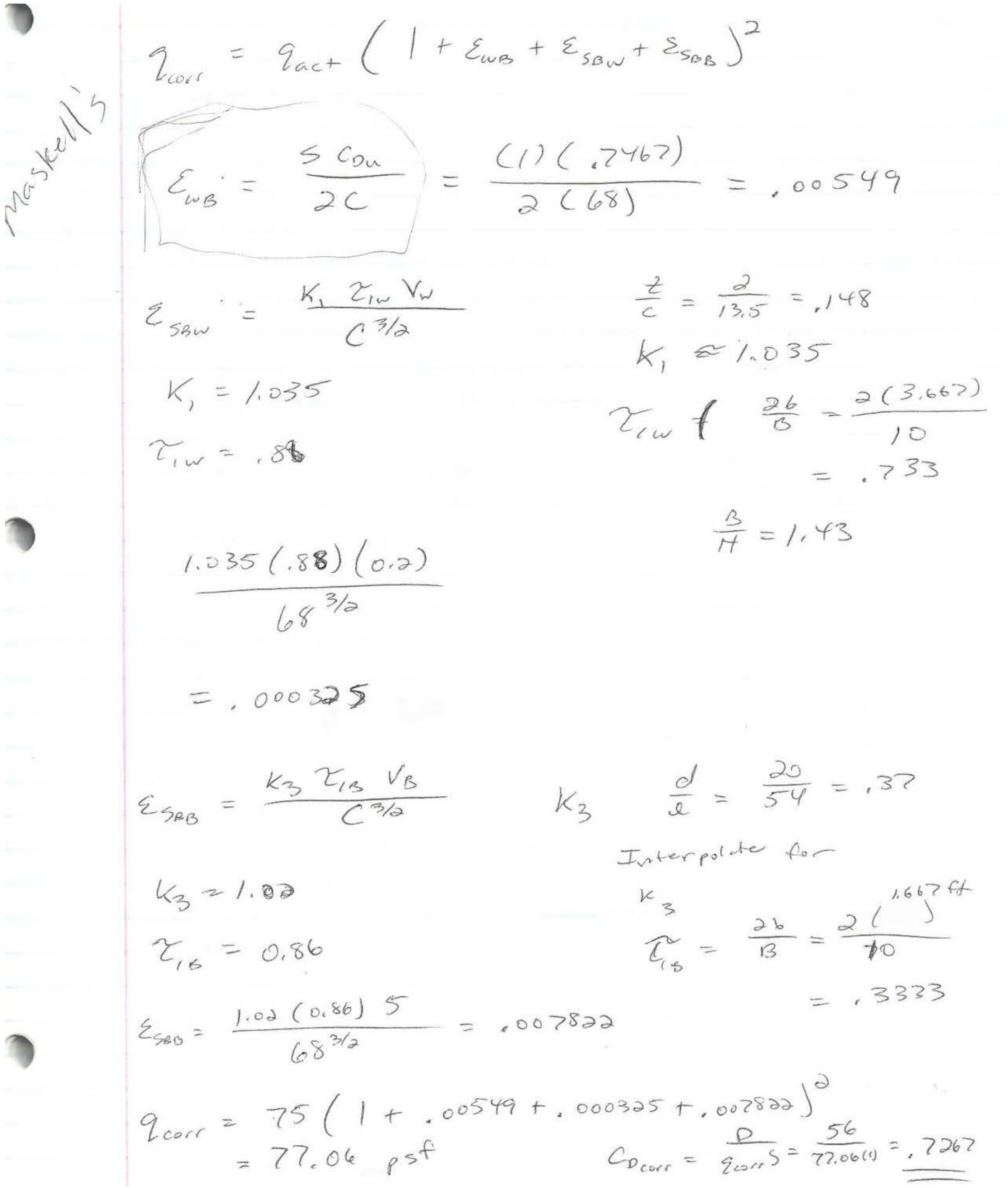
B = tunnel width = (10 ft)

H = 7 ft

C = 68 ft^2

Find $C_{D_{Corrected}}$

$$C_{D_{Corr}} = \frac{D}{q_{corr}}$$



Maskell's

$$q_{corr} = q_{act}\left(1 + \varepsilon_{WB} + \varepsilon_{SBW} + \varepsilon_{SBB}\right)^2$$

$$\boxed{\varepsilon_{WB} = \frac{S\,C_{Du}}{2C}} = \frac{(1)(.7467)}{2(68)} = .00549$$

$$\varepsilon_{SBW} = \frac{K_1\,\tau_{1W}\,V_W}{C^{3/2}}$$

$$\frac{t}{c} = \frac{2}{13.5} = .148$$

$$K_1 \approx 1.035$$

$$K_1 = 1.035$$

$$\tau_{1W} = .88$$

$$\tau_{1W}\ f\left(\ \frac{2b}{B} = \frac{2(3.667)}{10} = .733\right.$$

$$\frac{B}{H} = 1.43$$

$$\frac{1.035(.88)(0.2)}{68^{3/2}}$$

$$= .000325$$

$$\varepsilon_{SBB} = \frac{K_3\,\tau_{1B}\,V_B}{C^{3/2}}$$

$$K_3 \quad \frac{d}{l} = \frac{20}{54} = .37$$

Interpolate for K_3

$$K_3 = 1.02$$

$$\tau_{1B} = 0.86$$

$$\tau_{1B} = \frac{2b}{B} = \frac{2(\overset{1.667\text{ ft}}{\ })}{10} = .3333$$

$$\varepsilon_{SBB} = \frac{1.02(0.86)\,5}{68^{3/2}} = .007822$$

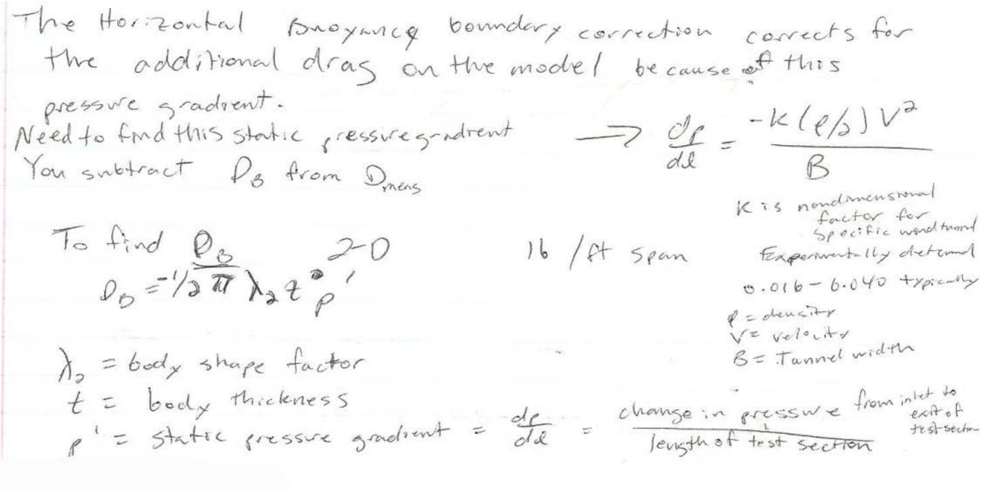
$$q_{corr} = 75(1 + .00549 + .000325 + .007822)^2 = 77.06\text{ psf}$$

$$C_{D_{corr}} = \frac{D}{q_{corr}S} = \frac{56}{77.06(1)} = \underline{\underline{.7267}}$$

- Horizontal Buoyancy Boundary Correction
    - Almost all wind tunnels have a variation in static pressure along the long axis of the test section that results from the thickening of

the boundary layer as it progresses toward the exit cone and to the resultant effective diminution of the jet area

- Pressure is progressively more negative as the exit cone is approached, so there is a tendency for the model to be “drawn” downstream



The Horizontal Buoyancy boundary correction corrects for the additional drag on the model because of this pressure gradient.

Need to find this static pressure gradient $\longrightarrow \frac{dp}{dl} = \frac{-K(\rho/2)V^2}{B}$

You subtract D_B from D_{meas}

K is nondimensional factor for specific wind tunnel
Experimentally determined
0.016 – 0.040 typically

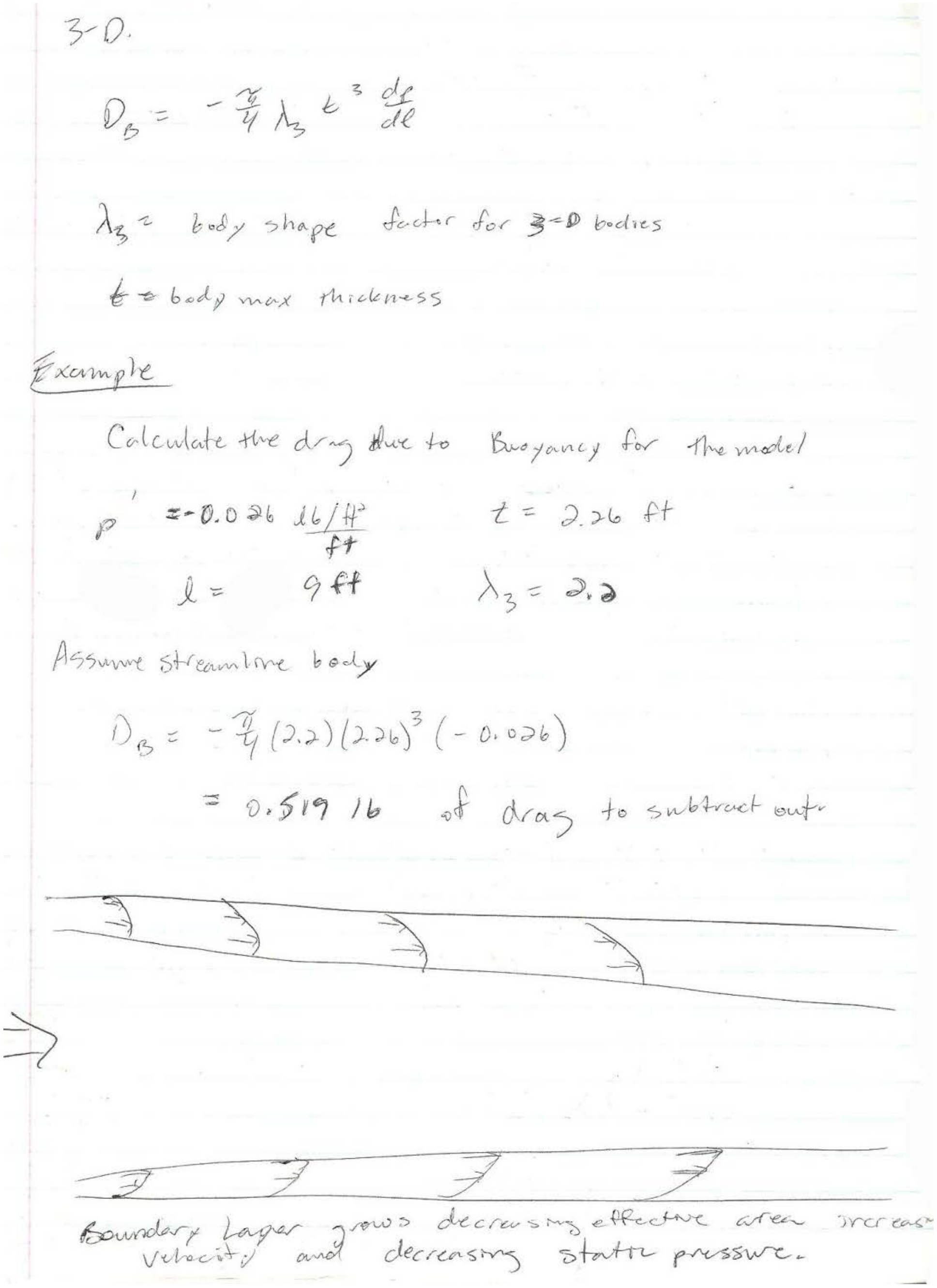
To find D_B 2-D 16 /ft span

$$D_B = -\frac{1}{2}\pi\lambda_2 t^2 p'$$

ρ = density
V = velocity
B = Tunnel width

λ_2 = body shape factor
t = body thickness
p' = static pressure gradient = $\frac{dp}{dl}$ = $\frac{\text{change in pressure from inlet to exit of test section}}{\text{length of test section}}$

- Need to find the static pressure gradient first



3-D.

$$D_B = -\frac{\pi}{4}\lambda_3 t^3 \frac{dp}{dl}$$

λ_3 = body shape factor for 3-D bodies

t = body max thickness

Example

Calculate the drag due to Buoyancy for the model

$p' = -0.026 \frac{lb/ft^2}{ft}$ $t = 2.26$ ft

$l = 9$ ft $\lambda_3 = 2.2$

Assume streamline body

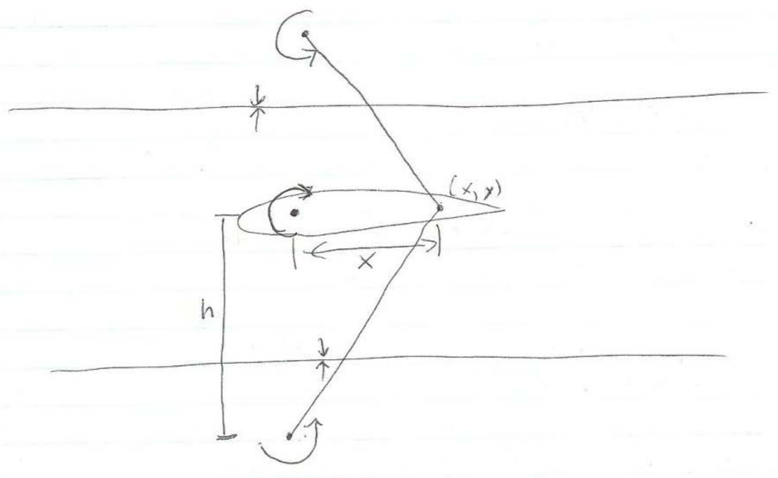
$$D_B = -\frac{\pi}{4}(2.2)(2.26)^3(-0.026)$$

$$= 0.519 \text{ lb}$$ of drag to subtract out.

Boundary Layer grows decreasing effective area increase velocity and decreasing static pressure.

- In LSWT, the walls are angled out slightly to alleviate the need for this boundary correction

- Streamline Curvature Boundary Correction
  - Only deals with a body that generates lift – airfoils, etc.
  - The presence of the ceiling and floor prevents the normal curvature of the free air that occurs about any lifting body, and relative to the straightened flow, the body appears to have more camber (around 1% typically) than it actually has.
  - This means an airfoil will generate more lift and more pitching moment about the quarter chord at a given angle of attack in a wind tunnel versus in free flight.
    - Not limited to cambered airfoils since any lifting body produces a general curvature in the airstream.
  - For 2-D assume airfoil is small and may be represented by a single vortex at its quarter chord. We have tunnel boundaries that are no penetration boundaries.



from simple vortex theory

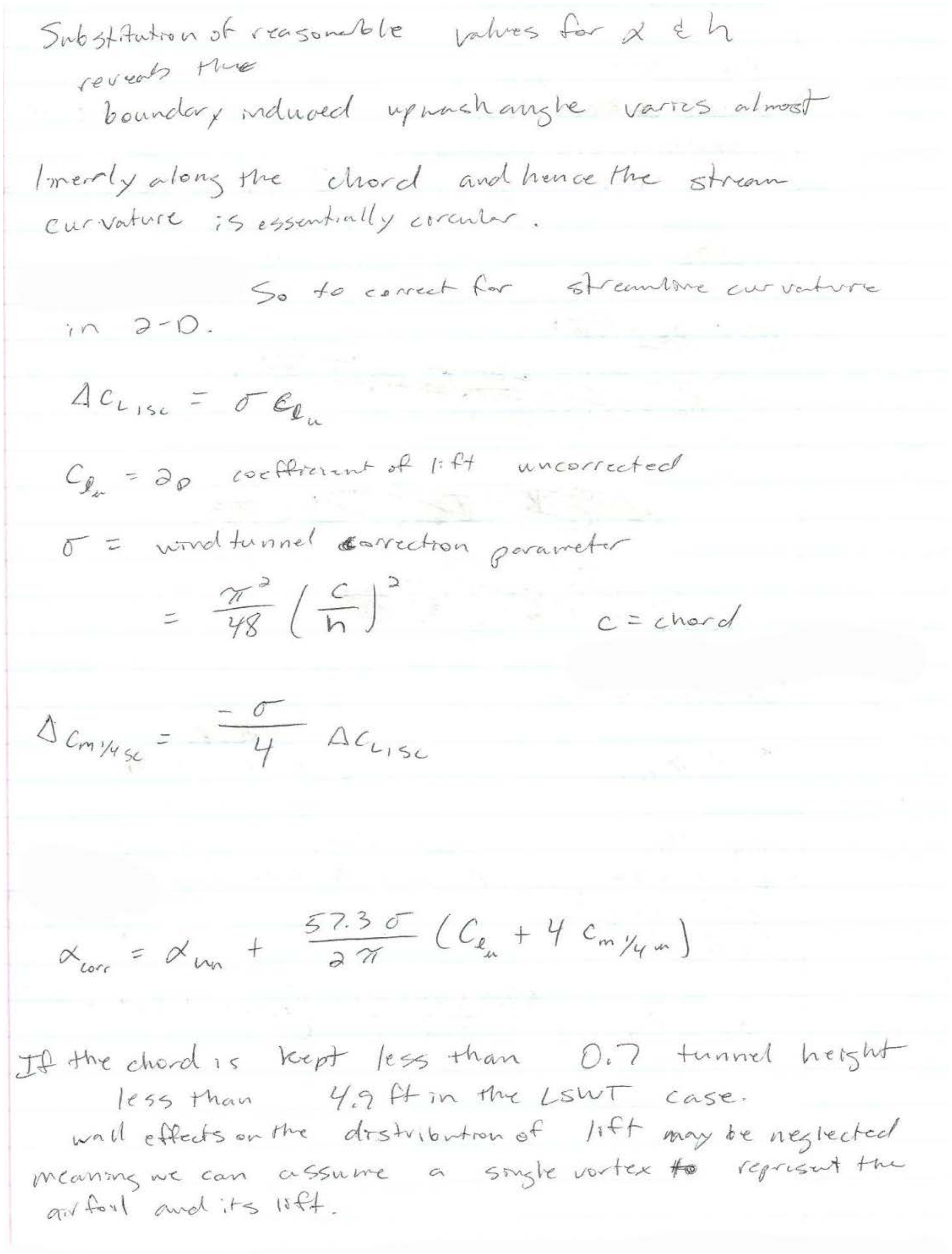
Horizontal components cancel, but vertical components add

$$\psi(x,y) = \frac{\Gamma}{2\pi} \ln r_h \qquad r = (x^2+y^2)^{1/2}$$

$$u = \frac{\partial \psi}{\partial y} = 0 \qquad v = -\frac{\partial \psi}{\partial x}$$

From simple vortex theory the vertical velocity at a distance x fr
the lifting line

$$v = \frac{\Gamma}{2\pi} \frac{x}{h^2+x^2}$$



Substitution of reasonable values for α & h reveals the boundary induced upwash angle varies almost linearly along the chord and hence the stream curvature is essentially circular.

So to correct for streamline curvature in 2-D.

$$\Delta C_{L_{sc}} = \sigma C_{\ell_u}$$

C_{ℓ_u} = 2D coefficient of lift uncorrected

σ = wind tunnel correction parameter

$$= \frac{\pi^2}{48}\left(\frac{c}{h}\right)^2$$

c = chord

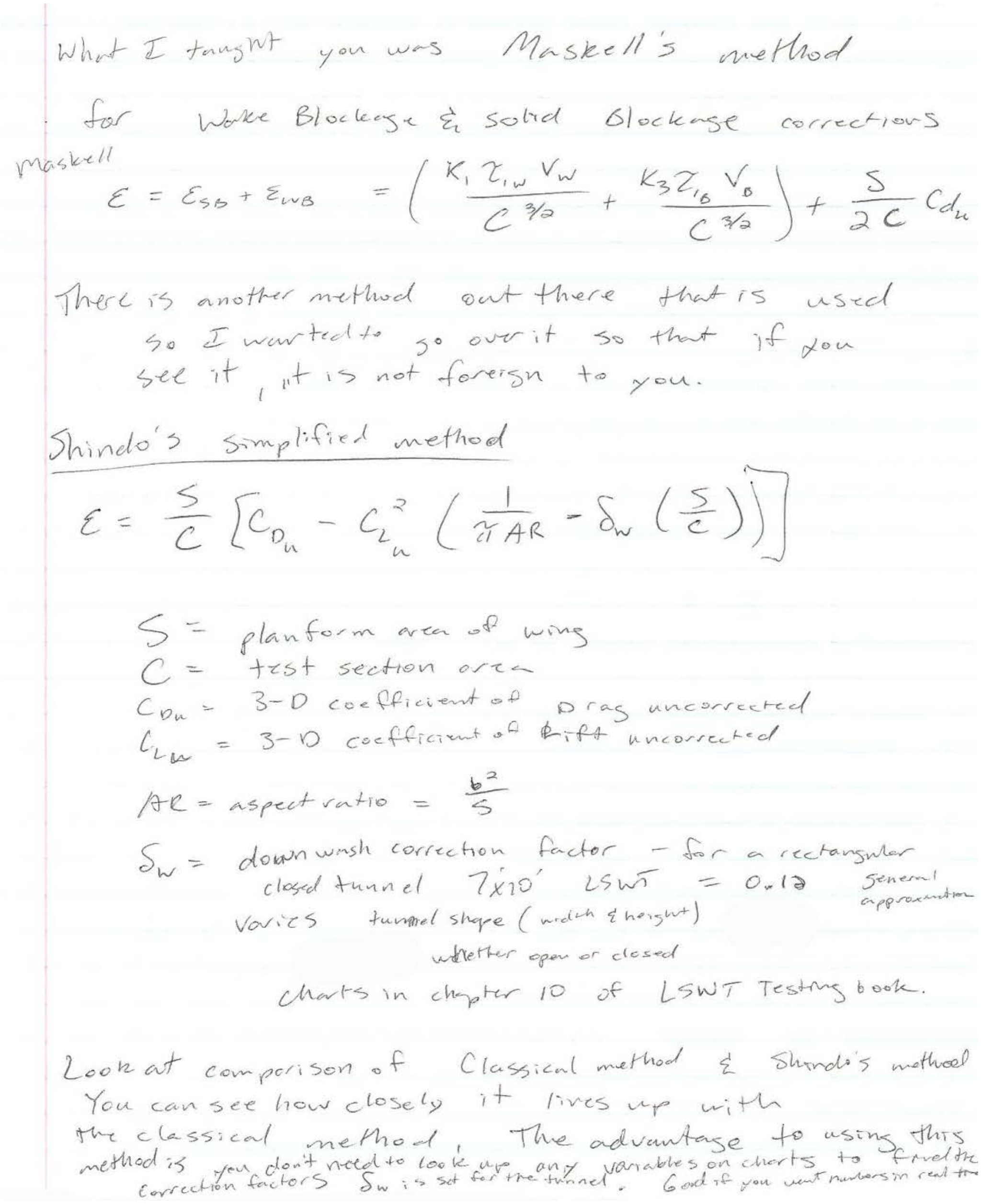
$$\Delta C_{m_{1/4\,sc}} = \frac{-\sigma}{4}\,\Delta C_{L_{sc}}$$

$$\alpha_{corr} = \alpha_{un} + \frac{57.3\,\sigma}{2\pi}\left(C_{\ell_u} + 4\,C_{m_{1/4\,u}}\right)$$

If the chord is kept less than 0.7 tunnel height less than 4.9 ft in the LSWT case. wall effects on the distribution of lift may be neglected meaning we can assume a single vortex ~~to~~ represent the airfoil and its lift.

- Shindo's Simplified Correction Method
    - Another method used for boundary corrections

- Do not need to look up any variables on charts to find correction factors so can process boundary corrections in real time in the tunnel



What I taught you was Maskell's method for Wake Blockage & solid Blockage corrections

Maskell

$$\varepsilon = \varepsilon_{SB} + \varepsilon_{WB} = \left(\frac{K_1 \tau_{1w} V_w}{C^{3/2}} + \frac{K_3 \tau_{1b} V_b}{C^{3/2}} \right) + \frac{S}{2C} C_{d_u}$$

There is another method out there that is used so I wanted to go over it so that if you see it, it is not foreign to you.

Shindo's simplified method

$$\varepsilon = \frac{S}{C} \left[C_{D_u} - C_{L_u}^2 \left(\frac{1}{\pi AR} - \delta_w \left(\frac{S}{C} \right) \right) \right]$$

S = planform area of wing

C = test section area

C_{D_u} = 3-D coefficient of Drag uncorrected

C_{L_u} = 3-D coefficient of lift uncorrected

AR = aspect ratio = $\frac{b^2}{S}$

δ_w = downwash correction factor – for a rectangular closed tunnel 7'x10' LSWT = 0.12 general approximation

varies tunnel shape (width & height)

whether open or closed

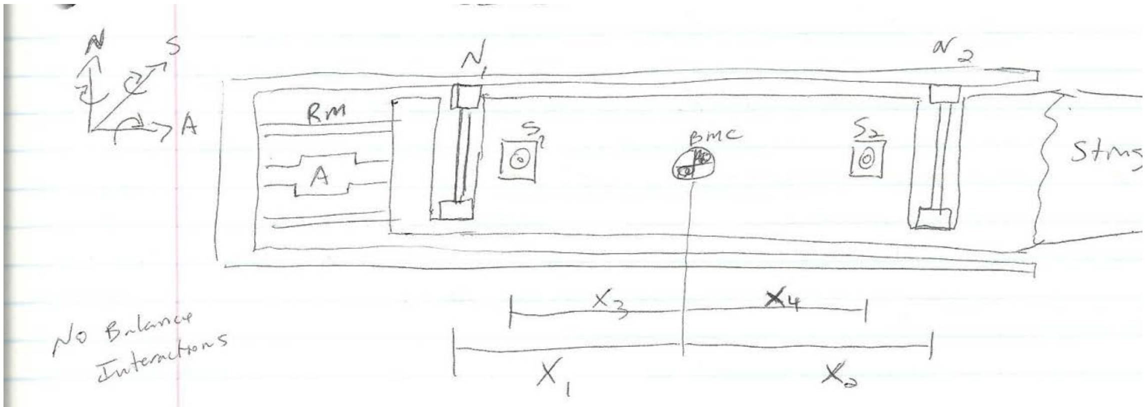
charts in chapter 10 of LSWT Testing book.

Look at comparison of Classical method & Shindo's method

You can see how closely it lives up with the classical method, The advantage to using this method is you don't need to look up any variables on charts to find the correction factors δ_w is set for the tunnel. Good if you want numbers in real time

Lesson 10

- Internal Balances



No Balance Interactions

5 Forces 1 moment

RM directly measured
Axial Directly measured

$N = N_1 + N_2$
$S = S_1 + S_2$

$PM = N_1 X_1 - N_2 X_2$

$YM = S_1 X_3 - S_2 X_4$

  - 2 general sources of error for internal balances
    - Misalignment of balance parts – caused by manufacturing tolerances in both parts and assembly
      - Linear or first degree
    - Elastic deformation of the parts caused by other forces and moments

- Nonlinear or second degree

If angular displacement between measuring axis & load axis

$$A' = A \cos\beta + N \sin\beta$$

$\uparrow$ misalignment angle

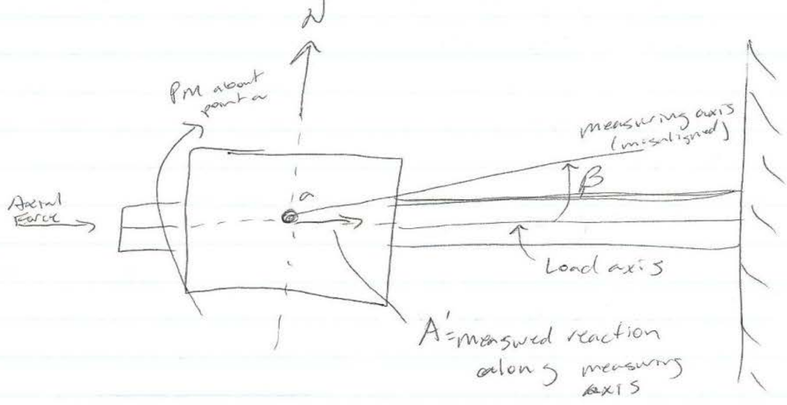
But since tolerances are tight assume β to be small

$\cos\beta = 1 \quad \sin\beta = \beta$

so

$$A' = A + N\beta$$

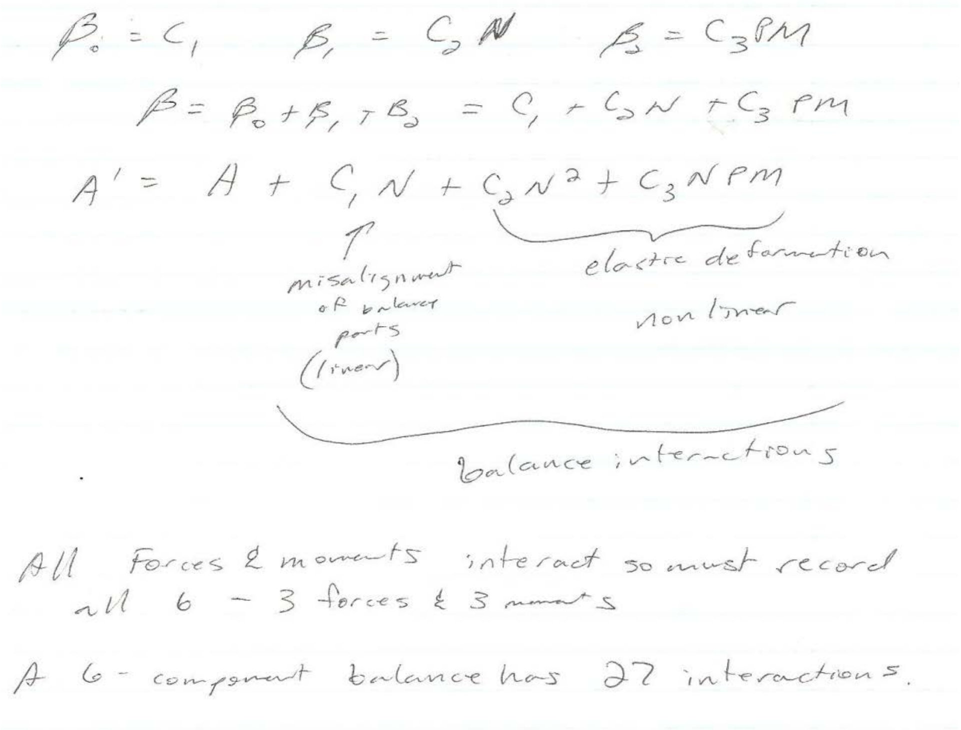
Now assume due to manufacturing tolerances small initial misalignment β_0 = constant



Add Normal Force which deflects sensor as an end load on a cantilevered beam – This results in misalignment due to normal force β_1

Add PM deflects sensor possibly in another mode – misalignment β_2

β_0 = constant $\quad \beta_1$ & β_2 vary with load



$\beta_0 = C_1 \qquad \beta_1 = C_2 N \qquad \beta_2 = C_3 PM$

$\beta = \beta_0 + \beta_1 + \beta_2 = C_1 + C_2 N + C_3 PM$

$$A' = \underbrace{A + \underset{\substack{\uparrow \\ \text{misalignment} \\ \text{of balance} \\ \text{parts} \\ \text{(linear)}}}{C_1 N} + \underbrace{C_2 N^2 + C_3 NPM}_{\substack{\text{elastic deformation} \\ \text{non linear}}}}_{\text{balance interactions}}$$

All Forces & moments interact so must record all 6 – 3 forces & 3 moments

A 6-component balance has 27 interactions.

- Calibration of Internal Balance
    - Very time intensive – for more complicated internal balances can take up to 100 hours of test time

Lesson 11

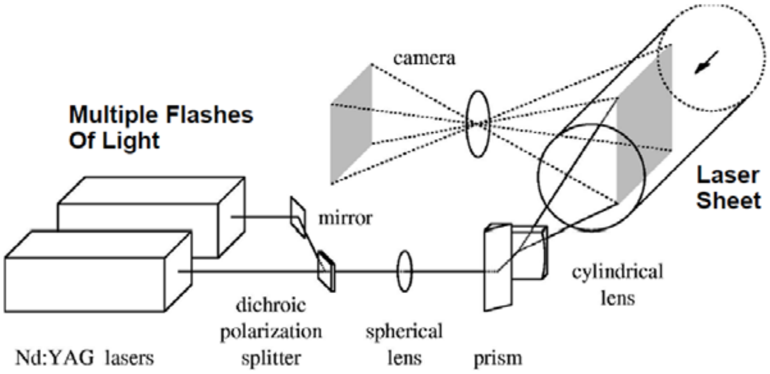
- Flow Visualization Techniques
    - Value of flow visualization techniques
        - Aids in giving a mental image of the aerodynamic problem
        - Visually determine stagnation point location, separation lines, boundary layer transition, characteristic unsteadiness in the flow, other types of critical points and their locations
    - Different methods for visualizing the flow in a wind tunnel
        - Tufts
            - Short length of yarn attached to a wind tunnel model – one end is fixed, the other is free
            - Usually glued or taped to the surface
            - Will affect the aerodynamic forces read by external/internal balance
            - Go over examples of tuft use in LSWT
        - China Clay
            - A mixture of kerosene, china clay, and fluorescent dye is applied to a model with the wind off
            - Turning the wind on causes the kerosene to evaporate as it follows the streamlines
            - China clay stays on the model indicating the direction of streamlines

    - Typical mix is 100ml of china clay per liter of kerosene
    - Can be extremely messy and difficult to get mixture correct
    - Produces great photographs though
- Oil film
    - When the wind is turned on, oil flow will follow streamlines
    - Great for a visualization on the laminar to turbulent boundary layer transition since the oil cannot flow past where this transition occurs
    - Show pictures of oil use for flow visualization
- Smoke
    - Most common type of flow visualization after tufts
    - Smoke generated by fog generator – like those used in nightclubs
        - Polyethylene glycol as the fuel and pressure from a peristaltic pump
    - Smoke wire only for very small wind tunnels and very low velocities
    - Will see this used in experiment number 3
- Particle Image Velocimetry (PIV)
    - Will get more into this in the next class

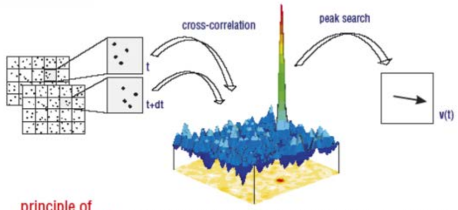
- Lights up small particles that have been seeded into the flow
- Can use several cameras to get 3-D flow visualization

Lesson 12

- Particle Image Velocimetry
    - Advantages
        - Non-intrusive
        - Ability to get instantaneous flow velocity
    - Disadvantages
        - Small area of focus (75mm x 56mm)
        - Expensive Instrumentation
        - Requires a lot of experience to set the many parameters
    - Illumination system of PIV always consists of a light source and optics
        - Light source – Lasers such as the Argon-ion laser or the Nd:YAG laser are frequently used in PIV because of their ability to produce monochromatic light with high energy density
        - Optics – always consist of a set of cylindrical lenses and mirrors to shape the light source beam into a planar sheet of light to illuminate the flow field

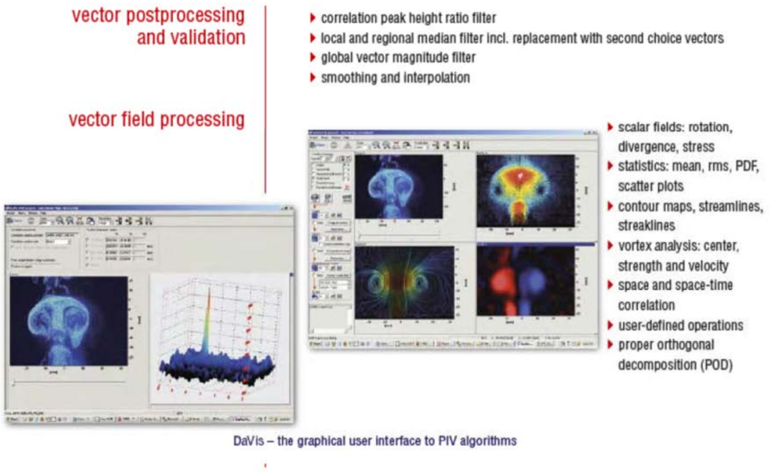


- Camera usually used for PIV
    - Charged-Coupled Device (CCD) camera
        - Fully digitized
        - Conventional or auto-cross correlation techniques combined with special framing techniques can be used to measure higher velocities
- Other equipment that needs to be selected carefully for PIV set-up
    - Lenses
    - Filters
    - Synchronizer
- Image processing for PIV
    - We use DaVis software for image processing cross-correlation



principle of
cross-correlation PIV

The position of the highest peak in the correlation plane indicates the mean displacement **ds** of the particles in a particular interrogation window. The displacement vectors of all interrogation windows are finally transformed into a complete instantaneous velocity map.



vector postprocessing and validation

- correlation peak height ratio filter
- local and regional median filter incl. replacement with second choice vectors
- global vector magnitude filter
- smoothing and interpolation

vector field processing

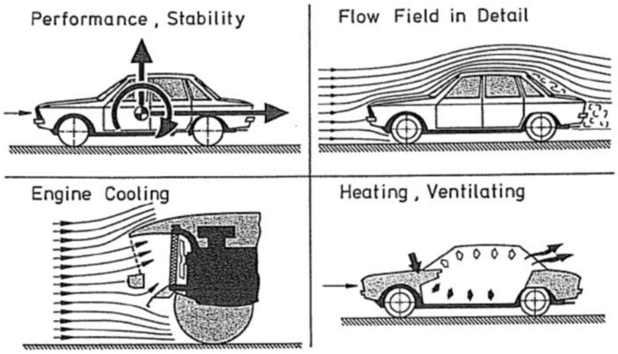
- scalar fields: rotation, divergence, stress
- statistics: mean, rms, PDF, scatter plots
- contour maps, streamlines, streaklines
- vortex analysis: center, strength and velocity
- space and space-time correlation
- user-defined operations
- proper orthogonal decomposition (POD)

DaVis – the graphical user interface to PIV algorithms

- Seeding Density
  - Low Density
    - Clear peaks after cross correlation, but risk having sub image without particles
  - High Density
    - Noisy correlation matrices
  - Ideal – 10-20 particles per sub-image

Lesson 13

- Ground Vehicle Testing
    - Comparatively aerodynamics are not as important for ground vehicles as for airplanes, but they still play a part.
    - 4 main ground vehicle objectives concerning wind tunnel tests



    - The flow field around ground vehicles is very complex
        - Large regions of flow separation
        - Ground effect
    - CFD becomes more difficult thus rendering wind tunnel tests more desirable
    - Full scale tests can be easily achieved and are preferred
    - Need for road simulation – i.e. moving belt that the ground vehicle drives on
    - Cabin ventilation
    - Climatic Wind Tunnel tests

- Wind Noise tests
- Windshield wiper tests

APPENDIX C

Aero 489 (Fall 2012) Homework #1

Due Tuesday 18 September 2012 – at the beginning of class

1. Write each value ($X \pm \sigma_X$) with the appropriate precision and accuracy.
   a. $M = 2.14167352$ and $\sigma_M = 0.03467296$
   b. $C_L = 6.187342$ and $\sigma_{CL} = 0.5167253098$
   c. $L = 25792$ lbf and $\sigma_L = 392.47829087$ lbf
   d. $C_M = 0.0000346721$ and $\sigma_{CM} = 0.0000007592345$

2. Given the following equation for the drag coefficient, C_D, find $C_D \pm \sigma_{CD}$. What input uncertainty contributes the most to the uncertainty in the drag coefficient?

$$\boldsymbol{C_{D=}\, C_{D_0} + KC_L^2}$$

Where:

C_{D_0} = drag coefficient at zero lift = 0.445790636; $\sigma_{C_{D_0}}$ = 0.001134
K = induced drag correction factor = 0.0343077; σ_K = 0.000151
C_L = lift coefficient = 5.12547; σ_{C_L} = 0.02597

*Assume the covariance is zero

3. Given the following equation for the moment coefficient, C_M , find $C_M \pm \sigma_{C_M}$ using relative uncertainty analysis. What input uncertainty contributes the most to the uncertainty in the moment coefficient?

$$\mathbf{C_M} = \frac{\boldsymbol{M}}{\frac{1}{2}\boldsymbol{\varrho V^2 Sc}}$$

Where:

M = 42.7992 ft-lbf; σ_M = 0.04389 ft-lbf
V = 225 ft/s; σ_V = 0.25 ft/s
S = 9.87534 ft^2 ; σ_S = 0.0145 ft^2
c = 6.7943 in. ; σ_c = 0.00912 in.
ϱ = 0.0023769 slug/ft^3; σ_ϱ = 0.000013467 slug/ft^3

Aero 489 (Fall 2012) Homework #1

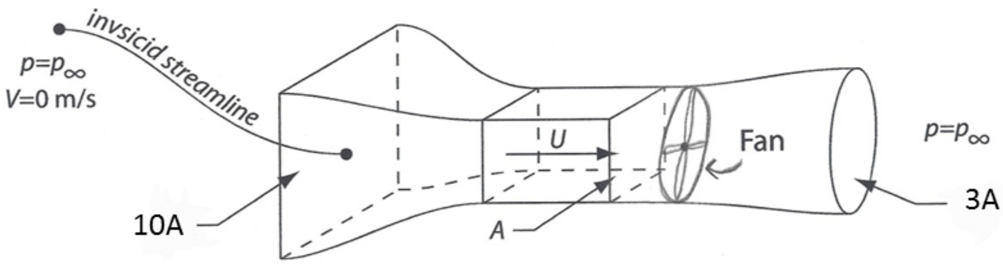
4. Consider the wind tunnel in the sketch below. Flow enters the tunnel through an inlet area **10A** on the left, passes through the test section in the middle where the area is **A** and the speed is **U** and exits through an exhaust area **3A** on the right. The exhaust pressure is p_∞, the pressure far upstream of the inlet where the velocity is zero. The fan is located between the test section and exhaust. Because the fan delivers power to the flow, Bernoulli's equation doesn't apply across the fan.
   a. Use the steady, inviscid streamline that enters the tunnel to calculate **p** at the inlet in terms of p_∞, A, ϱ, and U.

   b. Assuming that the flow is inviscid, isothermal, and incompressible, the energy equation can be written

   $$\iint (K + p)(\vec{v} \cdot \hat{n})dS = \dot{W}_S \quad \text{where} \quad K = ½ϱV^2$$

   and W_S is the shaft power delivered to the fan. The kinetic energy per unit volume, K, is a scalar. Find the W_S required to run the wind tunnel at speed U.

   c. There are no viscous losses in the tunnel and the temperature of the air doesn't increase. Why is power required to operate the tunnel? Where is the energy going? If this were a closed circuit wind tunnel would you need power to operate the tunnel? Why?



Aero 489: Wind Tunnel Test Engineering (Fall 2012)
Homework #2
Due 02 October 2012 at the beginning of class

1. Linear Regression Analysis
    a. Download the file at: https://dl.dropbox.com/u/104390946/Aero489HW2.xlsx and click on the Linear Regression Tab on the bottom of the spreadsheet.
    b. Using the equation for C_L below, apply uncertainty-weighted least squares fits to find a (the lift curve slope) and $\alpha_{L=0}$ (the angle of attack at zero lift).

$$C_L = a\,(\alpha - \alpha_{L=0})$$

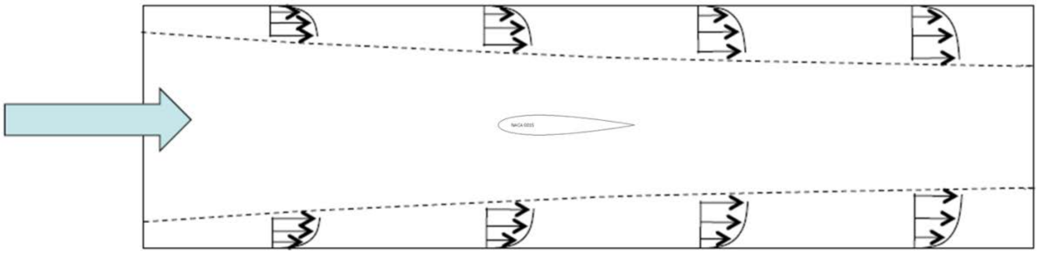
    c. Over what range of α (angle of attack) do you choose to take the fits? (Make sure you have sufficient data points (at least 20) and start with -9 degrees angle of attack)
    d. Are the fits good? (quantify goodness)
    e. What are the two quantities a and $\alpha_{L=0}$ and what are their respective uncertainties?
    f. Plot coefficient of lift versus angle of attack and superimpose your CL-fit linear regression line on the same graph.

2. Fast Fourier Transform
    a. Download the file at: https://dl.dropbox.com/u/104390946/Aero489HW2.xlsx and click on the FFT tab at the bottom of the spreadsheet.
    b. Perform an FFT of the data (Sample rate is 1000Hz)
    c. Plot the FFT magnitude vs. FFT frequency and show the dominant frequency on the graph

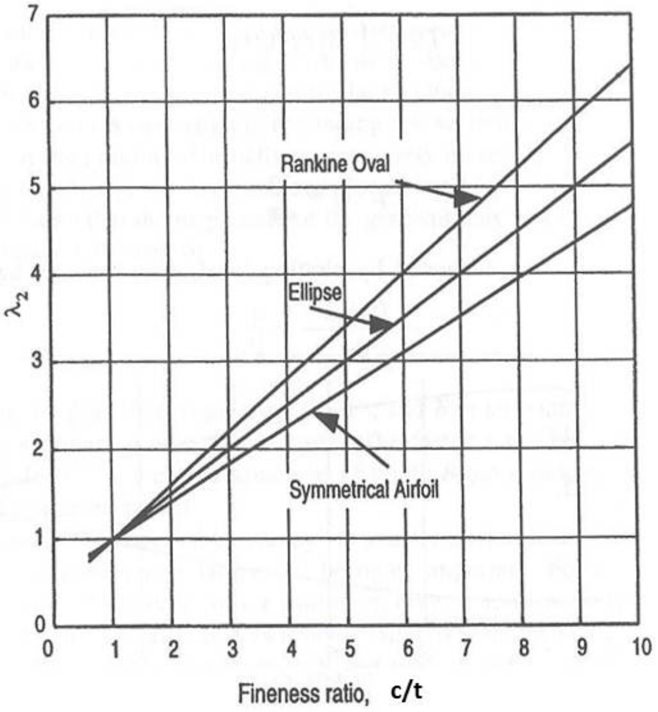
Aero 489 (Fall 2012) Homework #3

Due Thursday 25 October 2012 – at the beginning of class

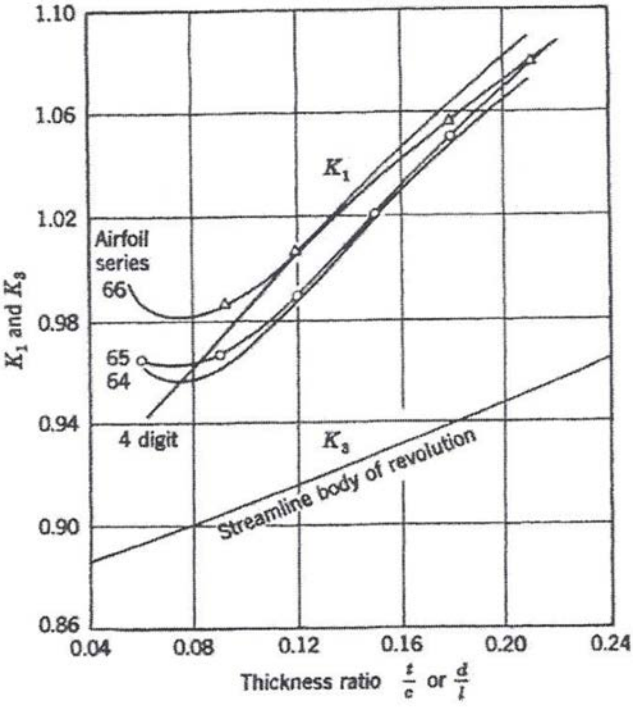
1. You have been tasked to conduct a wind tunnel test in the Oran W. Nicks Low Speed Wind Tunnel for a small airplane manufacturer. They have developed a new airplane and want to get data on it to validate their CFD models and check for stability at their projected cruise speed of 300mph at a projected altitude of 40,000 feet above sea level. The full size aircraft has a wingspan of 40.5 feet, a chord length of 3 feet, a body length of 35.8 feet, and a height of 9.8 feet. The PFA (projected frontal area) of the airplane is 100 ft^2. The LSWT test section area is 68 ft^2. Assume the max velocity of the LSWT is 220 mph and assume standard sea level conditions for the LSWT tests.
    a. What scale do you choose to build your model for the test section? Why?
    b. What q value [in psf] do you choose to conduct the test? Why?



2. A NACA 0015 airfoil is placed in a closed loop wind tunnel with a test section that is 7’ high x 10’ wide x 14’ long. The velocity of air in the tunnel is moving left to right at 150mph. The chord length of the airfoil is 2 ft. The volume of the airfoil is 5 ft^3. The area of the test section is 70 ft^2. The density of air in the test section is 0.002378 $slug/ft^3$. The non-dimensional wind tunnel factor for this wind tunnel is 0.025. $Drag_{uncorrected}$ = 55.43378 lb. $Lift_{uncorrected}$ = 15.73752 lb. (Note: a symmetric airfoil should not have any lift at 0° AOA, so there must be some upflow in the wind tunnel).
    a. Apply 2-D boundary corrections to find the corrected coefficient of drag that has been corrected for horizontal buoyancy, wake blockage, and solid blockage.
    b. Apply 2-D boundary corrections to find the corrected coefficient of lift that has been corrected for streamline curvature, wake blockage, and solid blockage.



Rankine Oval
Ellipse
Symmetrical Airfoil
λ_2
0
1
2
3
4
5
6
7
8
9
10
Fineness ratio, c/t



K_1 and K_3
1.10
1.06
1.02
0.98
0.94
0.90
0.86
0.04
0.08
0.12
0.16
0.20
0.24
K_1
Airfoil series
66
65
64
4 digit
K_3
Streamline body of revolution
Thickness ratio $\frac{t}{c}$ or $\frac{d}{l}$

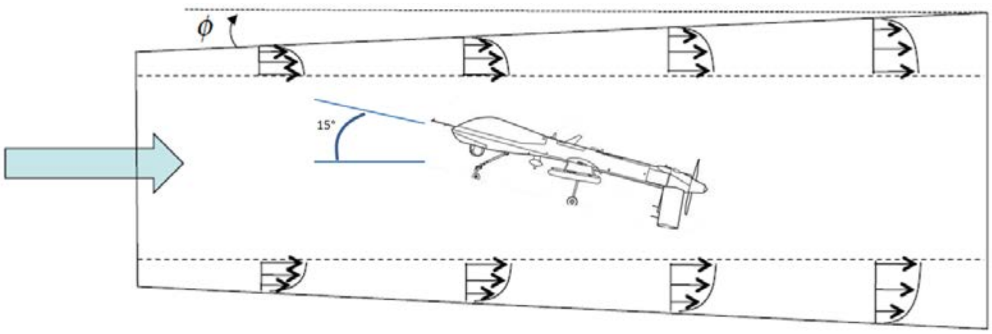
Aero 489 (Fall 2012) Homework #4

Due Tuesday 27 November 2012 – at the beginning of class

1. You are participating in the Army's Extended Range/Multi-Purpose Unmanned Aerial Vehicle (UAV) competition and have developed a new UAV with your company. The specifications required in the competition state that the UAV must be able to fly 150 mph at an altitude of 25,000 feet above sea level. It must stay in the air for at least 24 hours without refueling. You are the lone aerospace engineer in your company and have already developed a CFD model of the UAV. You want to validate your CFD model and check for stability at the airspeed and altitude set forth in the design competition. The full size UAV that you designed has a wingspan of 17 feet, a body length of 8.5 feet, a chord length of 1.0625 feet, and a height of 2.06 feet. The PFA (projected frontal area) of the UAV is 3 ft^2. The LSWT test section area is 68 ft^2. Assume the max velocity of the LSWT is 220 mph and assume standard sea level conditions for the LSWT tests. Other constraints: Model wingspan must be less than 80% of tunnel width so that span-wise downwash distortion is negligible.
    a. What scale do you choose to build your model for the test section? Why?
    b. What q value [in psf] do you choose to conduct the test? Why?

   Now assume that the wingspan is 56 feet, body length is 28 feet, chord length is 3.5 feet, and height is 6.8ft. The projected frontal area of the UAV is now 48ft^2.

    c. What scale do you choose to build your model for the test section? Why?
    d. What q value [in psf] do you choose to conduct the test? Why?



2. You placed your UAV in the closed loop LSWT which has a test section that is 7’ high x 10’ wide x 12’ long. The velocity of air in the tunnel is moving left to right at 195mph. There is a slight correction in the tunnel walls to account for boundary layer growth (i.e. tunnel walls are not parallel). The UAV is currently pitched up at 15 degrees. The uncorrected Drag, Lift, and Pitching Moment at an AOA of 15 degrees are:

   $\text{Drag}_{\text{uncorrected}}$ = 68.5387 lb. $\text{Lift}_{\text{uncorrected}}$ = 415.8731 lb. $\text{PM}_{\text{uncorrected}}$ = -22.1374 ft-lb.

   <u>Use the following parameters to find the boundary corrections:</u>
   ϱ_∞ = .002378 slugs/ft^3 S = 441 in^2 C = 68 ft^2 H = 7 ft
   B = 10 ft d_B = diameter of body = 8 in. l_B = length of body = 3.5 ft.
   t_W = wing thickness = 1 in. c_w = wing chord = 5.25 in. V_w = 441 in^3
   V_b = 2111 in^3 τ_{1w} = 0.98 δ_w = 0.12
   $t_{B\text{-max}}$ = max thickness of body = 10.2 in. l_t = tail length = 1.3125 in.

   $\frac{dp}{dl} \approx 5 \times 10^{-6}\ \frac{psf}{ft}$ λ = 0.7 a = lift curve slope = 0.89

   a. What 3-D boundary corrections are you going to apply to this model?

   b. What is the corrected angle of attack?

   c. What is the corrected Coefficient of Drag?

   d. What is the corrected Coefficient of Lift?

   e. What is the corrected Coefficient of Pitching Moment?

Wake Blockage and Solid Blockage (Maskell)

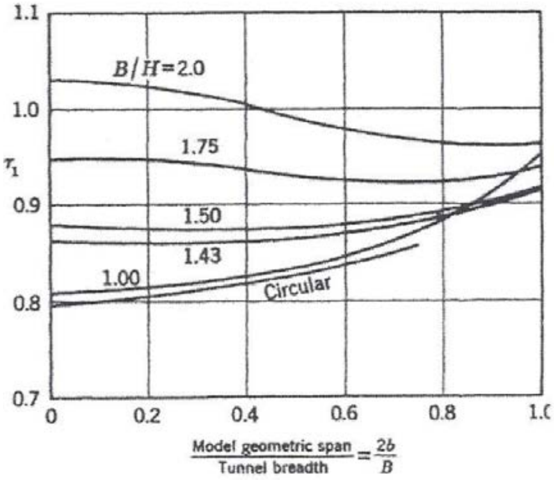
$q_{\text{corr}} = q_{\text{act}}(1+\varepsilon_{wb}+\varepsilon_{w}+\varepsilon_{b})^2$

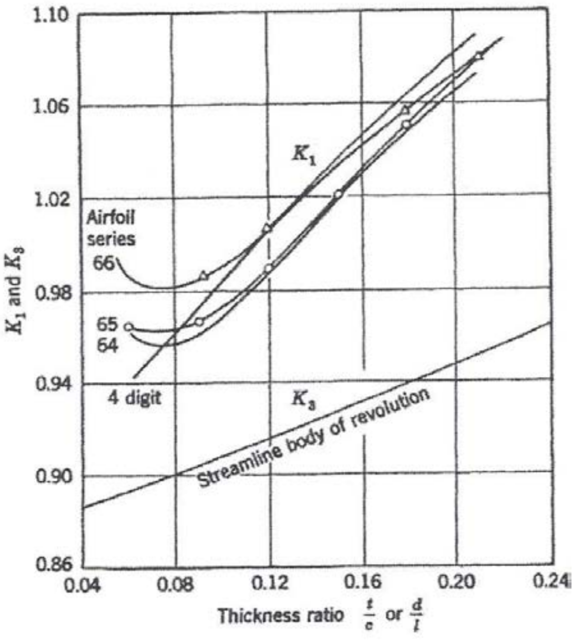
Wake Blockage — Model drag creates a decelerated wake that decreases effective flow cross-sectional area and increases effective q. $\varepsilon_{wb} = D/2Cq_{\text{act}}$

The above equation is when S = 1. When S $\neq$ 1, $\varepsilon_{\text{wb}} = \frac{S}{2C} C_{D_u}$

Solid Blockage — The flow accelerates due to the reduced cross-sectional area due to the model and increases the effective dynamic pressure near the model from q_{act} to q_{corr}.

$\varepsilon_w = K_1\tau_{1w}V_w/C^{3/2}$ and $\varepsilon_b = K_3\tau_{1b}V_b/C^{3/2}$. The subscript "$b$" refers to "body"; "$w$" refers to wing.





Shindo's Simplified Correction Method

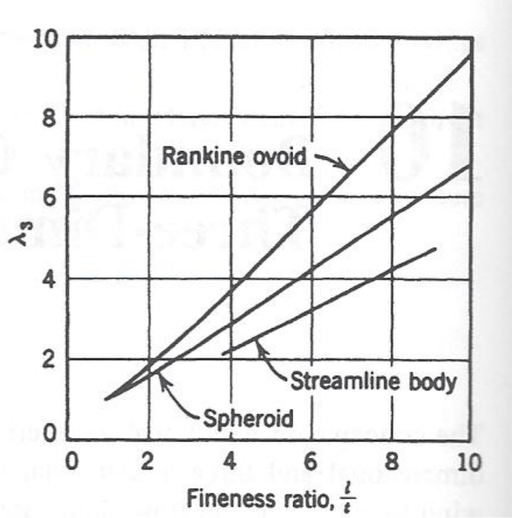
$q_{\text{corr}} = q_{\text{act}}(1+\varepsilon)^2$

$$\varepsilon = \frac{S}{C}\left[C_{D_u} - C_{L_u}^2\left(\frac{1}{\pi\frac{b^2}{S}} - \delta_w\left(\frac{S}{C}\right)\right)\right]$$

Horizontal Buoyancy

Horizontal Buoyancy – Variation of static pressure along the test section that produces a drag force analogous to the hydrostatic force on objects in a stationary fluid in a uniform gravitational field.

$$\Delta D_B = -\frac{\pi}{4}\lambda_3 t^3 \frac{dp}{dl}$$



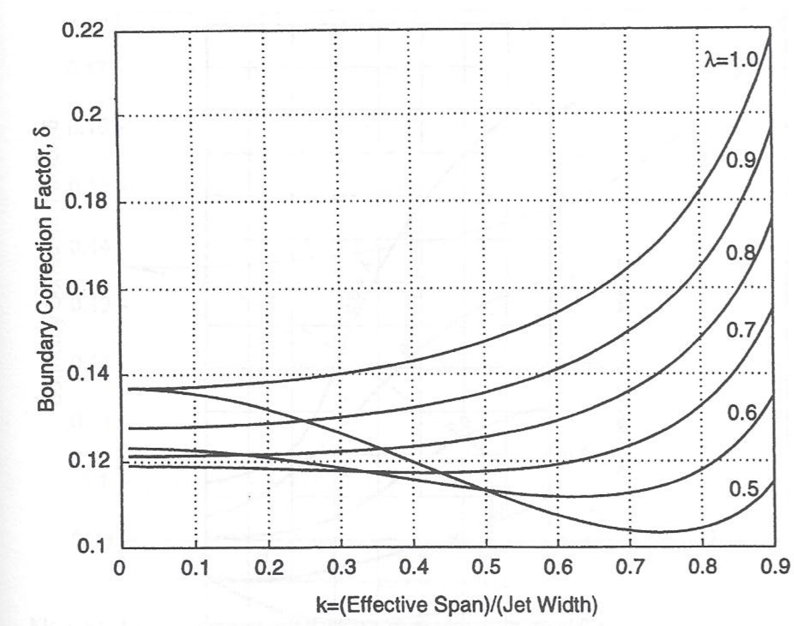
Streamline Curvature

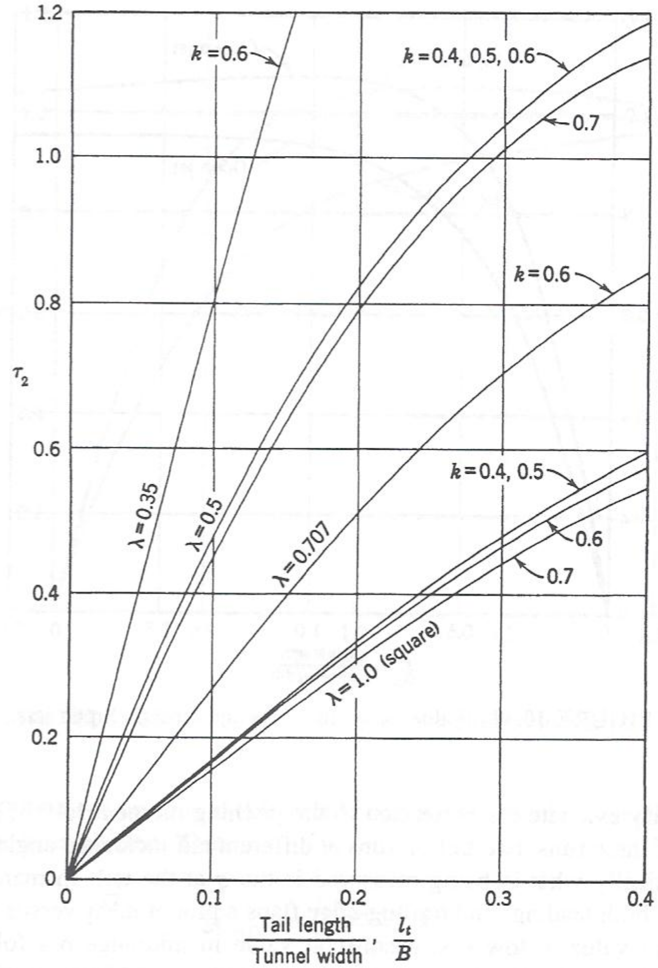
Streamline Curvature – alteration to the curvature of the streamlines of the flow about a body in a wind tunnel as compared to the corresponding curvature in an infinite stream. For a wing in a closed wind tunnel, the pitching moment coefficient, lift coefficient, and angle of attack are increased.

$$\triangle\ \alpha_{SC} = \tau_2 \delta \left(\frac{S}{C}\right) C_L$$

$$\Delta C_{L,SC} = -\Delta\alpha_{SC} \cdot \mathrm{a}$$

$$\Delta C_{PM,SC} = -0.25\ \Delta C_{L,SC}$$


0.22
0.2
0.18
0.16
0.14
0.12
0.1
Boundary Correction Factor, δ
λ=1.0
0.9
0.8
0.7
0.6
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
k=(Effective Span)/(Jet Width)

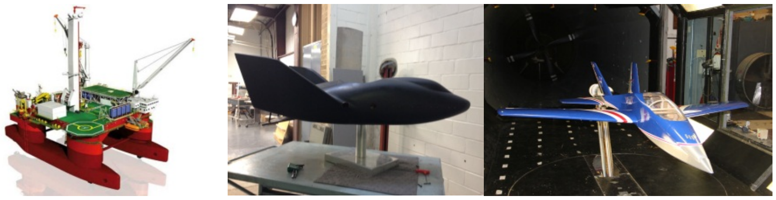

1.2
1.0
0.8
0.6
0.4
0.2
0
τ₂
k=0.6
k=0.4, 0.5, 0.6
0.7
k=0.6
k=0.4, 0.5
0.6
0.7
λ=0.35
λ=0.5
λ=0.707
λ=1.0 (square)
0
0.1
0.2
0.3
0.4
Tail length / Tunnel width, l_t / B

Group:___________

Do not put your name on this

Aero 489 (Fall 2012) Homework #5

Due Tuesday 4 December 2012 – at the beginning of class



1. **This survey will count as Homework #5 and is worth 5% of the total grade in the class. The purpose of this survey is to gather qualitative and quantitative data to further assess the class and improve it for future classes. I want to keep this survey as anonymous as possible while still trying to account for all of them. So I ask that you only put what group (i.e. Alpha, Bravo, Charlie) and not your name. I want you to be as honest as possible and feel some anonymity will aid in that endeavor.**
2. **Please circle the best answer based on the question "how confident are you that you can successfully meet each of the following educational objectives for the course?" A "5" means "Very confident" and a "1" means "Not Confident at all."**

	How confident are you that you can successfully meet each of the following educational objectives for the course?	Very Confident	Confident	Somewhat Confident	Marginally Confident	Not Confident at all
1	Apply Bernoulli's equation and conservation of mass to solve a steady, incompressible flow problem	5	4	3	2	1
2	Identify the components of a wind tunnel and describe the function of each component	5	4	3	2	1
3	Describe the advantages and disadvantages of an Eiffel type wind tunnel	5	4	3	2	1
4	Describe the advantages and disadvantages of a Gottingen type wind tunnel	5	4	3	2	1
5	Explain in your own words why we need to conduct uncertainty analysis of our experimental results	5	4	3	2	1
6	Distinguish between accuracy and precision in reported results	5	4	3	2	1
7	Calculate the absolute uncertainty and/or relative uncertainty for measured aerodynamic forces/moments found in experimentation	5	4	3	2	1
8	Calculate the linear regression best fit line using the equations from the Numerical Recipes book	5	4	3	2	1
9	Explain "Goodness of fit" measure and apply it to your linear regression results	5	4	3	2	1
10	Determine when it is better to use a hot wire anemometer instead of a pitot tube for velocity measurement and explain your reasoning	5	4	3	2	1
11	Calculate the Fast Fourier Transform (FFT) for a given set of data and identify the dominant frequency	5	4	3	2	1

	How confident are you that you can successfully meet each of the following educational objectives for the course?	Very Confident	Confident	Somewhat Confident	Marginally Confident	Not Confident at all
12	Identify the different types of pressure measurement devices for wind tunnel experiments	5	4	3	2	1
13	Identify the different ways of attaining the flow velocity measurement during a wind tunnel test and describe the principle behind each way	5	4	3	2	1
14	Identify the different techniques of measuring skin friction during a wind tunnel experiment and describe the principle behind each technique	5	4	3	2	1
15	Describe the purpose and operation of Fringe Imaging Skin Friction (FISF) interferometry	5	4	3	2	1
16	Calculate the API standard boundary layer profile given one hour mean wind speed at the reference height, averaging time period, and model scale	5	4	3	2	1
17	Transform forces and moments from the wind axis reference frame to the body axis reference frame and vice versa	5	4	3	2	1
18	Optimize the scaling of a model for a wind tunnel test given the full scale parameters and constraints	5	4	3	2	1
19	List the factors that affect scaling determination for a low speed wind tunnel test	5	4	3	2	1
20	Describe the four main types of external balances	5	4	3	2	1
21	List the advantages and disadvantages for each type of external balance	5	4	3	2	1
22	List the three quantities that any strut connecting a model to the external balance adds to the balance output	5	4	3	2	1
23	Explain how an internal force balance works	5	4	3	2	1
24	Describe the two general sources of error for internal balance measurements	5	4	3	2	1
25	Apply misalignment and elastic deformation corrections to the forces and moments measured from an internal balance	5	4	3	2	1
26	Calculate the free air loads on an aerodynamic body in the low speed wind tunnel by removing the tare and interference of the strut	5	4	3	2	1
27	Determine the up-flow angle in the low speed wind tunnel during an experiment given the upright and inverted configurations of a model	5	4	3	2	1
28	Describe the four main boundary corrections used in low speed wind tunnel testing	5	4	3	2	1
29	Identify what boundary corrections to apply during an experiment and apply those boundary corrections to the calculated free air loads	5	4	3	2	1
30	Distinguish between Maskell's boundary correction method and Shindo's simplified boundary correction method	5	4	3	2	1
31	List the different types of flow visualization techniques	5	4	3	2	1
32	Describe the basic principles and operation of particle image velocimetry	5	4	3	2	1
33	List the four aerodynamic objectives of ground vehicle wind tunnel tests	5	4	3	2	1

3. **Please answer the following questions about the course. Please circle the number that best corresponds to your feelings about the course. A "5" means "Strongly Agree" and a "1" means "Strongly Disagree".**

	Course Evaluation	Strongly Agree	Agree	Neutral	Agree	Strongly Disagree
1	Overall, this is an excellent course	5	4	3	2	1
2	I would recommend this course to others, if asked	5	4	3	2	1
3	Overall, I learned a great deal from this instructor	5	4	3	2	1

	Course Evaluation	Strongly Agree	Agree	Neutral	Agree	Strongly Disagree
4	The instructor related to students in ways that promoted mutual respect	5	4	3	2	1
5	The instructor told us what we could expect to learn as a result of taking this course	5	4	3	2	1
6	The instructor provided adequate opportunities for questions and discussion during class time	5	4	3	2	1
7	The instructor was available to students outside of class	5	4	3	2	1
8	The instructor provided useful feedback on my progress in the course	5	4	3	2	1
9	The instructor stimulated my interest in the course	5	4	3	2	1
10	As the course progressed, the instructor showed how each topic fit into the course as a whole	5	4	3	2	1
11	Overall, the instructors's explanations were clear and understandable	5	4	3	2	1
12	The instructor's use of teaching technology (e.g. Powerpoint, audio-visual presentations, etc.) was effective and appropriate	5	4	3	2	1
13	The general climate in this course was good for learning	5	4	3	2	1
14	Expectations for learning in this course were clearly communicated	5	4	3	2	1
15	There was a collaborative atmosphere in this course	5	4	3	2	1
16	The evaluation methods used in this course were fair and appropriate	5	4	3	2	1
17	The learning activites were well integrated into the course	5	4	3	2	1
18	The requirements of the course were adequately explained	5	4	3	2	1
19	The physical facilities for this course were appropriate (e.g. classroom / lab space, structure, furnishings, etc.)	5	4	3	2	1
20	The course materials (e.g. lecture notes, in-class exercises, etc.) contributed to learning the subject matter	5	4	3	2	1
21	I am usually well-prepared for class	5	4	3	2	1
22	The class assignments make sense to me; I understand their purpose	5	4	3	2	1
23	I feel encouraged to participate in class and respond to others	5	4	3	2	1
24	I get clear responses to what I say in class; I find out how to improve	5	4	3	2	1
25	The instructor treats students with respect	5	4	3	2	1
26	The instructor organized this course well	5	4	3	2	1
27	The instructor presented course material well	5	4	3	2	1
28	The instructor seemed well prepared for class	5	4	3	2	1
29	The instructor seemed enthusiastic about the subject	5	4	3	2	1

4. **What do you like best about this course? (Please list at least three things, if applicable)**

5. **What would you like to change about the course? (Please list at least three things, if applicable)**

6. **What are the instructor's strengths?**

7. **What suggestions do you have to improve the instructor's teaching?**
8. **My expected grade in this class is ______________.**

9. My attendance in this class has been approximately_______________%.
10. I have visited/emailed the instructor for help ______________times.
11. Please list any additional comments that you have about the course.

12. Please list any additional comments that you have for the instructor.

APPENDIX D

Aero 489 (Fall 2012) – Lab 1 Instructions (Revision A)

Lab will be conducted at the Oran W. Nicks Low Speed Wind Tunnel on
02 October 2012

Bravo	Charlie	Alpha
12:00-2:00p	1:30-3:30p	3:00-5:00p

Final reports are due on Thursday, 18 October at 4:00pm. Save your report as a .pdf and e-mail it to benjamin.recla@neo.tamu.edu. Group Alpha will give a presentation in class on Thursday 18 October. Follow the style shown in the style sheet and write to the report rubric. Do not exceed six pages. Name your file *GroupDesignation-Report 1.pdf*.

Offshore oil platforms are often subjected to harsh marine environments e.g. strong wind and currents. This makes the platform's dynamic positioning, mooring requirements, and stability of utmost importance. Tests of offshore oil platforms are routinely conducted in the Oran W. Nicks Low Speed Wind Tunnel (LSWT) for this reason.

Semi-submersible platforms with a small water plane area are very sensitive to weight changes. An over- dimensioned and very heavy mooring system is therefore unfavorable since it limits the payload capacity. Determining the wind and current loads by wind tunnel tests can reduce the dimensions of the moorings thus increasing the allowable weight for payload and increasing the overall cost effectiveness of the offshore oil platform.

To determine the wind induced effects with regard to stability, the above-water part of the platform is tested for even keel as well as inclined conditions. Based on the even keel load tests a critical axis is defined as the axis around which, the overturning (pitching) moment is the largest. Inclination tests are then made about the critical axis to determine the wind forces and overturning moments.

Given the time constraints of the lab, the even keel tests will have already been performed. Based on these even keel tests, the critical axis was determined for three different draft heights.

Each group will be taking force and moment data for a different draft height in meters.

Bravo **Draft Height = 18.5m (60.7 ft)**
Critical Angle = +10 degrees

Charlie **Draft Height = 15.0m (49.2 ft)**
Critical Angle = +10 degrees

Alpha **Draft Height = 7.95m (26.1 ft)**
Critical Angle = -40 degrees

Forces and moments are read by the external balance system of the LSWT. They must first be converted to full scale forces. Then they need to be transferred to the model. Once transferred to the model, they then need to be transferred from the wind axis reference system to the body axis system of the model. (Note that the reference center for the model is centered in the model at the waterline/floor of the wind tunnel)

For each draft height, we will be taking data for **two** different heel angles. These heel angles will be 5° and 30° and are heeled about the critical axis. At each heel angle the model will be rotated ±40° from the critical angle (based on the draft height). From these test runs, you will receive data for three forces (Surge, Sway, and Heave) and three moments (Roll, Pitch, and Yaw).

Plot each respective force/moment (as seen in the model's body axis) versus ψ (a positive rotation about the wind axis' positive Z-axis) for the different heel heights. Comment on the results. (Should be 6 plots with each plot having lines for two heel angles)

The above water part of the platform is exposed to a wind profile, which resembles an ocean wind with regards to velocity distribution and turbulence intensity. A standard American Petroleum Institute (API) profile at **70 knots** will be used for the boundary layer profile. This profile is found using the following equation for wind speed u(z,t) in ft/s at height (z) in ft above sea level:

$$u(z,t) = U(z) * [1 - 0.41 * I_u(z) * \ln(\frac{t}{t_0})]$$

Where the 1 hour mean wind speed U(z) in ft/s at a height (z) in ft is given by:

$$U(z) = U_0 * \left[1 + C * \ln\left(\frac{z}{32.8}\right)\right]$$

$$C = 5.73 * 10^{-2} * (1 + 0.0457 * U_0)^{\frac{1}{2}}$$

And where the turbulence intensity $I_u(z)$ at level z is given by:

$$I_u(z) = 0.06 * [1 + 0.0131 * U_0] * (\frac{z}{32.8})^{-0.22}$$

Where U_0 (ft/s) is the 1 hour mean wind speed at the reference height of 32.8 ft (10m)., and t(s) is an averaging time period [where t $\leq t_0$; t_0 = 3600 seconds], so if your averaging time period is less than 1 hour, your likelihood of catching a wind gust without a corresponding lull increases as time decreases. If your averaging time period is 1 hour, then the ln(1) = 0 and your boundary layer is only determined by U(z).

Plot what the boundary layer should look like [height (z) in inches vs. velocity (ft/s)] based on the API standards. Plot curves for +4% and -4% uncertainty so that you have three curves on one graph. Assume U_0 = **188 ft/s** and t = 1800 seconds. Based on using a 1:190 scale model, the API reference height of 32.8 ft corresponds to 2.07 inches. Plot the height(z) from **1 inch** to 35 inches.

Since we cannot adjust the velocity at different heights in the tunnel, a boundary layer fence will be used. This slows the velocity of the air down sufficiently at specific heights by blocking the flow with horizontal bars. The placement of these bars is not an exact science and depends on the scale of the model. A lot of trial and error is used, but since this is time consuming, we will not be doing this in the lab, but just know that it is an integral step in getting the correct boundary layer for the test.

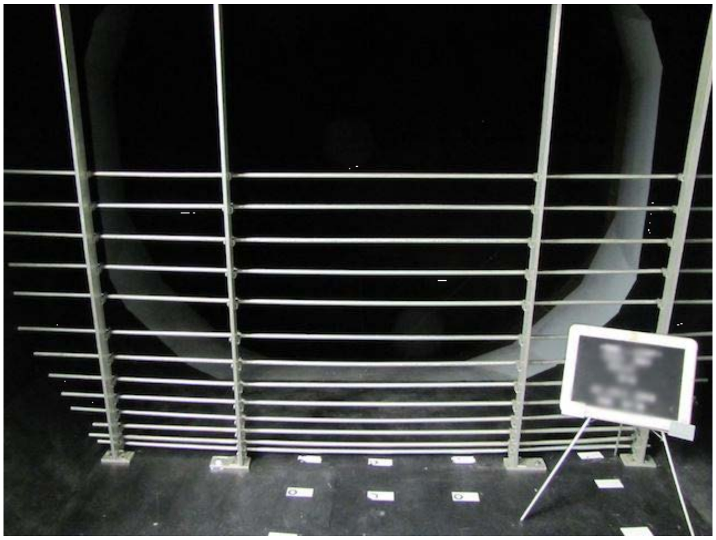


Figure 1. Boundary Layer Fence.

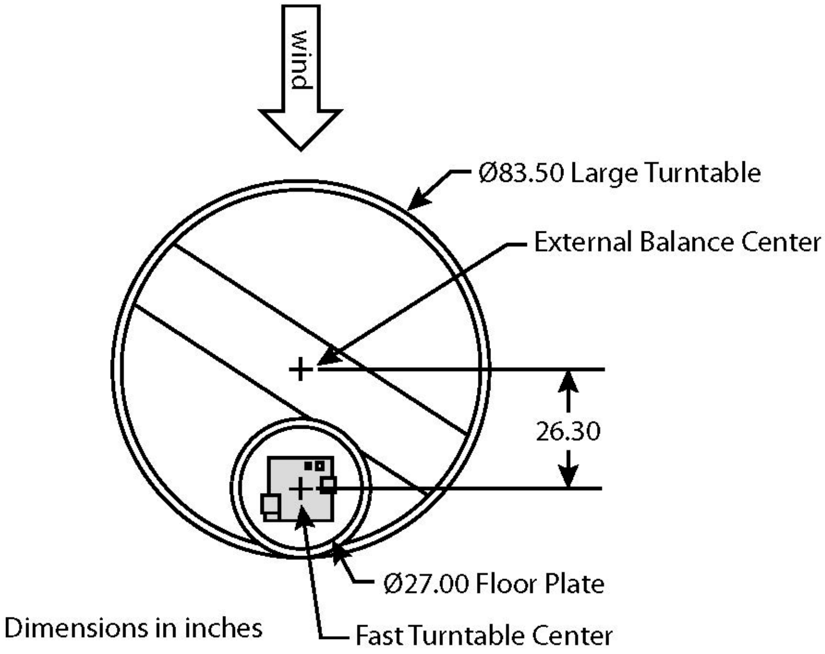


Figure 2. Overhead view of Oil Platform in the LSWT.

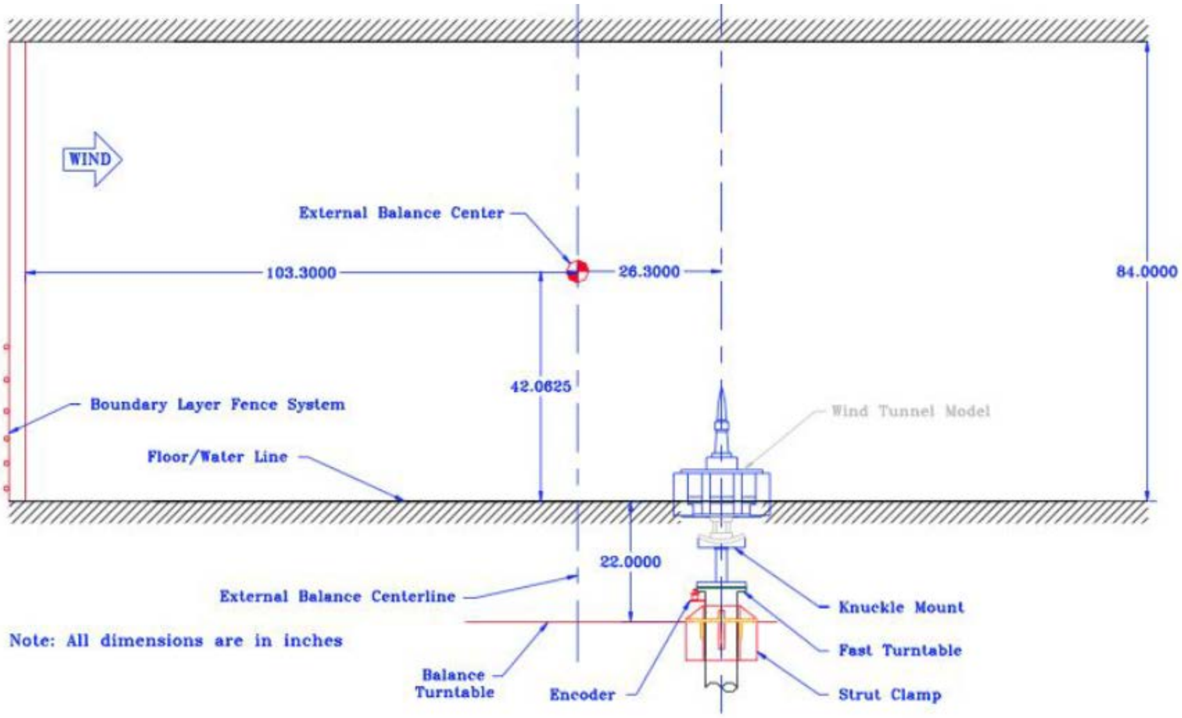


Figure 3. Profile view of Oil Platform in the LSWT

$$D = -F_{x_w} \qquad S = F_{y_w} \qquad L = -F_{z_w}$$

$$RM = +M_{x_w} \qquad PM = +M_{y_w} \qquad YM = +M_{z_w}$$

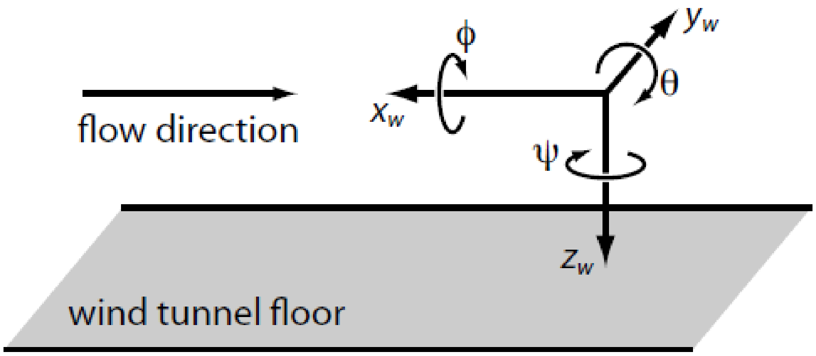


Figure 4. Wind Axis Global Coordinate System

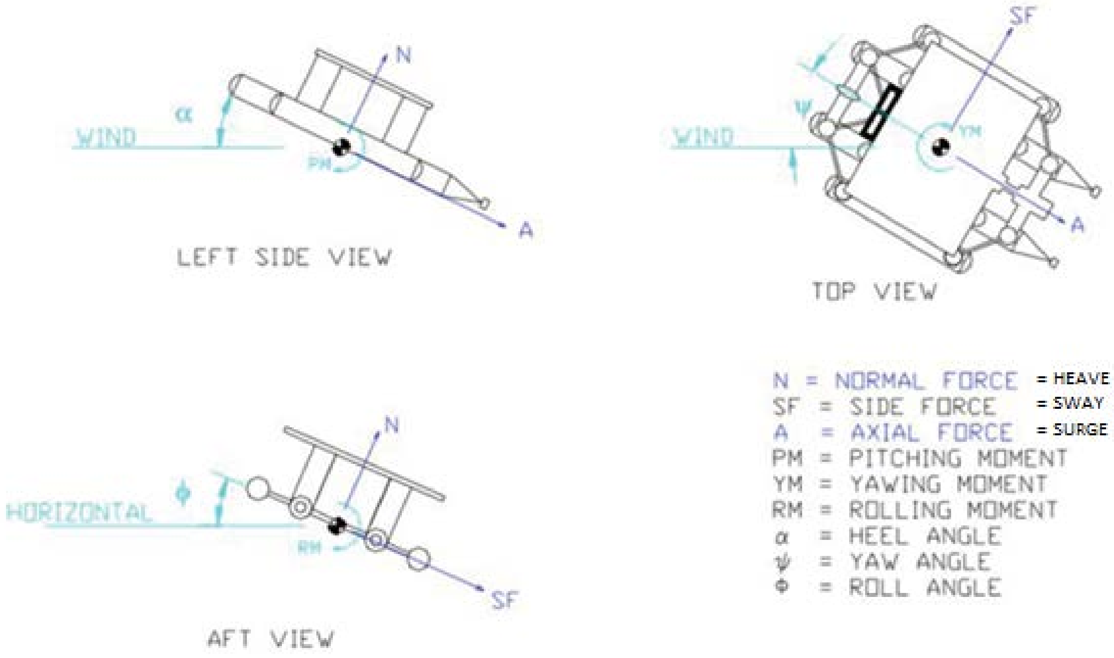


Figure 5. Body Axis Coordinate System

The critical axis is determined through a series of steps. First the full 360° wind profile at even keel is determined. Next, the maximum overturning moments, or pitching moment, from the full 360° even keel testing is recorded along with the Z-axis rotational angle, ψ, that corresponds to the maximum overturning moment. The critical axis is then defined as the Y-axis line in the wind-axis coordinate system when the model is rotated in ψ to place the maximum pitching moment profile into the wind. A critical axis diagram is provided below.

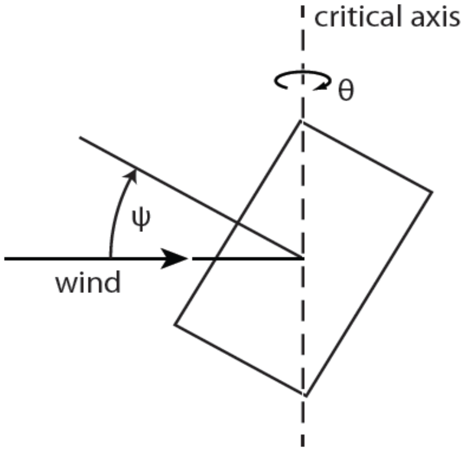


Figure 6. Critical Axis Determination

Aero 489 (Fall 2012) – Lab 2 Instructions(Revision A)

Lab will be conducted at the Oran W. Nicks Low Speed Wind Tunnel on

11 October 2012

Charlie	**Alpha**	**Bravo**
09:00-11:00	**12:30-2:30p**	**2:30-4:30p**

Final reports are due on Thursday, 1 November at 4:00pm. Save your report as a .pdf and e-mail it to benjamin.recla@neo.tamu.edu. Group Bravo will give a presentation in class on Thursday 1 November. Follow the style shown in the style sheet and write to the report rubric. Do not exceed ten pages. Name your file *GroupDesignation-Report 2.pdf*.

NASA's X-38 Crew Return Vehicle (CRV) is shown in the picture below.

This is an example of a wingless lifting body. Wingless lifting bodies generate aerodynamic lift - essential to flight in the atmosphere - from the shape of their bodies.

When operational, the CRV will be an emergency vehicle to return up to seven International Space Station (ISS) crewmembers to Earth. It will be carried to the space station in the cargo bay of a space shuttle and attached to a docking port. If an emergency arose that forced the ISS crew to leave the space station, the CRV would be undocked and - after a deorbit engine burn - the vehicle would return to Earth much like a space shuttle. A steerable parafoil parachute would be deployed at an altitude of about 40,000 feet to carry it through the final descent and the landing. The CRV is being designed to fly automatically from orbit to landing using onboard navigation and flight control systems. Backup systems will allow the crew to pick a landing site and steer the parafoil to a landing, if necessary.

The key question is: **Is the X-38 a directionally stable platform after re-entry into the atmosphere but prior to the parafoil parachute's deployment?**

In order to test this question, we are going to place a 1:10 scale model of the X-38 into the LSWT and take data at two different angles of attack while performing a beta sweep for **±35°** at each angle of attack.

We need the free air loads on the model and so must do a tare and interference. Because of time constraints for the lab, each group will only do one configuration for this tare and interference (upright w/image, upright w/o image, inverted w/o image, inverted w/image).

Each group will see the following configuration on lab day:

09:00 to 11:00	**Charlie**	**Upright without image strut**
12:30 to 2:30p	**Alpha**	**Inverted without image strut**
2:30 to 4:30p	**Bravo**	**Inverted with image strut**

Each group will see two angles of attack: **0°** and 10° respectively. For each angle of attack a tare run will be performed for the external balance and then a beta sweep run of **±35°** will be performed.

Data will be delivered uncorrected for blockage and strut tare but with vehicle orientation and load signs corrected for upright or inverted.

Data is q_∞, lift, drag, side force, pitch, roll, and yaw in units of psf, lbf, or ft-lbf.

Take $\sigma_q = 0.2$ psf, $\sigma_\alpha = 0.1°$, and the forces and moments to be accurate to 0.5%. There are no covariances. Assume β is exact.

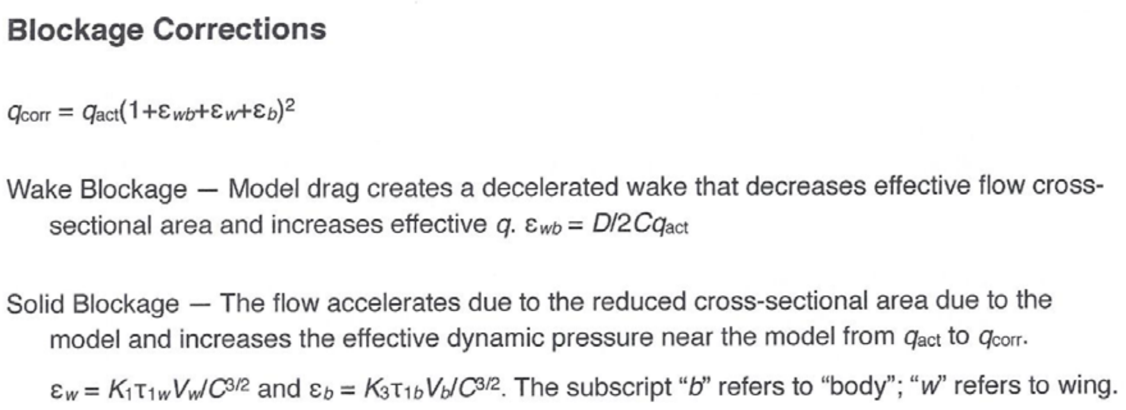
You can assume that the CG of the model corresponds to the reference balance center of the external balance, which means that you do not have to do any moment transfers, but still must do the transfers from the wind axis to the body axis.

Assume $S = 1$ ft^2 when calculating your coefficients. $\sigma_S = 0.02$ ft^2.

Deliverables for this lab:

1. **Plot of <u>corrected</u> C_{YM} vs. β and an explanation of whether the model has directional stability or not and if so, what angle range it has directional stability. Include error bars.**
2. **Plot of <u>uncorrected</u> C_L vs. β for inverted w/ image and inverted w/o image and the difference between w/ and w/o image. Include error bars.**
3. **Plots of <u>corrected</u> C_L, C_D, C_{SF}, C_{PM}, and C_{RM} vs. β for both angles of attack. (Put both angles of attack on same plot). Include error bars.**
4. **Plot of <u>uncorrected</u> C_L vs. α for the upright with image and inverted with image cases on the same plot. Include error bars.**
5. **Find the upflow angle and its uncertainty (Use the Inverted w/image strut and Upright w/image strut data at a Beta of 0°). Apply the upflow angle to the data prior to doing the tare and interference calculations.**

In order to find the corrected coefficients, you need to apply the solid blockage and wake blockage corrections. Use the following graphs to find the blockage corrections:



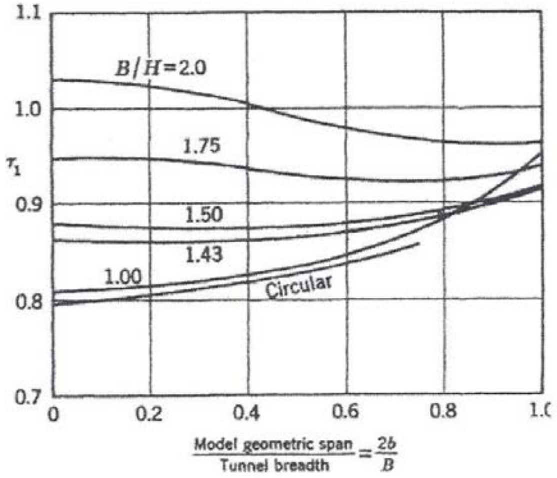
Blockage Corrections

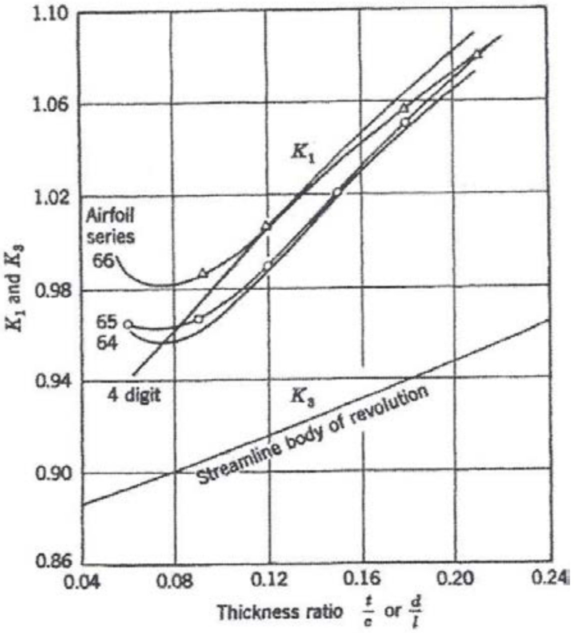
$q_{corr} = q_{act}(1+\varepsilon_{wb}+\varepsilon_w+\varepsilon_b)^2$

Wake Blockage — Model drag creates a decelerated wake that decreases effective flow cross-sectional area and increases effective q. $\varepsilon_{wb} = D/2Cq_{act}$

Solid Blockage — The flow accelerates due to the reduced cross-sectional area due to the model and increases the effective dynamic pressure near the model from q_{act} to q_{corr}.

$\varepsilon_w = K_1\tau_{1w}V_w/C^{3/2}$ and $\varepsilon_b = K_3\tau_{1b}V_b/C^{3/2}$. The subscript "$b$" refers to "body"; "$w$" refers to wing.





Since the X-38 is a lifting body, there is no wing. This means that $\varepsilon_w = 0$. You still need to find ε_b though.

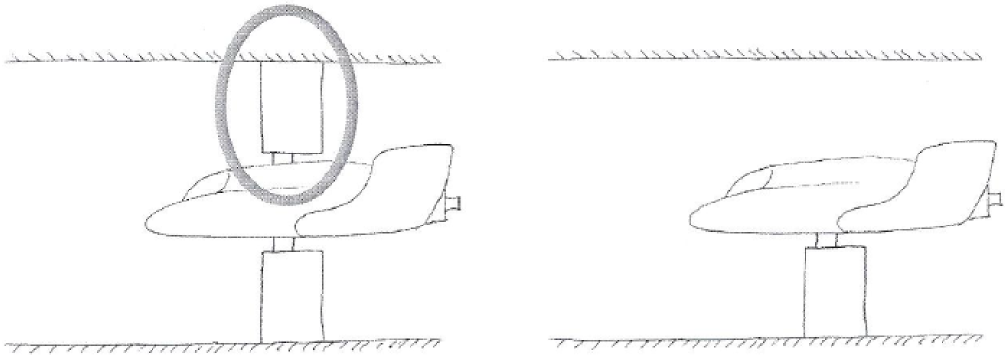
For these equations, use the following parameters:

C = area of test section = 68 ft^2
B = width of test section = 10ft
H = height of test section = 7ft
d = diameter of body = 1ft
l = length of body = 38 inches
V_b = volume of the body = 2.5 ft^3

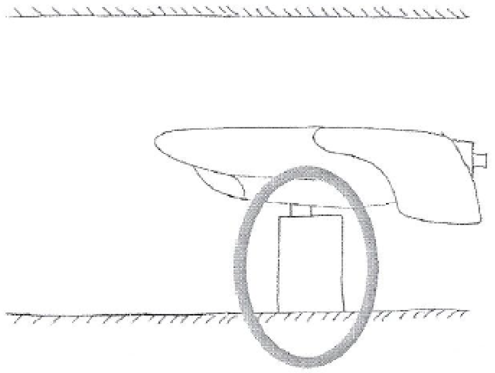
Strut Tare and Interference

T&I runs provide the strut drag and pitch moment plus the effect of the strut on the model.

upright with image – upright w/o image = dorsal strut T&I



inverted w/o image – dorsal strut T&I = free air loads



Aero 489 (Fall 2012) – Lab 3 Instructions

Lab will be conducted at the Oran W. Nicks Low Speed Wind Tunnel on
08 November 2012

Alpha	**Bravo**	**Charlie**
08:00-09:30	**09:30-11:00**	**12:30-2:00p**

Final reports are due on Thursday, 29 November at 4:00pm. Save your report as a .pdf and e-mail it to benjamin.recla@neo.tamu.edu. Group Charlie will give a presentation in class on Thursday 29 November. Follow the style shown in the style sheet and write to the report rubric. Do not exceed ten pages. Name your file *GroupDesignation-Report 3.pdf*.

NASA microgravity facilities include drop towers (limited to 3-4 seconds) and the expensive manned 727 aircraft. The NASA Unmanned Microgravity Flight Program aims to develop a small, unmanned, turbine-powered aircraft capable of carrying 8-10 lb. payloads in a shoe-box size compartment on microgravity parabolas up to 12 seconds in length. A phased approach to testing will take place once flight clearance is granted. Phase I will see the aircraft flown manually by a pilot in a virtual cockpit. The autopilot will downlink telemetry to populate virtual ground displays. During phase II the aircraft roll and yaw axes will be stabilized by the autopilot; off-loading the human pilot to concentrate solely on pitch and throttle. During phase III the autopilot software will be modified to fly the entire parabola automatically while the vehicle is taken off and landed manually.

Fig. 1. *DV8R "unmanned microgravity flight platform."*

Since this program is still in the initial phase of testing, wind tunnel test data is required to validate the CFD data in order to develop the autopilot function and take this program to the next phase.

The key question: **Is there aerodynamic hysteresis after stall? Why is this important?**

In order to test this question, we are going to place a full scale model of the DV8R radio controlled (RC) Jet into the LSWT, apply various control surface inputs, and take force and moment data while performing an alpha sweep from -15° to 20°.

We will attach the DV8R RC jet to the High Attitude Robotic Sting (HARS) and use the Task Mark XIII internal balance to gather our force and moment data. Specifications for the internal balance are found at the back of this packet. You do not have to perform a tare and interference correction, but must still find the up flow angle and apply this to your data in order to get correct plots.

Each group will see the following configuration on lab day:

08:00 to 09:30	**Alpha**	**Alpha sweeps with no control inputs (upright and inverted)**
09:30 to 11:00	**Bravo**	**Alpha sweeps with separate -5° inputs (elevator, aileron, and rudder)**
12:30 to 2:00p	**Charlie**	**Alpha sweeps with separate 5° inputs (elevator, aileron, and rudder)**

Data will be delivered with vehicle orientation and load signs corrected for upright or inverted.

Data is q_∞, normal force, axial force, side force, pitch, roll, and yaw in units of psf, lbf, or ft-lbf.

Take $\sigma_q = 0.2$ psf, $\sigma_\alpha = 0.1°$, and the forces and moments to be accurate to 0.5%. There are no covariances. Assume control surface deflection angles are exact.

You can assume that the CG of the model corresponds to the reference balance center of the internal balance, which means that you do not have to do any moment transfers. You must transform the forces and moments **from the body axis system to the wind axis system** though.

Assume S = 1 ft^2 when calculating your coefficients, and it is exact.

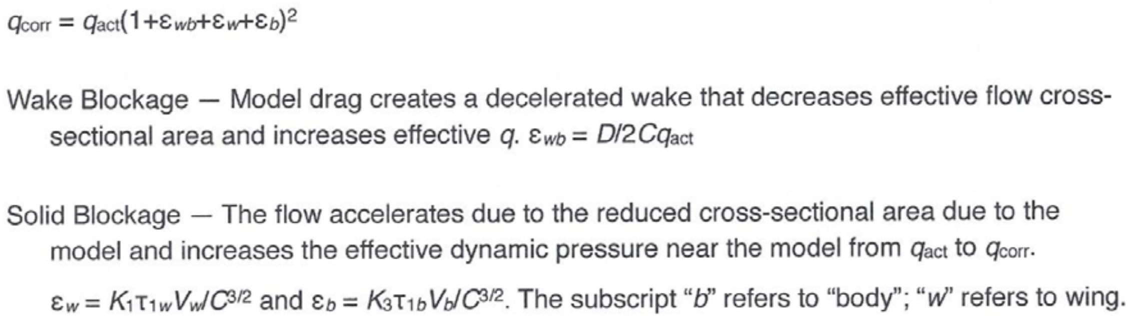
I will also send you data for sting deflection corrections. This is will be calculated experimentally on Wednesday at the LSWT.

Deliverables for this lab:

1. **Find the up-flow angle, sting deflection correction angles, and streamline curvature correction and apply them to your angles of attack for plotting purposes.**
2. **Plot of <u>corrected</u> C_X vs. α. Include error bars. (i.e. Plot coefficients of all forces and moments vs. α; X = L, D, SF, RM, PM, YM)**
    a. **<u>Group Alpha</u> – All plots with no control inputs**
    b. **<u>Group Bravo/Charlie</u> – Lift, Drag, and PM plots with elevator input; SF and YM plots with rudder input, RM plot with aileron input**
3. **Find $C_{D,0}$ and its uncertainty by applying uncertainty weighted least squares fit.**
4. **Plot of <u>corrected</u> C_D vs. C_L (drag polar). Include error bars. Include Cd-fit curve and explain goodness of fit.**
5. **Include all work for finding the boundary corrections, uncertainties, and uncertainty least squares fits as an appendix at the back of the report. (The number of pages in the appendix does not count toward the number of pages in the report.)**

In order to find the corrected coefficients, you need to apply the solid blockage, wake blockage, horizontal buoyancy and streamline curvature corrections. Use the following graphs to find the blockage corrections:

<u>Wake Blockage and Solid Blockage</u>

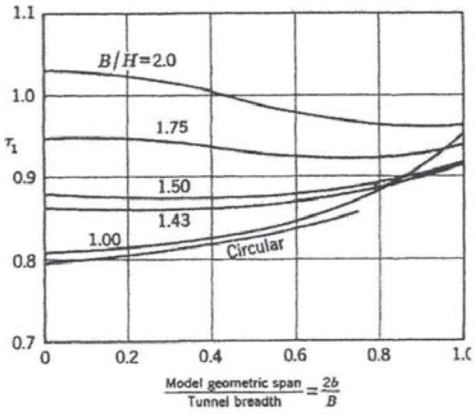


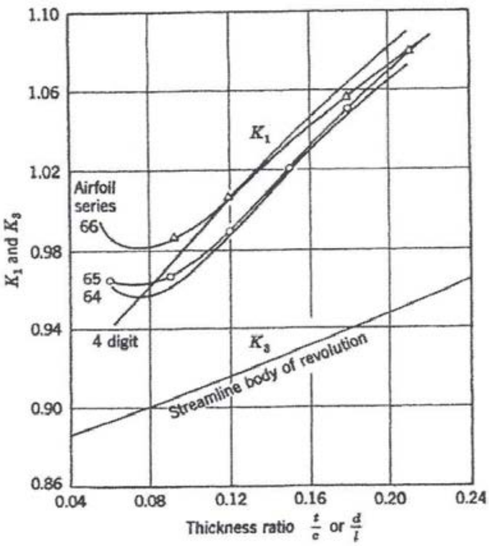
$q_{corr} = q_{act}(1+\varepsilon_{wb}+\varepsilon_{w}+\varepsilon_{b})^2$

Wake Blockage — Model drag creates a decelerated wake that decreases effective flow cross-sectional area and increases effective q. $\varepsilon_{wb} = D/2Cq_{act}$

Solid Blockage — The flow accelerates due to the reduced cross-sectional area due to the model and increases the effective dynamic pressure near the model from q_{act} to q_{corr}.

$\varepsilon_w = K_1\tau_{1w}V_w/C^{3/2}$ and $\varepsilon_b = K_3\tau_{1b}V_b/C^{3/2}$. The subscript "$b$" refers to "body"; "$w$" refers to wing.





For solid blockage and wake blockage, use the following parameters for the DV8R RC Jet:

C = area of test section = 68 ft^2
H = height of test section = 7 ft
l = length of body = 87 inches
V_w = 1.5 ft^3
b = wingspan = 83 inches
t = thickness of wing = 1.965 inches

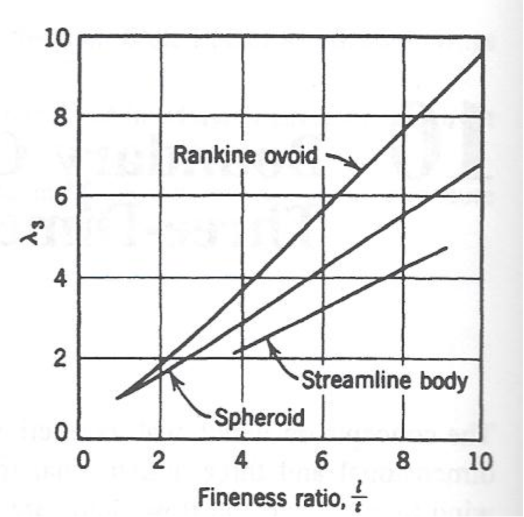
B = width of test section = 10 ft
d = diameter of body = 8 inches
V_b = volume of the body = 3.25 ft^3
c = wing chord = 16.25 inches
τ_{1_w} = 0.98

Horizontal Buoyancy

Horizontal Buoyancy – Variation of static pressure along the test section that produces a drag force analogous to the hydrostatic force on objects in a stationary fluid in a uniform gravitational field.

$$\Delta D_B = -\frac{\pi}{4}\lambda_3 t^3 \frac{dp}{dl}$$

t = body maximum thickness = 8 inches
l = length of body = 87 inches
$\frac{dp}{dl} \approx 0.002\,\frac{psf}{ft}$



Streamline Curvature

Streamline Curvature – alteration to the curvature of the streamlines of the flow about a body in a wind tunnel as compared to the corresponding curvature in an infinite stream. For a wing in a closed wind tunnel, the pitching moment coefficient, lift coefficient, and angle of attack are increased.

$$\triangle\ \alpha_{SC} = \tau_2 \delta \left(\frac{S}{C}\right) C_L$$

$$\Delta C_{L,SC} = -\Delta\alpha_{SC} \cdot \mathrm{a}$$

$$\Delta C_{PM,SC} = -0.25\ \Delta C_{L,SC}$$

b = effective span = 83 inches

λ = 0.7

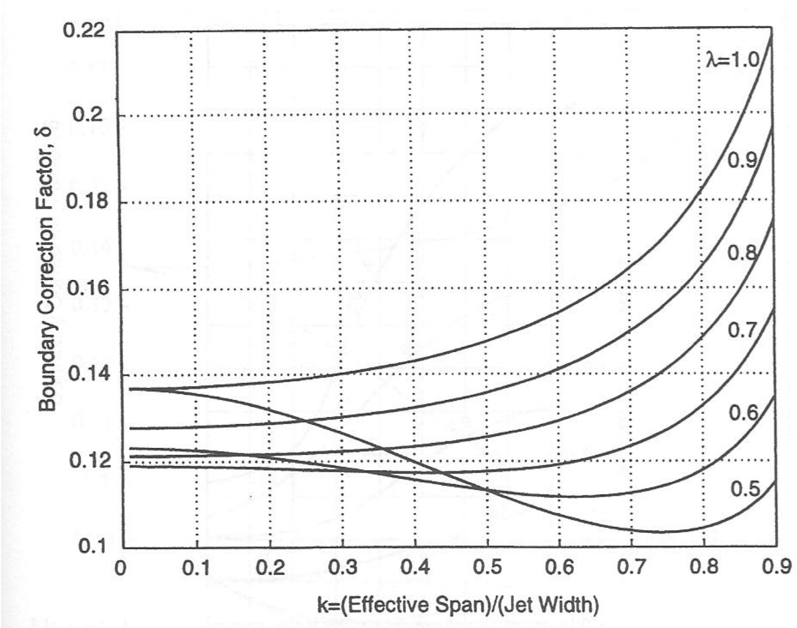
B = jet (tunnel) width = 10 ft

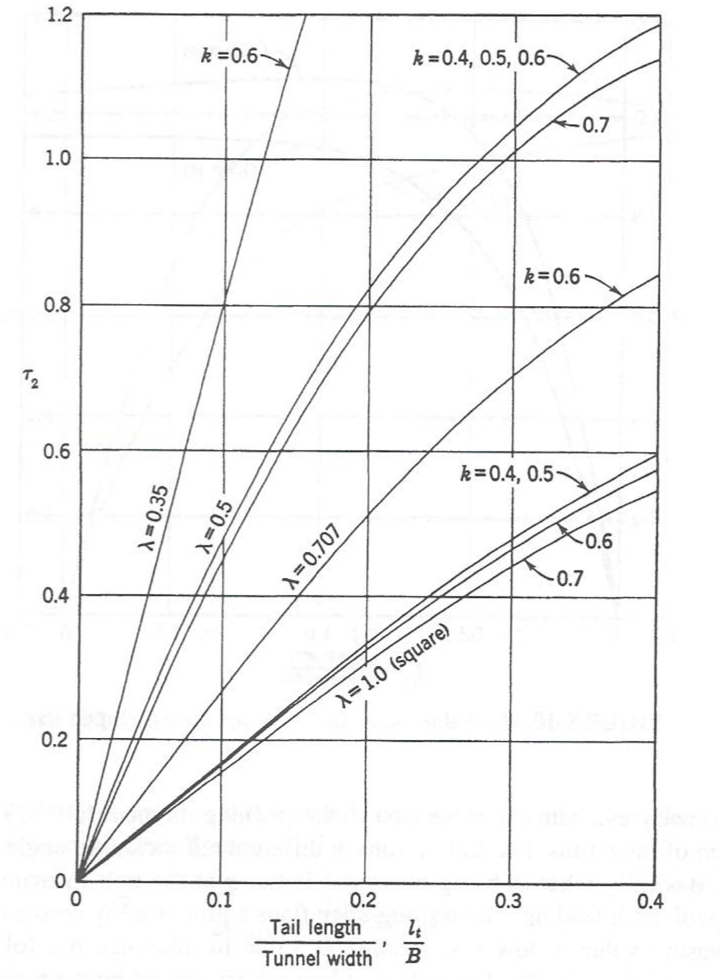
l_t = tail length = 4.0625 inches

S = area of the wing = 1350 in^2

C = test section area = 68 ft^2

a = lift curve slope (use uncorrected lift curve slope from the experimental data)


0.22
0.2
0.18
0.16
0.14
0.12
0.1
Boundary Correction Factor, δ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
k=(Effective Span)/(Jet Width)
λ=1.0
0.9
0.8
0.7
0.6
0.5



Uncertainty Weighted Least Squares fits

Within some limits before stall onset:

$$\begin{array}{ccccc} C_D & = & C_{D,0} & + & \kappa C_L^2 \\ \| & & \| & & \| \; \| \\ y & = & a & + & b\,x \end{array}$$

Then use the equations from *Numerical Recipes* to find values for “a” and “b”. They can be found below:

$$a = \frac{S_{xx}S_y - S_xS_{xy}}{S\,S_{xx} - S_xS_x} \quad \text{and} \quad b = \frac{S\,S_{xy} - S_xS_y}{S\,S_{xx} - S_xS_x}$$

$$\sigma_a^2 = \frac{S_{xx}}{S\,S_{xx} - S_x S_x} \quad \sigma_b^2 = \frac{S}{S\,S_{xx} - S_x S_x}$$

Where:

$$S = \sum_{i=1}^{N} \frac{1}{\sigma_{y_i}^2} \quad S_x = \sum_{i=1}^{N} \frac{x_i}{\sigma_{y_i}^2} \quad S_y = \sum_{i=1}^{N} \frac{y_i}{\sigma_{y_i}^2}$$

$$S_{xx} = \sum_{i=1}^{N} \frac{x_i^2}{\sigma_{y_i}^2} \quad S_{xy} = \sum_{i=1}^{N} \frac{x_i y_i}{\sigma_{y_i}^2}$$

Goodness of fit measure (chi squared):

$$\chi^2 = \sum_{i=1}^{N} \left[\frac{y_i - (a + b\,x_i)}{\sigma_{y_i}} \right]^2$$

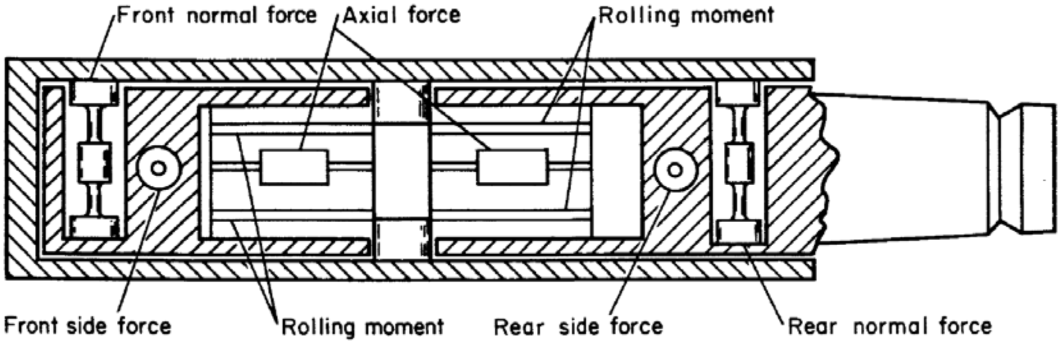
We expect that, on average, each deviation will be about equal to its uncertainty. Therefore, we expect that $\chi^2 \sim N$. We use this idea to define a **reduced chi squared value**

$$\frac{\chi^2}{N-2}$$

The -2 is there because there are two adjustable parameters. (This is similar to the -1 in the denominator of the standard deviation's definition.)

Task Mark XIII Internal Force Balance specifications and limitations

Task Mark XIII	
Diameter	1.25 in.
N1	500 lbs.
N2	500 lbs.
S1	500 lbs.
S2	500 lbs.
Axial Force	150 lbs.
Rolling Moment	800 in-lbs.
Pitching Moment	*2625 in-lbs.*
Yawing Moment	*2125 in-lbs.*



(above) Typical Internal Force Balance Schematic

APPENDIX E

Course Objectives – Aero 489(Fall 2012):

The primary goals of this course are to:

1. Provide students with an opportunity to perform real world tests in a commercial low speed wind tunnel in order to reinforce aerodynamic concepts introduced in previous courses;
2. Increase knowledge of the practical elements of experimental aerodynamics and to develop an appreciation for how aerodynamic data is acquired;
3. Apply modern instrumentation and measurement techniques to the acquisition of aerodynamic data and understand the inherent limitations of each technique;
4. Gain proficiency in estimating experimental uncertainty;
5. Introduce and apply boundary corrections to wind tunnel test data
6. Teach students to critically analyze the results of their experiments and present them in a concise and logical fashion, both in written and oral forms;

Educational Objectives:

Introductory Objectives

1. Apply Bernoulli’s equation and conservation of mass to solve a steady, incompressible flow problem
2. Identify the components of a wind tunnel and describe the function of each component
3. Describe the advantages and disadvantages of an Eiffel type wind tunnel
4. Describe the advantages and disadvantages of a Gottingen type wind tunnel
5. Explain in your own words why we need to conduct uncertainty analysis of our experimental results
6. Distinguish between accuracy and precision in reported results
7. Calculate the absolute uncertainty and/or relative uncertainty for measured aerodynamic forces/moments found in experimentation
8. Calculate the linear regression best fit line using the equations from the Numerical Recipes book
9. Explain “Goodness of fit” measure and apply it to your linear regression results
10. Determine when it is better to use a hot wire anemometer instead of a pitot tube for velocity measurement and explain your reasoning
11. Calculate the Fast Fourier Transform (FFT) for a given set of data and identify the dominant frequency

Pressure, Flow, and Shear Stress Objectives

12. Identify the different types of pressure measurement devices for wind tunnel experiments
13. Identify the different ways of attaining the flow velocity measurement during a wind tunnel test and describe the principle behind each way
14. Identify the different techniques of measuring skin friction during a wind tunnel experiment and describe the principle behind each technique
15. Describe the purpose and operation of Fringe Imaging Skin Friction (FISF) interferometry
16. Calculate the API standard boundary layer profile given one hour mean wind speed at the reference height, averaging time period, and model scale

Reference Frames and Scaling Objectives

17. Transform forces and moments from the wind axis reference frame to the body axis reference frame and vice versa
18. Optimize the scaling of a model for a wind tunnel test given the full scale parameters and constraints
19. List the factors that affect scaling determination for a low speed wind tunnel test

External/Internal Balance Objectives

20. Describe the four main types of external balances
21. List the advantages and disadvantages for each type of external balance
22. List the three quantities that any strut connecting a model to the external balance adds to the balance output
23. Explain how an internal force balance works
24. Describe the two general sources of error for internal balance measurements
25. Apply misalignment and elastic deformation corrections to the forces and moments measured from an internal balance

Boundary Correction Objectives

26. Calculate the free air loads on an aerodynamic body in the low speed wind tunnel by removing the tare and interference of the strut
27. Determine the up-flow angle in the low speed wind tunnel during an experiment given the upright and inverted configurations of a model

28. Describe the four main boundary corrections used in low speed wind tunnel testing
29. Identify what boundary corrections to apply during an experiment and apply those boundary corrections to the calculated free air loads
30. Distinguish between Maskell's boundary correction method and Shindo's simplified boundary correction method

<u>Flow Visualization/Misc. Objectives</u>

31. List the different types of flow visualization techniques
32. Describe the basic principles and operation of particle image velocimetry
33. List the four aerodynamic objectives of ground vehicle wind tunnel tests

Laboratory Experiments:

1. Offshore oil rig – force and moment data
    a. Boundary layer measurement
    b. Reference frame transformation
2. Space re-entry vehicle (NASA X-38) – stability during re-entry conditions
    a. Tare and interference
    b. External Balance measurements
    c. Apply boundary corrections and up-flow angle correction
3. NASA Microgravity RC Jet project – force and moment data
    a. Internal Balance measurements
    b. Apply boundary corrections
    c. Uncertainty analysis / linear regression

	How confident are you that you can successfully meet each of the following educational objectives for the course?	**Very Confident / Confident Percentage**	**Somewhat / Marginally Confident Percentage**	**Not Confident at all Percentage**
1	Apply Bernoulli's equation and conservation of mass to solve a steady, incompressible flow problem	100.0%	0.0%	0.0%
2	Identify the components of a wind tunnel and describe the function of each component	93.3%	6.7%	0.0%
3	Describe the advantages and disadvantages of an Eiffel type wind tunnel	46.7%	40.0%	13.3%
4	Describe the advantages and disadvantages of a Gottingen type wind tunnel	53.3%	33.3%	13.3%
5	Explain in your own words why we need to conduct uncertainty analysis of our experimental results	93.3%	6.7%	0.0%
6	Distinguish between accuracy and precision in reported results	93.3%	6.7%	0.0%
7	Calculate the absolute uncertainty and/or relative uncertainty for measured aerodynamic forces/moments found in experimentation	80.0%	20.0%	0.0%
8	Calculate the linear regression best fit line using the equations from the Numerical Recipes book	73.3%	20.0%	6.7%
9	Explain "Goodness of fit" measure and apply it to your linear regression results	66.7%	33.3%	0.0%
10	Determine when it is better to use a hot wire anemometer instead of a pitot tube for velocity measurement and explain your reasoning	40.0%	60.0%	0.0%
11	Calculate the Fast Fourier Transform (FFT) for a given set of data and identify the dominant frequency	80.0%	20.0%	0.0%
12	Identify the different types of pressure measurement devices for wind tunnel experiments	80.0%	20.0%	0.0%
13	Identify the different ways of attaining the flow velocity measurement during a wind tunnel test and describe the principle behind each way	66.7%	33.3%	0.0%
14	Identify the different techniques of measuring skin friction during a wind tunnel experiment and describe the principle behind each technique	40.0%	60.0%	0.0%
15	Describe the purpose and operation of Fringe Imaging Skin Friction (FISF) interferometry	26.7%	33.3%	40.0%
16	Calculate the API standard boundary layer profile given one hour mean wind speed at the reference height, averaging time period, and model scale	60.0%	33.3%	6.7%
17	Transform forces and moments from the wind axis reference frame to the body axis reference frame and vice versa	93.3%	6.7%	0.0%
18	Optimize the scaling of a model for a wind tunnel test given the full scale parameters and constraints	100.0%	0.0%	0.0%
19	List the factors that affect scaling determination for a low speed wind tunnel test	100.0%	0.0%	0.0%
20	Describe the four main types of external balances	66.7%	33.3%	0.0%
21	List the advantages and disadvantages for each type of external balance	60.0%	33.3%	6.7%
22	List the three quantities that any strut connecting a model to the external balance adds to the balance output	73.3%	26.7%	0.0%
23	Explain how an internal force balance works	86.7%	13.3%	0.0%
24	Describe the two general sources of error for internal balance measurements	60.0%	40.0%	0.0%
25	Apply misalignment and elastic deformation corrections to the forces and moments measured from an internal balance	46.7%	46.7%	6.7%
26	Calculate the free air loads on an aerodynamic body in the low speed wind tunnel by removing the tare and interference of the strut	86.7%	13.3%	0.0%
27	Determine the up-flow angle in the low speed wind tunnel during an experiment given the upright and inverted configurations of a model	93.3%	6.7%	0.0%
28	Describe the four main boundary corrections used in low speed wind tunnel testing	100.0%	0.0%	0.0%
29	Identify what boundary corrections to apply during an experiment and apply those boundary corrections to the calculated free air loads	100.0%	0.0%	0.0%
30	Distinguish between Maskell's boundary correction method and Shindo's simplified boundary correction method	93.3%	6.7%	0.0%
31	List the different types of flow visualization techniques	100.0%	0.0%	0.0%
32	Describe the basic principles and operation of particle image velocimetry	80.0%	20.0%	0.0%
33	List the four aerodynamic objectives of ground vehicle wind tunnel tests	73.3%	26.7%	0.0%
		🟩 **> 70%**		
		🟨 **< 70% > 50%**		
		🟥 **< 50%**		

APPENDIX F

Aero 489, Fall 2012 [redacted]
Lab #1 Report Evaluation **Section 500**

Overall Grade: The possible ratings are excellent, good, fair, or poor.

Title — Convey the key idea of the experiment in a few words. Don't be so generic as to not convey any useful information.

Abstract — Summarize the key point or two from each section of the report. Be clear about the main objective and whether it has been met. Give a specific statement of the numerical result and its uncertainty. Clarity and especially brevity are at a premium in the Abstract.

Introduction — Begin the report in a natural way; do not presume the reader already knows specific details of the background, relevance, objective or approach. Be sure to establish relevance and the theoretical context of the method. But, don't stray into details of the method. Be absolutely clear about the experiment's objective.

Methods — Describe the experimental setup, physical procedure and data analysis procedure. Write using logically grouped sentences and paragraphs; do not give a list of instructions. Explain the physical setup such that a technically competent person could build a similar apparatus. Give parameters of the physical setup (size, mass, etc.) with appropriate uncertainties and describe the sources (measurement, cited reference, etc.) of the parameters and their uncertainties. Give a description and equations for how key results and their uncertainties are computed. Write values and uncertainties using the ± sign and the appropriate level of precision. Include units wherever appropriate.

Results —While retaining readable prose get to the point quickly and report the measured and calculated values. Write values and uncertainties using the ± sign and the appropriate level of precision. Include units wherever appropriate. If a theoretical question is at issue, be clear whether the theory has been validated. Cite all figures and tables from the text.

Be sure that your graph is readable and includes all necessary information. Ensure the font size, line weights and symbol sizes are appropriate. Include units on the axes and scale the axes such that most of the plot is data, not whitespace. Include a clear caption.

Discussion — Begin with a clear overall summary of the objective, approach and result. Identify any potential shortcomings of the experiment, if any, and explain to what extent these might affect the result and conclusion. Be specific and realistic. If appropriate, identify how the experiment might be improved.

Technical Error — See the TA or professor for clarification.

Group: ____________________

Aero 489 Presentation Feedback/Evaluation Form

	poor	fair	good	excellent
Performance (36 total points)	(0 pt)	(2 pts)	(3 pts)	(4 pts)
well-prepared and able to start on time				
pacing of speech and slide presentation was good (i.e., not rushed or too slow)				
clear and audible voice				
varied intonation, facial expressions (i.e., not monotone and expressionless)				
no distracting habits (e.g., saying “um” a lot, playing with hair, etc.)				
language appropriate for audience				
appropriate body positioning (e.g., did not constantly have back to audience)				
frequent eye contact with audience				
responded to questions confidently and professionally				
Content (48 total points)	(0 pt)	(2 pts)	(4pts)	(6 pts)
purpose/central thesis clearly presented				
key points/issues adequately covered (see rubric)				
a. Introduction Section				
b. Methods Section				
c. Results Section				
(1) - Graphs				
d. Discussion Section				
accuracy of material				
presented clear conclusion that supported purpose /central thesis				
Visual Aids (15 total points)	(0 pt)	(2 pts)	(4 pts)	(5 pts)
uncrowded slides				
visible, easy-to-read font				
no typographical, spelling, or grammatical errors				

Additional Comments:

Aero 489 Group Assessment — Lab #1, Fall 2012

Group:

Your Name:

Instructions: Write your group name and your name where indicated to the left. Then, write the names of each of your group members below. Mark a box indicating your assessment of each group member's contribution, including your own contribution. **This is not a group exercise, but an individual one. Please do not share your evaluation with the rest of your group.**

Use last names please!

	Excellent	Very Good	Satisfactory	Marginal	Deficient	Unsatisfactory	No Show
You							
Member 2							
Member 3							
Member 4							
Member 5							

Excellent	Consistently went above and beyond, tutored group members, carried more than his/her fair share of the load
Very Good	Consistently did what (s)he was supposed to do, well prepared and cooperative
Satisfactory	Usually did what (s)he was supposed to do, acceptably prepared and cooperative
Marginal	Sometimes failed to show up or complete assignments, minimally prepared and cooperative
Deficient	Often failed to show up or complete assignments, rarely prepared
Unsatisfactory	Consistently failed to show up or complete assignments, unprepared
No Show	No participation at all

Ratings are not your opinion of the grade that is appropriate for each group member. Ratings are used to adjust the group grade to reflect individual contributions. If a group grade is an "A" and the group members all receive equal ratings, all will receive an "A", regardless of whether their ratings were "excellent" or "satisfactory". If the same hypothetical group had a group grade of "C" and decided to all rate each other as "excellent", everyone would still receive a "C". Please use the guidelines above to select your ratings so that I can have a correct understanding of the dynamics of each group. It is my intention that "satisfactory" be a typical and honorable rating.