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EA203 Laboratory Handbook

Applied Experiments in Fluid Dynamics, Aerodynamics, Propulsion, and Flight Mechanics

(Clockwise from upper left): Boeing 777-200 commercial airliner, Scaled Composites SpaceShipOne suborbital vehicle, Grob G-115C Bavarian general aviation aircraft, Northrop Grumman X-47A unmanned combat aerial vehicle (UCAV).

To me it seems that all sciences are vain and full of errors that are not born of experience, mother of all certainty, and that are not tested by experience.

— Leonardo da Vinci, *Trattato della Pittura*

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List of Symbols

(Standard units are shown in parentheses)

a	=	Acceleration (ft/sec² or m/sec²)
a	=	Lift curve slope, $dC_L/d\alpha$ (1/deg)
a	=	Speed of sound (ft/sec or m/sec)
a	=	Temperature gradient in an atmospheric gradient layer (°R/ft or K/m)
A	=	Axial force (lb or N)
AC	=	Aerodynamic center
AOA	=	*Angle of Attack* (deg)
AR	=	Aspect ratio, b^2/S
$ARDC$	=	*Air Research and Development Command* (U.S. Air Force)
b	=	Wing span (ft or m)
c	=	Wing chord (ft or m)
C_A or C_a	=	Axial force coefficient
$CADIG$	=	*Computer Aided Design/Interactive Graphics*
CAS	=	*Calibrated airspeed*
C_D or C_d	=	Coefficient of drag
C_{D_0}	=	Drag coefficient at zero lift (3D)
CFD	=	*Computational Fluid Dynamics*
C_L or C_ℓ	=	Coefficient of lift
C_M or C_m	=	Pitching moment coefficient
C_{M_0}	=	Pitching moment coefficient at zero lift

$C_{M_{AC}}$	=	Pitching moment coefficient about the AC
C_N or C_n	=	Normal force coefficient
C_p	=	Pressure coefficient
D	=	Drag (lb or N)
dh	=	Differential in height
dp	=	Differential in pressure
dV	=	Differential in velocity
e	=	Span efficiency factor (2D); Oswald's efficiency factor (3D)
EAS	=	*Equivalent airspeed*
EWT	=	*Educational Wind Tunnel*
F	=	Force (lb or N)
F_B	=	Buoyant force (lb or N)
g	=	Gravitational acceleration (ft/sec² or m/sec²)
GUI	=	*Graphical User's Interface*
h	=	Height (ft or m)
IAS	=	*Indicated airspeed*
ℓ	=	Reference length (ft or m)
L	=	Lift force (lb or N)
LE	=	*Leading Edge*
m	=	Mass (slug or kg)
M	=	Mach number
M	=	Pitching moment (ft-lb or N-m)
MAC	=	Mean aerodynamic chord (ft or m)
N	=	Normal force (lb or N)
p	=	Pressure (lb/ft² or Pa)
p_s	=	Static pressure
p_T	=	Total pressure
q	=	Dynamic pressure
R	=	Ideal gas constant (ft-lb/slug/°R or J/kg/K)
Re	=	Reynolds number
S	=	Reference area (ft² or m²)
$S.G.$	=	*Specific Gravity*
T	=	Temperature (°R or K)
TAS	=	*True airspeed*
TE	=	*Trailing Edge*
$\forall$	=	Volume (ft³ or m³)
V_∞ or U_∞	=	Freestream velocity (ft/sec or m/sec)
VFD	=	*Variable-Frequency Drive*
W	=	Weight (lb or N)
α	=	Angle of attack (deg)
α_{L_0}	=	AOA at zero lift (deg)
β	=	Ballistic parameter (ft²/lb or m²/N)
β	=	Sideslip angle (deg)
Γ	=	Circulation (ft²/sec or m²/sec)
Λ	=	Leading edge sweep angle (deg)
μ	=	Fluid viscosity (slug/ft-sec or kg/m-sec)
θ_{ideal}	=	Ideal glide angle for maximum range (deg)
ρ	=	Fluid density (slug/ft³ or kg/m³)

Laboratory

1

EA 203

Technical Writing
Elements of a Formal Report

Introduction

In this exercise, you will identify and categorize the elements of a formal technical report. This organization will be required for all the laboratory deliverables submitted in EA203, as well as laboratory content of all subsequent courses in Aerospace Engineering.

To accomplish the goals of this exercise, it will be necessary to procure a technical article from an engineering journal in the library holdings at USNA. Bound journals are located on the Second Deck of Nimitz Library. Some are available as electronic journals through the library's web site.

Procedure

Follow these steps to execute this laboratory exercise:

1) Form into teams of two members each. Locate an interesting bound journal in Nimitz Library; they are shelved in alphabetical order on the Second Deck. Identify an article of interest by searching the index. Look for something related to aircraft performance, aerodynamics, propulsion, structures, or stability and control. Some suggested journal titles are:
   - NOTE: Aerospace America is NOT considered a journal!!!
   - The Aeronautical Journal
   - AIAA Journal (American Institute of Aeronautics and Astronautics)
   - Journal of Aerospace Engineering (American Society of Civil Engineers)
   - Journal of Aerospace Engineering (Institution of Mechanical Engineers)
   - Journal of Aircraft (AIAA)
   - Journal of Guidance, Control, and Dynamics (AIAA)
   - Journal of Propulsion and Power (AIAA)
   - Progress in Aerospace Sciences
2) Get your instructor's approval for your article. The article should have substantive technical content with a graphical presentation of results.
3) Photocopy the article at sometime during the exercise. Most journal articles are 10-20 pages in length, so bring enough change for the photocopy machine. The article might seem like gibberish now, but you'll be amazed at how much of it you understand at the end of the semester.
4) Identify the eight parts of a formal technical report by writing down the section headings of your article. Correlate these with the heading names discussed in class (Introduction, Theory, etc).

Deliverables

Only one submission is required per team. You must completely answer the following questions on a separate sheet of paper, and attach a copy of your article. Do not leave the library until you've handed in your answers.

Questions

1) Write down the complete citation of your journal article.
2) How long is the article (in pages)?
3) Does the article have a cover page? What kind of information is listed at the head of the article?
4) How many sentences are in the abstract? Try to categorize each sentence (i.e., what was done, how it was done, what were the principal results, etc.).
5) List out a few of the conclusions (even if you can't understand them). Is the conclusion section just a summary? What can you learn about the research just by reading the abstract and the conclusions?
6) What kind of information is included in the introduction (or equivalent)? Sometimes this section is labeled as "Background."
7) Is there a theory section? What kind of information is included there?
8) What was used to generate the data and results? Are the equipment, codes, or methods detailed in the paper? How is it discussed?
9) Are there figures, pictures, or diagrams? How are they used? List some of the attributes of well laid-out graphics. Pay particular attention to the relative sizes of comparative plots, or the details of graph labels or annotations.
10) How is the results section organized? Is there a separate discussion section? How is that section organized? What is the relative percentage of the results/discussion, in number of pages (approximately)? How many data tables and plots are included in this section?
11) Is there an appendix or appendices? What is included there that isn't presented in the body of the report?

Laboratory

2

Aerostatics
Observations of Archimedes Principle

Introduction

In this laboratory, we will explore the nature of lighter-than-air flight by measuring the lifting capacity of several large helium balloons. The data and knowledge gained in this experiment will be used to answer design-oriented questions regarding aerostatics.

Balloon Flight

The first manned flight in history was accomplished with the use of a hot-air balloon on November 21, 1783. Frenchmen Jean-François Pilâtre de Rozier and François Laurent, Marquis d'Arlandes ascended over Paris in a 100-foot diameter balloon built by Joseph and Étienne Montgolfier. Their flight lasted approximately 23 minutes, covered 5.5 miles, and required them to burn wool and straw to keep the balloon's air temperature high enough for lift.

Early experiments with hydrogen and hydrogen-filled balloons were conducted by such notable scientists as Cavendish, Black, and Cavello. Physicist Henry Cavendish (1731-1810) determined that hydrogen was seven times lighter than air and that it would be useful for designing lighter-than-air flight vehicles. Then in December of 1783, J. A. C. Charles and Nicolas-Louis Robert of France were carried aloft and traveled 27 miles in a hydrogen-filled balloon.

Archimedes Principle

Aerostatics involves vehicle flight that is not dependent upon relative motion of the air. By contrast, aerodynamics involves the motion of air over a surface, which generates a lifting force. In aerostatic flight, a buoyancy phenomenon is responsible for generating a lift for such vehicles as weather balloons, blimps, and dirigibles. The Greek mathematician, physicist, and inventor Archimedes was the first to observe the behavior of buoyant objects and is credited with describing the fundamental principle of buoyancy:

> *"A body immersed in a fluid will be buoyed up by a force equal to the weight of the fluid that the body displaces."*

When this concept is applied to a balloon, we consider the displacement of the total volume occupied by the enclosed gas and the balloon membrane. This total volume is known as the balloon's envelope.

Derivation of the Buoyant Force

Mathematically, the buoyant force (F_B) represents the gross lift on the system, or the total positive contribution to the vertical force. It is expressed in units of pounds and can be represented by the equation:

$$F_B = \rho_{ext} \cdot g \cdot \mathcal{V} = L_{gross} \tag{2.1}$$

In this equation, the displaced (external) fluid density is expressed as ρ_{ext} (in units of slugs/ft³), the gravitational acceleration is expressed as g (in units of ft/sec²), and the enclosed volume of the envelope is expressed as $\mathcal{V}$ (in units of ft³). The product $\rho_{ext} \cdot g$ is often called the weight density of the fluid because is it expressed in units of lbs/ft³. L represents the lift in units of lbs.

To determine the *net lift* of the system, we must add the negative contribution to the vertical force to the gross lift. This contribution involves the weights of the following balloon components: the weight of the gas

in the envelope (W_{gas}), the weight of the envelope material (W_{env}), and the weight of the payload (W_{pay}), all in units of lbs. Thus:

$$L_{net} = L_{gross} - W_{total} = F_B - \left(W_{gas} + W_{env} + W_{pay}\right) \tag{2.2}$$

When the balloon is in a steady state, it is not accelerating in any direction. Thus, it is neither ascending nor descending and the total system is in equilibrium. In this case, the net lift equals zero and thus equation (2.2) becomes:

$$F_B = \left(W_{gas} + W_{env} + W_{pay}\right) \tag{2.3}$$

However, we know that the weight of the gas in the envelope is a function of its density (i.e., the internal gas density, expressed as ρ_{int}) and the volume of the envelope. Thus:

$$W_{gas} = \rho_{int} \cdot g \cdot \mathcal{V} \tag{2.4}$$

Substituting equations (2.1) and (2.4) into equation (2.3) and rearranging a bit yields the following equation:

$$g\left(\rho_{ext} - \rho_{int}\right)\mathcal{V} = W_{env} + W_{pay} \tag{2.5}$$

The left-hand side of this equation represents the theoretical force produced by displacing a volume of air with an equal volume of another gas (e.g. helium). This would be the envelope's overall ability to lift a vehicle.

The right-hand side represents the gross weight of our vehicle. This gross weight consists of the envelope material itself and the weight of the payload. For the helium balloon experiment, the payload weight will consist of the actual cargo weight (i.e. steel shot) and the weight of the support structure (i.e. cup, string, paper clips).

For this experiment, the internal fluid is gaseous helium. At standard temperature (59°F) and pressure (29.92″ Hg), the density of helium is 0.0003282 slugs/ft³. For non-standard days, use the equation of state with the proper value of the specific gas constant to determine the actual helium density:

$$\rho_{int} = \rho_{He} = \frac{p_{atm}}{R_{He} T_{room}} \tag{2.6}$$

Note that the pressure and temperature of the helium are assumed to be the ambient conditions.

Procedure

Follow these steps to inflate your balloon and determine its buoyancy:

1) Record the room temperature and the day's barometric pressure.
2) Inflate your balloon with helium and tie it off tightly (use a bowline or a slipknot). Keep a good grip on it, especially as it nears capacity. The buoyant force may exceed one pound.
3) Measure the circumference using a sewing tape. Make your measurements along three different orientations and average them, since the balloon won't be perfectly spherical.
4) Connect the payload cup with string and paper clips and fill it with steel shot until the total vehicle reaches a steady state. You will probably need to trim out your cargo with scraps of paper. Be careful of slight air currents in the room, as they may cause the balloon to gradually rise or fall.
5) Deflate the balloon and make a separate measurement of the mass of the deflated balloon membrane using an analytic balance. Now determine your total payload mass (shot + cup + string + paper clips).
6) Tabulate the circumference of your balloon and the measured weights on the chalkboard with the data from the other teams.

Data Reduction

Your data reduction should involve the following calculations for all the balloons used in your class section:

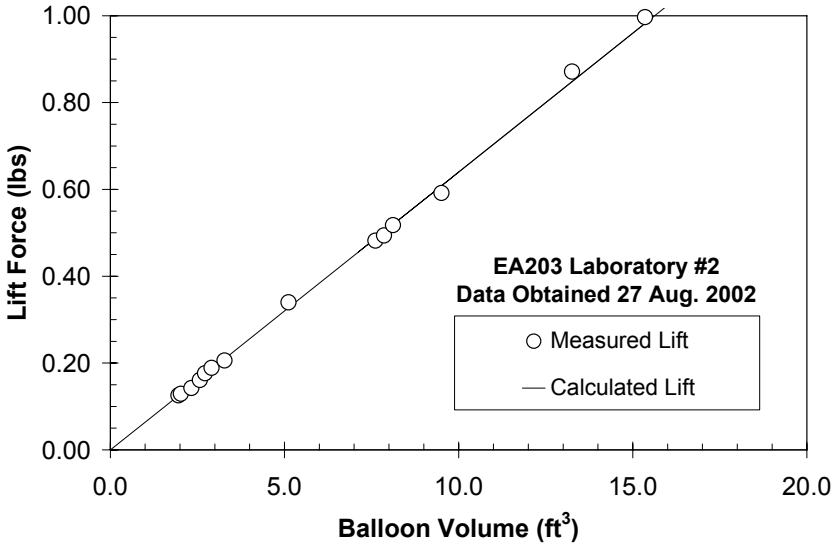
- Tabulate the volume of the balloon in cubic feet.
- Calculate the density of the air in the room and that of the contained helium.
- Calculate the theoretical lift in pounds, L_{theory}, based on the circumference. This comes from the value of the left-hand side of equation (2.5).
- Determine the total weight lifted in pounds, $\left(W_{env} + W_{pay}\right)$. This is the measured lift of the balloon.
- Using the appropriate graphical conventions for experimental and theoretical data, plot the calculated and measured lift against the balloon volume. NOTE: If you're using Microsoft Excel, you should NOT be using the trendline function! You will need to plot two separate data series on the same set of axes.
- Calculate and tabulate the percent error between the theoretical predictions and the actual weight lifted.

Creating a Data Table and Plot

Use the examples below to create your table of data and a plot. Clearly label all columns and axes and indicate the engineering units used.

• Table 1. Sample table: The lift of helium balloons

Experimental Measurements					Calculations	
C (in)	**Volume (ft^3)**	**W_{env} (lb)**	**W_{pay} (lb)**	**W_{total} (lb)**	**L_{theory} (lb)**	**% Error**
-	0	-	-	-	0.0000	-
66.75	2.91	0.1004	0.0886	0.1890	0.1859	1.65
69.50	3.28	0.0720	0.1340	0.2060	0.2099	1.84
80.60	5.12	0.0715	0.2684	0.3399	0.3273	3.84
92.00	7.61	0.1003	0.3815	0.4818	0.4868	1.03
93.00	7.86	0.0704	0.4234	0.4938	0.5028	1.80
94.00	8.12	0.0650	0.4528	0.5178	0.5192	0.28
99.10	9.51	0.0986	0.4930	0.5916	0.6084	2.76
110.70	13.26	0.1094	0.7618	0.8712	0.8481	2.73
116.25	15.35	0.1048	0.8918	0.9966	0.9821	1.48
-	20	-	-	-	1.2794	-



- Figure 1. Sample plot: Measured and calculated lift of helium balloons

Deliverables

Although the data were gathered in teams, each write-up must be done and submitted on an individual basis. You must hand in the following deliverables to complete this laboratory:

- A formal abstract for this experiment
- A plot and data table of the whole section's data (follow the technical graphics guidelines)
- Sample calculations for your balloon that are used to obtain your graphical results
- Answers to the following questions

Questions

1) If we cut the payload loose (cup, string, shot), but keep the envelope tied off, how high would your balloon rise (to the nearest 10 ft)? Assume constant balloon volume and standard atmospheric conditions, for both the air and the helium.

2) Based on Archimedes' Principle, will a balloon have a higher buoyant force in air or in water? What is the ratio of water/air buoyancy for a fixed volume?

3) A hot air balloon rises to a maximum altitude of 2,000 ft. If the entire vehicle weighs 550 lbs and the balloon volume is 33,510 ft^3, what must be the average air temperature inside the balloon? Assume standard atmospheric conditions.

Laboratory

3

Introduction to Programming
The MATLAB Programming Environment

Introduction

The purpose of this lab is to introduce you to an engineering tool that will help you to solve certain problems found in the field of aerospace engineering. The tool is similar to your TI-92 calculator or an EXCEL spreadsheet in that it *crunches numbers.* The tool is called MATLAB. MATLAB is not a programming language; it is a programming environment. Like your calculator, MATLAB has more features than you will need in the majority of your undergraduate studies. Don't let the extra features overwhelm you. Just get comfortable using the features we cover in this lab.

By this point you should have installed MATLAB on your personal computer. You have the student version of MATLAB. Here in the lab, you will be working with the standard version. For our purposes, there is no difference between them. Throughout the lab, I am assuming that you have a working knowledge of the Microsoft Windows operating system. That is the operating system installed on the computers in the CADIG (Computer Aided Design/Interactive Graphics) labs. You will need to find some time to practice moving files between your CADIG account and the local computer on which you are working. The lab exercises focus on how to write MATLAB programs and interact with MATLAB from something called the *command prompt.* It is left to you to explore the pull down menus and Help files. The interface is the similar to the GUI you are used to in other Microsoft Office applications.

Start up MATLAB from the start menu. Hint: it is under **Start ➔ Programs ➔ Applications ➔ MATLAB 7** on the CADIG computers in Rickover 114, 116, or 119.[1] The MATLAB window may contain more than one sub-window. For now, we will just use one of them. Find the window titled Command Window, and click the cursor anywhere in that window. Now you are in the MATLAB workspace and the flashing bar next to the double carrots is MATLAB's way of telling you that it is ready for you to type something. The double carrot is termed the command prompt. MATLAB is ready to solve your problems. Type `why` at the command prompt and MATLAB will give you a randomly generated generic answer.

Programming Basics

Variable Assignment

The MATLAB workspace is a little bit like the display on you calculator. You can type simple math commands and MATLAB will crunch the numbers. For instance, type `1-2+3*4`. Notice that the multiplication sign is the * symbol. The division sign is the backslash symbol found on the same key as the question mark symbol. When you hit enter, MATLAB should respond with `ans = 11`.

`ans` is actually a variable in the workspace. It is meant to suggest the word answer. Since you did not assign the result of the mathematical operation to a variable, MATLAB assigned it to the default variable `ans`. A variable can be any name formed using the standard 26 letters of the alphabet and the underline symbol. MATLAB is case sensitive, so `total`, `Total`, and `TOTAL` are all different variables. The equals sign, =, in MATLAB really is an assignment operator. It means assign to the variable on the left, the value found on the right. That last sentence is worth reading again. Go ahead, read it slowly. Here are some examples. Type them in MATLAB to get the hang of it.

```
NumPennies = 4
```

[1] MATLAB is also available on the computers in Rickover 213.

```
NumNickels = 2
NumDimes = 1
TotalCents = NumPennies*1 + NumNickels*5 + NumDimes*10
```

MATLAB should have answered with:

```
TotalCents = 24
```

If you create enough variables, you may not remember them all. Type `who` at the command prompt, and MATLAB will list the variables in the workspace. Type the variable name at the command prompt, and MATLAB will display its value. Try it. OK, that is enough playing with loose change. Type `clear` at the command prompt and MATLAB removes all the variables from the workspace. If you don't believe it, type `who` at the command prompt and check. They are all gone; the workspace is empty. As a habit, it is a good idea to clear the workspace before you start a new problem.

MATLAB Built-In Functions

Great, so you can create and remove variables from the workspace and perform simple arithmetic on them. To do more, you need to use the built in functions in MATLAB. The functions available on your calculator are obvious because they are printed on the keys. For instance, your calculator has a key to perform the square root. In MATLAB, you would type `sqrt`. Your calculator has a key to compute the sine of a number. In MATLAB you would type `sin`. Let's try it. Type `a = 100`. Now, take the square root of 100 by typing `b = sqrt(a)`. There are now two variables in the workspace: a, which has a value of 100, and b, which has a value of 10. How many functions are there in MATLAB? What is the function for the arcsine of a number? Well, your MATLAB manual lists a lot of the available functions. Most are pretty intuitive. For instance, `round` is a function that rounds a variable to the nearest integer value. Generally, you will want to use the MATLAB help menu to find a function that you have not used before.

Under the **Help** menu in the main window, select **MATLAB Help.** Then select the hyperlink, **MATLAB Functions Listed by Category.** Remember the part earlier about not getting overwhelmed. This would be a good time to re-read that sentence. Many of the functions will not make sense to you until you are further along in the curriculum. For now, you will need to use less than a dozen of the MATLAB functions. The most commonly used functions are listed under **Mathematics: Elementary Math Functions.** Go ahead and browse though them. They are basically like the keys on your calculator. The absolute value function is the first one listed. Its function name is `abs`. Close the help window and go back to the command window. Type `c = -5` at the command prompt. Suppose we want to find the absolute value of c. Type `d = abs (c)` at the command prompt. If you can't remember what the `abs` function did, type `help abs` at the command prompt. MATLAB explains the absolute value function. All MATLAB functions have quick help available from the command prompt. Type `help log` to find out about the logarithm function. For instance, does it compute the base-10 logarithm or the natural logarithm of a number? Unfortunately, you have to know the name of the function to get help on it from the MATLAB command prompt. If you don't know the abbreviated name of the function, you will have to take an educated guess, or go through the help menu to find it.

Working With the Command Prompt

We are going to calculate the temperature in the standard atmosphere from sea level to 10,000 feet at increments of 1000 feet. The formula for temperature as a function of altitude is given on page 98 of Anderson's *Introduction to Flight* as:

$$T(h) = T_1 + a(h - h_1) \tag{3.1}$$

where a = -0.003565 °R per foot, and T_1 and h_1 are the reference temperature and altitude, respectively. These are usually set to sea-level standard conditions.

Of course, this equation is written in a language called *mathematics* and we need to translate it into another language called *programming*. This process is not unlike studying a foreign language, with the exception that the vocabulary is limited to a few dozen words. However, a small translation error results in potentially huge consequences. Remember the 1999 debacle of the Mars Climate Orbiter and the Mars Polar Lander?

On 23 SEP 1999, the Orbiter burned up in the Martian atmosphere because propulsion engineers failed to convert English and metric units in their computer calculations. Then, a few months later on 03 DEC, the Lander augered in because a "software glitch" shut off the descent engines prematurely. "Software glitch" is a euphemism for programming error. These two massive failures were the result of small, correctible programming errors. The cost to NASA was $328 million in lost spacecraft.

If we translate the equation properly, we'll type it in as the following statement:

```
t = t1 + a*(h-h1)
```

To begin with, enter the initial altitude at sea-level, the temperature of the standard atmosphere at the initial altitude, and the temperature lapse rate into the MATLAB workspace:

```
h1 = 0
t1 = 518.69
a = -0.003565
```

Suppose we are interested in the temperature at 1000 feet. Specify:

```
h = 1000
```

Next, calculate the temperature at 1000 feet using the above statement:

```
t = t1 + a*(h-h1)
```

Next, change the variable `h` to 2000 feet and calculate the temperature at 2000 feet.[2] Finally, repeat the process for the rest of the altitudes up to 10,000 feet. At each altitude, you will want to record the corresponding temperature on a sheet of paper.

Sure it works, but it is tedious. Basically, you keep repeating the same commands in the MATLAB workspace with some small changes to the variable `h`. This is about as time consuming as solving the problem on your calculator.

The MATLAB Editor

Under the **File** menu, select **New, M-file.** MATLAB will open the MATLAB editor. The MATLAB editor is a bit like Notepad in that it is a basic text editor with some additional features. To begin with, type the following text into the new document:

```
h1 = 0
t1 = 518.69
a = -0.003565
h = 1000
t = t1 + a*(h-h1)
```

These are just the commands that we would like to have executed in the workspace in succession.

To have these commands executed in the workspace in order, go under the **debug menu,** and select **save and run.** The first thing MATLAB asks is for you to save the file. Notice that the file is saved in a folder called **MATLAB71\work.** That's fine for now if you're working in your room. If you're on one of the CADIG computers and you have an account, then change the directory to the N drive (you'll notice it's labeled with your account ID). Choose a name for the file; I am calling mine `temperature.m`. MATLAB is written to work with a wide range of operating systems, so stay away from file names containing blank spaces and odd characters, like the "@," "$," or "-" characters. Use only letters, numbers, or the "_" character. The file name needs to end in `.m` or it would not make any sense to call it an M-file. For now, choose `XXXX.m` where the X's are simply letters. Go back to the workspace, and you will see that MATLAB has executed each command in order. If you made a typing mistake, you may get an error message.

[2] ***Power user tip:*** *Use the up arrow key to quickly cycle through previous commands in the MATLAB workspace. You can save time typing by quickly editing a previous command.*

MATLAB will tell you in the workspace what line number in your M-file caused the error. The line numbers are on the left-hand side of the MATLAB editor. Fix the typos and run the script again.

Congratulations, you have just written your first self-contained program in MATLAB. You can change the value of h in your program and re-run it to calculate the temperature at the new altitude.[3]

If I want to run my program,[4] and have MATLAB display only the final result, my code would look like this:

```
h1 = 0;
t1 = 518.69;
a = -0.003565;
h = 1000;
t = t1 + a*(h-h1)
```

The MATLAB Directory

The **MATLAB71\work** folder is the default directory for all user-written programs. If you have been working on a program in your room, and want to continue working on it in the lab, you should copy it to the **MATLAB71\work** folder on the local computer. The Current Directory window should show **MATLAB71\work,** and show you all of the files in the work folder. As it matter of policy, all programs left in the **MATLAB71\work** directory on a local computer are fair game to be deleted once you log off the machine. Be sure to move a copy of your program to a floppy, zip disk, or network account at the end of a computer lab. If you sit down to work on a program in a CADIG computer lab and the work directory is clobbered with old files, feel free to delete them.

Lab Assignment: Part 1

The standard atmosphere begins by defining a set of standard atmospheric conditions at sea level. We've already written a command-line program to compute the temperature profile up to 10,000 feet given the standard temperature lapse rate below 10,000 feet. If we assume that the gravitational constant is, in fact, a constant between zero and 10.000 feet, we can relate pressure to temperature via the hydrostatic equation. Follow Anderson's development on pages 94-98 in *Introduction to Flight.*

The resulting relationship is shown in Equation 3.12 as:

$$\frac{p}{p_1} = \left(\frac{T}{T_1}\right)^{-\left(\frac{g_0}{aR}\right)} \quad \text{or} \quad p = p_1\left(\frac{T}{T_1}\right)^{\left(\frac{-g_0}{aR}\right)} \tag{3.2}$$

Once the pressure and temperature are known, the density comes from the equation of state:

$$\rho = \frac{p}{RT} \tag{3.3}$$

Write a MATLAB program that computes the pressure, temperature and density in the standard atmosphere anywhere from 0 to 10,000 feet. Start by defining standard sea level conditions. Next, compute the temperature at a specified altitude using the standard lapse rate for low altitudes (i.e. the troposphere). Then, compute the pressure at the specified altitude via Anderson's *Introduction to Flight* equation 3.12. Next, compute the density at that altitude via the equation of state. Finally, use your program to compute the standard atmosphere from 0 to 10,000 feet in increments of 1000 feet. Compare your results with Andersons' in Appendix B of *Introduction to Flight.* Save your program. You'll need it later in the lab.

---

[3] ***Power user tip:*** *Each time a line of code is executed, MATLAB shows its result in the workspace. To suppress the display of the result in the workspace, put a semi-colon after the line of code in the M-file.*

[4] ***Power user tip:*** *To start your program from the workspace, simply type the file name without the* `.m` *extension at the command prompt. For example, I would type* `temperature` *to run my program. But be careful, because MATLAB will run the last SAVED file. Save your M-file after you make a change. Try it.*

If you have been following along carefully, then you've worked the *bugs* out of your code and have a useful program for computing properties in the standard atmosphere. You probably ran the program 10 times, once at, each altitude. Each time you ran the program, it was basically the same code, just the altitude of interest changed. There is a way tell MATLAB to repeat the same program 10 times, or however many times you like. It is a powerful tool and it is surprisingly simple to use. It is called a loop. But, before we modify your code to cover how to make use of a loop, we need to look at something called an array in MATLAB.

Arrays: Vectors and Matrices

Consider the array of four numbers [2, 5, 7, 9]. It has four elements and each element has a certain value. For instance, the third element has the value 7. I could assign this row of four numbers a variable name in MATLAB by typing `RowVec = [2, 5, 7, 9]`. Notice that the elements are separated by a comma and that the row is contained within square brackets. Those little particulars, 'separated by commas,' 'contained within square brackets,' are called rules of syntax. Syntax is to programming what spelling is to writing a composition. When you spell a word wrong, you leave it to the reader to infer what word you had in mind. Perhaps you were close to the correct spelling, and it is easy to tell what you meant. Perhaps not. The computer has very little ability to infer what you had in mind when you use the wrong syntax. Syntax errors are often frustrating when you first learn a programming language, and they are the most common source of error in your code. Pay close attention in this lab to not only the meaning of <u>what</u> I write, but the syntax of <u>how</u> I write it. There is a big difference in a programming language between the use of a comma, a semi-colon; or a colon: really.

Back to our array of four numbers. Open MATLAB, and create the variable `RowVec` as defined above. Instead of using a single row and four columns to hold the elements, I could have just as easily used a single column and four rows. In MATLAB, I would do this by using a semi-colon between the elements instead of a comma. This is another example of a rule of syntax in MATLAB. Type `ColVec = [2; 5; 7; 9]` at the command prompt. `RowVec` and `ColVec` are both variables in the MATLAB workspace. They both have the same four elements, but they are not the same *size.* `RowVec` is said to be a row vector, and has the dimensions of a 1 by 4 matrix. That is, its size is 1 row by 4 columns. `ColVec` is said to be a column vector, and has the dimensions of a 4 by 1 matrix. That is, its size is 4 rows by 1 column. Previously, we typed `who` at the prompt to see a list of our variables in the workspace. This time, type `whos` at the command prompt. Notice that MATLAB now tells you the size of your variable, i.e. how many rows and columns.

A variable that has multiple elements arranged in a single row or a single column is termed a vector. However, when the variable has multiple rows and multiple columns, we call it a matrix. Here is an example of a matrix with 2 rows and 3 columns. Type `mat = [1, 2, 3; 4, 5, 6]` into your workspace. Notice the careful use of semi-colons, commas, and square brackets.[5]

Addressing Elements in Vectors and Matrices

You now have three variables in the workspace which are all arrays: a row vector, a column vector, and a matrix. The elements in an array are addressed by referencing the row number first, and then the column number. Type `RowVec`. MATLAB returns the entire array. If we want to see the value of the second element in `RowVec`, we would type `RowVec(1,2)`. Notice that I used soft parenthesis and a comma between the row and column number. If you type `mat(2,3)`, MATLAB should return `ans = 6`. Now you can change the row 2, column 3 element in `mat` to 7 by typing `mat(2,3) = 7` at the command prompt.

Notice that the variable, `mat`, could be thought of as composed of two row vectors, one stacked on top of the other. Perhaps we are interested in just the first row of `mat`. MATLAB has a way to address a sub-block of an array. In this case, we are interested in the sub-block of row 1, columns 1 through 3 of the variable `mat`. At the prompt, type `sub = mat (1,1:3)`. MATLAB should have returned with the row vector `sub = [1 2 3]`. The syntax uses a comma to separate the row from the column entry, and a colon to indicate

[5] ***Power user tip:*** *You can separate elements in the same row with a blank space, a comma, or both. You can separate elements on different rows with a semi-colon, a line return, or both. Thus, the following command will fill the array with the exact same values:*

```
mat = [1  2  3
       4  5  6]
```

that we are assigning to the variable named `sub` the values in the variable `mat` on the first row, in the first through third columns. Change the variable `sub` to the 1st and 2nd rows, and 1st and 2nd columns of `mat`. Type `sub = mat (1:2,1:2)`. The result should be a two-by-two matrix. It takes a little practice to get used to reading the MATLAB syntax. Like any new language, proficiency comes only through practice.

Loops in MATLAB

Now that we understand arrays, we are ready to tell MATLAB to repeat a section of code a fixed number of times. Recall in the first lab we began with sea-level (0 ft) conditions and computed the atmospheric properties up to 10,000 feet in increments of 1000 feet. Let's begin by creating a row vector with 10 entries. Each entry in our row vector will be an altitude of interest. Type at the prompt `h = [1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000 10000]`.[6]

The syntax to loop in MATLAB is written as `for index = beginning value: increment: ending value`. Next, the lines of code we want repeated are listed. Finally, an `end` statement tells MATLAB where to end the loop. Here is an example:

```
for i = 1:1:10
      altitude = h(l,i)
end
```

The variable `i` is called the index. You need not choose the letter `i`. Any legal variable name will do. The index starts at a value of 1. Then, the variable `altitude` is assigned the value of 1000, since that is the value of the element in the 1st row, 1st column of the row vector `h`. This is the line of code we want repeated, and it is inside our `for` loop. At the end statement, the program jumps back up to the first line. The index, `i`, is incremented by 1, and MATLAB checks if this new value of the index is less than the ending value of the `for` loop, 10. Of course, 2 is less than 10, so the line between the `for` and `end` statements is repeated. The code to be repeated in the loop should be indented to visually indicate to the reader that this is the section inside the loop.

Open a new M-file, type in the above code, and get your first loop in MATLAB to run. Notice that the M-file editor automatically uses different colors and indenting to visually indicate the use of the `for` loop in the code. Reading code is never easy, but proper formatting will help a lot.

Application: Computing Temperature in the Standard Atmosphere

Recall the formula for the temperature below 10,000 feet in the standard atmosphere as a function of altitude: `t = t1 + a * (h – h1)`, where `t1 = 518.69`, `h1 = 0`, and `a = -0.003565`. Instead of creating a row vector of altitudes ahead of time, we will build it as we progress through the loop. Open an M-file, and define the variables `t1` and `h1` and `a` in the first three lines of code. Since we want to take 10 steps, write the code for a `for` loop that counts from 1 to 10 in increments of 1. Your code should look something like this:

```
h1 = 0
t1 = 518.69
a = -0.003565
for i = 1:1:10
      …
end
```

Although there is nothing inside the loop, it is best to run your code and check for errors along the way. Even experienced programmers rarely write error-free code. It is hard to debug large sections of code, but much easier to debug small sections of code. Run and debug your code. Next, let's have the loop generate the row vector h whose elements are the altitudes of interest. There are lots of ways to do this. Here is one idea:

---

[6] ***Power user tip:*** *The same vector can be quickly generated with the syntax:* `h = [1000:1000:10000]`*. In MATLAB-speak that reads: create a vector h, make the first element equal to 1000, add additional elements whose values are increasing in increments of 1000 up to 10,000. It sounds complicated, but is easy to use in practice.*

```
h1 = 0
t1 = 518.69
a = -0.003565
for i = 1:1:10
      h(i) = i*1000
end
```

Again, run and debug. Finally, at each altitude, compute the temperature. Just as h was a row vector of altitudes, let's build t as a row vector of temperatures at each altitude. It might look something like this:

```
h1 = 0
t1 = 518.69
a = -0.003565
for i = 1:1:10
      h(i) = i*1000
      t(i) = t1 + a*( h(i)-h1 )
end
```

Run and debug your code. When run correctly, the variables h and t should be:

```
h = [1000 2000 3000 4000 5000 6000 7000 8000 9000 10000]
t = [515 512 508 504 501 497 494 490 487 483]
```

Note: I have rounded the values off to the nearest integer.[7]

Viewing the Data: Graphics

We would like to see how the temperature varies with altitude on a graph. The command in MATLAB is simple. Type `plot (h, t, 'o')`, which will open a figure window and plot the elements of h versus the elements of t using the symbol ○. The first vector in the plot command provides the x-axis values. The second vector provides the y-axis values. Experiment with the pull-down menus in the figure window to add labels to the axis; a title to the graph; and fit a line to the data.[8]

Lab Assignment: Part 2

Write a MATLAB program that uses a loop to compute the pressure, temperature, and density in the standard atmosphere from 0 to 10,000 feet in increments of 1000 feet. Store your results in four row vectors, one each for altitude, pressure, temperature, and density. Generate plots of altitude versus the three atmospheric properties. Repeat the process using an increment of 100 feet.

When you hand in your program, you will want to explain what each line of code does. You will also want to include your name, date, section number, etc. at the top of the program. However, if you simply type this information into the M-file, MALAB will think that they are commands. In order to add this documentation to your program without confusing MATLAB, you need to use the percent sign. The percent sign tells MATLAB to ignore any characters that follow on that line. Properly documenting code is important. Without documentation, your code can be difficult to read or use, even a day later.

Here is an example of a simple program with brief documentation.

```
% Name/Date/Section:  Joe Student/04 SEP 2002/EA203.1001
% Title:  A Program to count from 1 to 10
% Clear all workspace variables AND erase the workspace...
clear
clc
```

[7] ***Power user tip:*** *Suppress the display of all the intermediate results in the workspace while the program is running by placing semi-colons at the end of each line. Add two lines of code, simply h and t, without semi-colons, at the end of your program to display all the results.*

[8] ***Power user tip:*** *Type `help plot` at the command prompt to find out more about plotting in MATLAB. The demos under Help:Demos:Graphics:2-D Plots are very good.*

```
% Initialize a counter at zero
counter = 0;
% Set up a loop to go from 1 to 10
for i = 1:1:10;
      counter = counter + 1    %Add 1 to the previous value
end
% End of the loop
```

Hand in your completed program with documentation, and graphs of the output of your program for each of the atmospheric properties.

For the Power User

We have covered how to write and run a simple program in MATLAB. MATLAB has some nice built-in demos available under the help menu. Most are beyond the scope of the class for now. If you have a little background in matrix math, run through the MATLAB:Desktop Environment demo. It comes in five short parts. Feel free to use any of the built-in power user features in MATLAB that you discover.

Laboratory

4

Airspeed Determination
Bernoulli's Equation and the Pitot-static tube

Introduction

The accurate indication of airspeed is critical for both flight operations and wind tunnel testing of aircraft components. In this laboratory, we will study the nature of Bernoulli's Principle (sometimes referred to as the "Venturi Effect") and apply it to the measurement of the velocity of an air stream. The results will be used to calibrate the speed control on the USNA Flow Bench in Rickover 023, and the implications on aircraft airspeed indicators will be discussed.

Bernoulli's Equation

What is now known as Bernoulli's equation was formulated by mathematician/physicist Daniel Bernoulli (1700-1782). Much of his work involved studies in fluid mechanics and the kinetic motion of gases and their applications to jet propulsion, manometers, and flow in pipes. Although Daniel originally published the concept involving the Bernoulli equation in 1738, it was through the observations of his father, Johann, and the insight of his close friend, Leonhard Euler, that resulted in the present derivation of the Bernoulli Equation.

The Euler Equation originates out of the steady-state momentum equation applied to a streamline when the effects of friction are assumed to be negligible. This assumption is common in fluid dynamics, and characterizes a fluid as *inviscid*. Thus, for an inviscid flow that is invariant with time, the resulting Euler Equation can be written as:

$$dp + \rho V dV + \rho g dh = 0 \tag{4.1}$$

Equation (4.1) holds true as long as we restrict ourselves to the streamline on which the fluid element is traveling. Note that it also includes the term $\rho g dh$, which is known as the hydrostatic term. If we restrict ourselves to the flow of *air* rather than *water*, then this term is negligibly small compared to the others. The result is the form of the Euler Equation as presented in Anderson's *Introduction to Flight* text (equation 4.8 on p.132):

$$dp + \rho V dV = 0 \quad \text{(or } dp = -\rho V dV \text{)} \tag{4.2}$$

This equation is easily integrated over a streamline when we make the additional assumption that the density is constant. This last assumption is valid for low-speed flows, where the velocity is less than about 330 ft/sec (230 mph or 200 knots). When the density is constant throughout the flow, it is said to be in the incompressible flow regime. The resulting indefinite integral is:

$$\int \left(dp + \rho V dV \right) = \int dp + \rho \int V dV = p + \frac{1}{2}\rho V^2 + C_1 \tag{4.3}$$

where C_1 is a constant. This can also be represented as:

$$p + \frac{1}{2}\rho V^2 = \mathrm{C}_2 \tag{4.4}$$

where C_2 is a different constant. Remember that this constant holds everywhere along the streamline, according to our derivation assumptions. Thus, we can relate any two points along this streamline without actually knowing the value of this constant:

$$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2 \tag{4.5}$$

The constant on the right-hand side of equation (4.4), denoted as the *total* pressure and written as p_T, represents the total energy of the fluid particles along a streamline. This total energy is a constant value when we confine ourselves to the streamline along which we integrated. Thus we can write the total pressure as:

$$p_T = p + \frac{1}{2}\rho V^2 = C_2 = \text{ Constant along a streamline} \tag{4.6}$$

This is known as Bernoulli's Equation. It is obvious that the total pressure consists of two terms that are added. The first term (p) is called the fluid pressure (often called *static* pressure or p_s). The fluid pressure represents the energy associated with the random motion of the fluid particles and is a state property of the fluid. This is analogous to, for instance, the potential energy of a swinging pendulum. The second term ($\frac{1}{2}\rho V^2$) is called the *dynamic* pressure of the moving fluid. The dynamic pressure is denoted by q and is thus defined:

$$q \equiv \frac{1}{2}\rho V^2 \tag{4.7}$$

> ***NOTE:*** *This definition for* q *is* <u>*always true*</u> *and does NOT depend on the assumption of incompressibility, unlike Bernoulli's Equation.*

The dynamic pressure represents the energy associated with the ordered motion of the fluid traveling at velocity V . This is analogous to, for instance, the kinetic energy of a swinging pendulum. In such an analogy, the total energy is the sum of the potential energy and the kinetic energy. Thus, the total pressure is the sum of the static pressure and the dynamic pressure. When consistent units for ρ and V are used, the dynamic pressure will be in units of lbs/ft² or Pa.

With the definition of the dynamic pressure from equation (4.7) and substituting this into equation (4.6), we can thus rewrite Bernoulli's Equation in its simplest form:

$$p_T = p_s + q \tag{4.8}$$

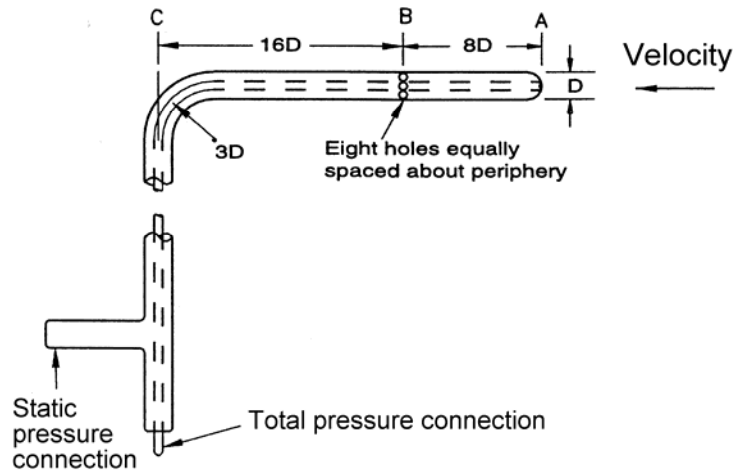
Note that if the dynamic pressure were a known quantity, then the velocity can be calculated by rewriting equation (4.7) as:

$$V = \sqrt{2q/\rho} \tag{4.9}$$

This is the principal approach used to determine the airspeed of a flight vehicle.

Airspeed Measurement

In order to determine airspeed from equation (4.9), we need the value of the dynamic pressure, but it is impossible to directly measure q. However, we can easily measure p_s and p_T using a device called a Pitot-static tube in order to indirectly determine the dynamic pressure. Figure 2 shows the geometry of a standard Pitot-static pressure probe and how it measures both total and static pressures.



• Figure 2. A standard Pitot-static pressure probe

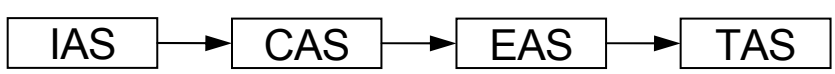
Thus it follows from equations (4.7) and (4.8):

$$V = \sqrt{\frac{2q}{\rho}} = \sqrt{\frac{2\left(p_T - p_s\right)}{\rho}} \tag{4.10}$$

Equation (4.10) is just another formulation of the Bernoulli equation. We see that it's not even necessary to measure both p_T and p_s, but simply the difference between the two. That is why a differential measurement system, like a manometer, a dial-type pressure gauge, or a differential pressure transducer, is often used.

Flight Vehicle Application

Obviously, the calculation of velocity requires an accurate measurement of the dynamic pressure of the air stream and the actual air density of the fluid. However, a conventional cockpit airspeed indicator is a simple dial-type pressure gauge that only measures the pressure difference $\left(p_T - p_s\right)_{measured}$. This pressure difference is also known as the "impact pressure" in the aviation community and is denoted as q_c. Note that the impact pressure is not really an absolute pressure measurement, but a differential measurement. The dial on the airspeed indicator is calibrated to read out in units of knots, but it is labeled "indicated airspeed" and not "true airspeed." Thus, the conventional airspeed indicator calibration involves several assumptions, including standard-day, sea level values for the density (0.002377 slug/ft³) and pressure (2116.2 lb/ft²). The airspeed is thus displayed in units of knots, indicated airspeed (KIAS). The value of the true airspeed must involve several corrections for the probe's position on the aircraft, the vehicle pressure altitude, and the density altitude. The different components of the airspeed are progressively related according to the figure below. The airspeed components are defined as:



Indicated Airspeed (IAS). Indicated airspeed is equal to the Pitot-static airspeed indicator reading as installed in the aircraft. It involves no corrections for system errors, but it does include a correction for sea level compressible flow (which is included in the instrument dial calibration) so that its reading is valid above 200 knots. The assumed air conditions are standard, sea level pressure and density.

Calibrated Airspeed (CAS). CAS is the result of correcting IAS for errors resulting from the positioning or location of the Pitot-static probe installation. The error is provided in a table by the aircraft manufacturer and is designed to be as small as possible, but the static pressure port is generally more susceptible to position and location errors than is the Pitot pressure. At low speeds, CAS will be greater than IAS, but at high

speeds this trend reverses due to compressibility effects. Assuming that the impact pressure has been corrected for these errors, the calibrated airspeed can be calculated:

$$CAS = a_{std}\sqrt{5\left[\left(\frac{q_c}{p_{std}}+1\right)^{2/7}-1\right]} \tag{4.11}$$

The term a_{std} is the standard, sea level value for the speed of sound (1116 ft/sec or 661.5 knots).

Equivalent Airspeed (EAS). EAS is the CAS that has been corrected for altitude compressibility effects. Thus, the equivalent airspeed is literally the "equivalent" flight speed at standard sea level density that would produce the same dynamic pressure at the actual flight speed and altitude. Essentially, it is a correction of CAS to the true pressure altitude, while still assuming a standard, sea level value of the density. At sea level, EAS = CAS. The equation to calculate EAS is given by:

$$EAS = a_{std}\sqrt{5\frac{p}{p_{std}}\left[\left(\frac{q_c}{p}+1\right)^{2/7}-1\right]} \tag{4.12}$$

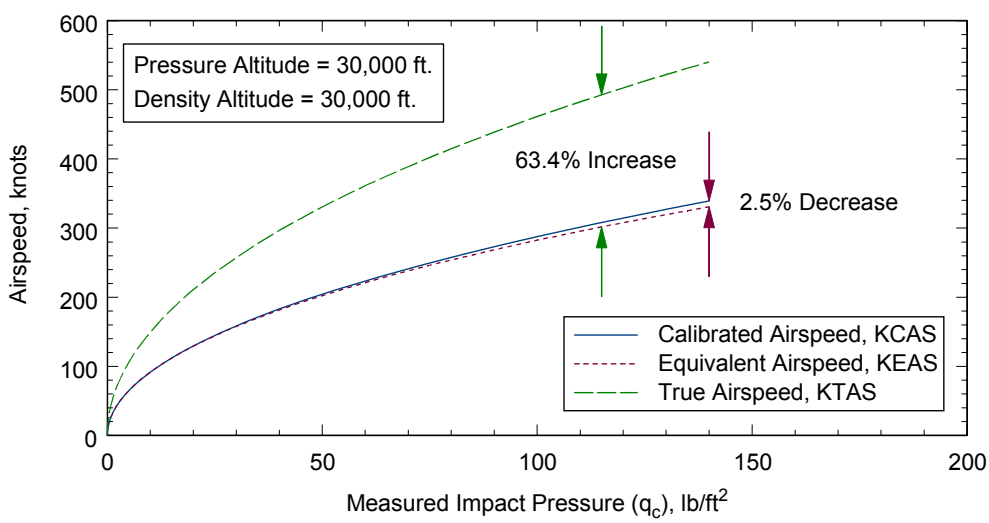
True Airspeed (TAS). The true airspeed results when the EAS is corrected for density altitude. Because the airspeed indicator is calibrated for standard sea level density, it must be corrected to account for the actual density at altitude so that an accurate dynamic pressure determination can be made. Essentially, it is a correction of EAS to the true density altitude. At sea level, TAS = EAS. The equation to calculate TAS is given by:

$$TAS = a_{std}\sqrt{5\frac{p}{p_{std}}\frac{\rho_{std}}{\rho}\left[\left(\frac{q_c}{p}+1\right)^{2/7}-1\right]} \tag{4.13}$$

The common (but not standard) units used for airspeed measurement are knots, or **nautical miles per hour**. Thus, we would notate the airspeed components as "knots indicated airspeed" (KIAS); "knots equivalent airspeed" (KEAS); and "knots true airspeed" (KTAS). For the purpose of this laboratory, we can assume a low-speed, incompressible flow such that the following is true: $IAS \approx CAS = EAS$.

Take note of the conversion factors involving statute miles and nautical miles:

$1\ statute\ mile = 5,280\ ft$ and $1\ nautical\ mile = 6,076\ ft$



• Figure 3. Comparison of airspeed measurements

These different values of airspeed are summarized in Figure 3, which is a plot of airspeed as a function of the impact pressure. These numbers assume the flight conditions of a typical jetliner (standard altitude of 30,000 ft and speeds up to 500 knots). Note that the correction from CAS to EAS is at most a 2.5% decrease. The correction from EAS to TAS is a constant 63.4% increase.

Pressure Conversions and Measurement

There are many different units commonly used for pressure measurement. Care must be taken when working with the different units because fluid equations are usually derived on the basis of standard units. Thus, the standard units of pressure (force per unit area) are N/m² or lb/ft². All other units of pressure measurement are referenced to 1 atmosphere, which is the sea level barometric pressure of the ARDC 1959 Standard Atmosphere (tabulated in Anderson's *Introduction to Flight*, Appendices A and B). To do pressure conversions, just remember that…

1 atmosphere = 101,325 N/m²
101,325 Pa
1013.25 mbar
1.01325 bars
1,013,250 dynes/cm²
760 mm Hg
2116.2 lb/ft²
14.696 lb/in²
29.92 in. Hg
406.78 in. H_2O

Notice how many units of pressure are expressed in the units of the height of a fluid column, such as millimeters of mercury or inches of water. These units originate from the pressure exerted by a column of fluid having a specified height at standard temperature (22 °C). In the laboratory, the fluid column is constrained by U-shaped length of glass tubing known as a manometer, and the difference in height between the two fluid columns represents a difference in pressure. In this experiment, we'll use a manometer filled with green water. When recording data, the height of the fluid column is usually recorded as the symbol h (rather than p), but this is always understood to be a pressure measurement.

Frequently, fluids other than water or mercury are used in the laboratory. On the USNA Fluids Lab Deck, a mixture of ethyl and methyl alcohol is used in most of the manometer tubes. This fluid is dyed pink to increase its visibility. To get the effective pressure in units of inches of water, the height of the alcohol column is multiplied by the specific gravity ($S.G.$) of the fluid. Thus:

$$h\ (in.\ H_2O) = h\ (in.\ alcohol) \times S.G. \tag{4.14}$$

Procedure

This experiment uses the USNA Flow Bench in Rickover 023. To operate the flow bench, a control pendant has a push button that turns the blower on and off and a knob that adjusts the flow velocity. The readout on the pendant gives the Blower Control Voltage (BCV), an analog signal to the motor controller which is proportional to the blower flow rate. The motor controller is capable of a maximum BCV of 10 volts, but the control pendant limits the maximum value to somewhat less than this. The following procedure will be used to calibrate the BCV so it is a reliable indicator of the velocity of the jet.

A Pitot-static probe is mounted 6″ above the nozzle exit plane, and it is connected to a U-tube manometer filled with green-colored water. The manometer has a tape measure glued to the board for height measurements.

Follow these steps to determine the calibration for the flow bench:

1) Record the room temperature and the day's barometric pressure.
2) Measure the diameter of the nozzle exhaust.

3) Ensure that the Pitot-static tube is centered over the nozzle of the jet in the flow bench. Securely connect the total pressure line to the left side of the U-tube manometer. Now connect the static pressure line to the right side so that a differential measurement is possible.

4) Measure both levels in the manometer tube with the blower off. These will be your "Zero" readings, in units of inches of water. Note that this is your first data point!

5) Put on the proper protective equipment.

6) With the BCV set to 0, start the blower. Carefully increase the flow rate until a BCV of about 1 is achieved on the control pendant.

7) After the flow stabilizes, record the height of the two fluid columns in the manometer. These measurements will be your "run" readings, h_1 and h_2, in units of inches of water.

8) Increase the flow rate by BCV = 0.25-0.5 and repeat step 7) until the maximum flow rate is achieved.

9) Turn off the blower and record the final temperature and barometric pressure.

Data Reduction

Your data reduction should involve the following calculations:

1) Calculate the differential height in the manometer, Δh (in. water) for each data point.

2) Convert the differential to the units of psi for each point. This is the dynamic pressure, $p_T - p_S$.

3) From your raw data, use the air temperature and barometric pressure to calculate the air density (slug/ft^3) for each point. If the temperature varied much, assume a linear increase with time, from the initial temperature at the first measurement, to the final temperature at the last measurement.

4) Calculate EAS and TAS in knots, and the percent difference between them for each data point. Do not be tempted to use equations (4.12) and (4.13); these are too involved for this test. Instead, assume that the flow is incompressible (and it is) so that you can use Bernoulli's equation (4.10).

5) Plot the EAS as a function of BCV (i.e., BCV on the x-axis). What type of relationship does this appear to be? Put in a trendline and determine the equation for EAS in terms of BCV. Make sure you include the first data point (0, 0). In other words, your trendline has to go through (0, 0). Make sure your plot follows an appropriate format for technical plots.

6) Plot the dynamic pressure as a function of BCV. What type of relationship does this appear to be? Put in a trendline and determine the equation for q in terms of BCV.

Deliverables

Although the data were gathered in teams, each write-up must be done and submitted on an individual basis. You must hand in the following deliverables to complete this laboratory:

- A formal **EXPERIMENTAL SETUP** write-up for this experiment
- Two plots and a data table of your data
- Sample calculations for one data point that was used to obtain your graphical results
- Two calibration equations, one for the blower velocity and one for the dynamic pressure
- Answers to the following questions

Questions

1) What is the maximum dynamic pressure (in psi), velocity (in KEAS), and volumetric flow rate (ft^3/min or CFM) of the test? What are the maximum capabilities of the USNA Flow Bench (i.e., if we could get BCV = 10 volts)?

2) An aircraft is flying 165 KTAS at an altitude of 5,000 ft. What is the dynamic pressure in psi? What is the static pressure in psi? What is the total pressure in psi?

3) How do we convert from EAS to the TAS for an incompressible flow regime? Derive the relationship and <u>write out the equation</u>. (Note: review the definition of the equivalent airspeed and how it relates to true airspeed).

4) If we are flying a Cessna Citation V at an airspeed of 165 KEAS at an altitude of 5,000 ft, what is the percent difference from our true airspeed? What would be our actual airspeed (i.e., KTAS)?

• Table 3. Raw data table for airspeed experiment

Date & Time: _____

"Zero" Readings (h_0): _____

Barometric Pressures (start/end): _____

Room Temperatures (start/end): _____

Data Point No.	BCV (volts)	h_1 (in. water)	h_2 (in. water)	Δh (in. water)	$q = \Delta p$ (lbs/in²)	Airspeed (KEAS)	Airspeed (KTAS)	Percent Difference
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Laboratory

5

Drag on Basic Shapes
Determination of the Drag Coefficient

Introduction

An object's speed and shape greatly affect its aerodynamic characteristics. In this laboratory, we will study the effects of velocity, size, and geometry on the aerodynamic drag of several basic shapes. A comparison of the results will underscore the competing influences between the friction drag and the pressure drag on the overall measured drag.

Dimensional Analysis

The formula describing aerodynamic drag on an object of fixed orientation a the flow stream can be derived using the Buckingham Pi Theorem, which is outlined in section 5.3 of John Anderson's *Introduction to Flight*. This approach uses dimensional analysis and assumes that the drag, D, can be expressed in terms of the fluid density, ρ, the flow velocity, V, an area representing the size of the object in some way, S, the fluid viscosity, μ, and the local speed of sound, a. The equation for the drag on an object can thus be written in these terms:

$$D = Z\rho^b V^c S^d \mu^e a^f \tag{5.1}$$

Equation (5.1) depends on six dimensionless constants: Z, b, c, d, e, and f. Dimensionally, this combination of units must yield a force (say, Newtons). Thus, this equation can be used to compare the combination of units on both sides of the equation. Plugging-in standard SI units:

$$N = \frac{kg\text{ - }m}{sec^2} = \left(\frac{kg}{m^3}\right)^b \left(\frac{m}{sec}\right)^c \left(m^2\right)^d \left(\frac{kg}{m - sec}\right)^e \left(\frac{m}{sec}\right)^f \tag{5.2}$$

Because the units need to work out, this leads directly to equating the value of each exponent on a dimensional basis only:

$1 = b + e$ (mass, in kg),

$-2 = -c - e - f$ (time, in sec), and

$1 = -3b + c + 2d - e + f$ (length, in m) (5.3)

But we have three equations and five unknowns, so some of these constants will remain undetermined. Solving these equations in terms of e and f results in:

$b = 1 - e$,

$c = 2 - e - f$, and

$$d = \frac{(1 + 3b - c + e - f)}{2} = \frac{1 + 3(1 - e) - (2 - e - f) + e - f}{2} = 1 - \frac{e}{2} \tag{5.4}$$

Now these relationships can be substituted into equation (5.1):

$$D = Z \cdot \rho^{1-e} \cdot V^{2-e-f} \cdot S^{1-\frac{e}{2}} \cdot \mu^e \cdot a^f \tag{5.5}$$

Combining and separating some terms, we arrive at:

$$D = Z \cdot \rho \cdot V^2 \cdot S \cdot \frac{\mu^e}{\rho^e V^e S^{e/2}} \cdot \frac{a^f}{V^f} = Z \rho V^2 S \left(\frac{\mu}{\rho V S^{1/2}} \right)^e \left(\frac{a}{V} \right)^f \tag{5.6}$$

It is obvious that the units of $S^{1/2}$ are length. Thus, we can define some representative length, ℓ. Then we see the last two terms become:

$$\left(\frac{\mu}{\rho V S^{1/2}} \right)^e = \left(\frac{\mu}{\rho V \ell} \right)^e = \left(\frac{1}{Re} \right)^e \text{ and}$$

$$\left(\frac{a}{V} \right)^f = \left(\frac{1}{M} \right)^f \tag{5.7}$$

Note that these are the dimensionless Reynolds and Mach numbers, respectively. The former describes the relative interaction between momentum and viscous effects and the latter, compressibility effects on the flowfield.

Drag Formulation

Having determined the functionality of the different terms in the drag equation (5.6), all the dimensionless terms can be collected and renamed $C_D/2$. This now defines C_D as the dimensionless **drag coefficient**. Different values of C_D for several common shapes are listed in Figure 4. Note that these drag coefficients assume a laminar boundary layer development.

Now, with this information, the drag equation can be written in its simplest form:

$$D = \frac{C_D}{2} \rho V^2 S = C_D \left(\frac{1}{2} \rho V^2 \right) S = C_D q S \tag{5.8}$$

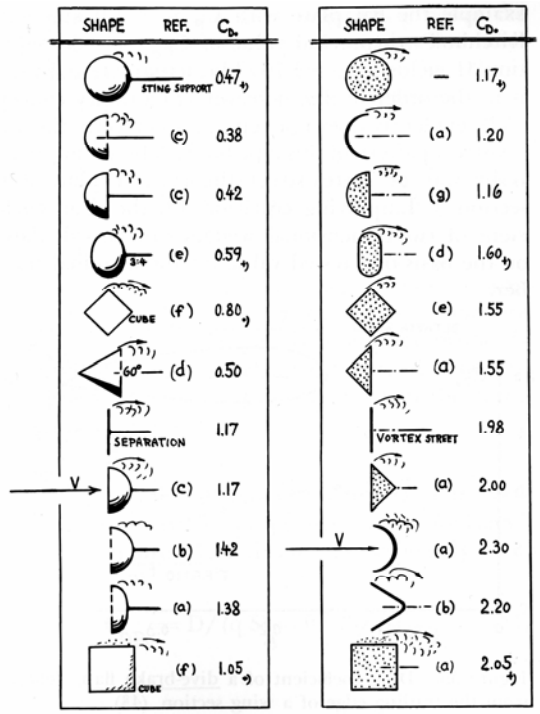
This gives us understanding as to the factors which affect the drag coefficient. Recall that in functional notation, it can be written:

$$C_D = C_D \left(Re, M \right) \tag{5.9}$$

Later on, we will show how C_D also varies with the orientation of the body in the flow (i.e., incidence angle or angle of attack). But for now, it is important to note that the drag coefficient is NOT a function of anything other than the Reynolds and Mach numbers. Thus, if we put two objects having the same <u>shape</u> in a flow, then the drag coefficients will be equal if we match Re and M. This is a necessary and sufficient condition. It doesn't require us to match the velocity, or the density, or even the size in order to obtain the same value of the drag coefficient. By this basic principle, wind tunnel tests are conducted on sub-scale models, and reliable full-scale aerodynamic drag coefficients are obtained. The only condition is that the Reynolds and Mach numbers be matched.

In this lab, we'll measure the area, the velocity, and the drag so that the drag coefficient can be determined using graphical means. Should we be interested in a single-point calculation, we could solve for C_D:

$$C_D = \frac{D}{qS} \tag{5.10}$$



• Figure 4. Drag on basic shapes with laminar flow[9]

Procedure

Follow these steps to determine the variation of drag with dynamic pressure:

1) Apply AC power to the control computer of the Educational Wind Tunnel (EWT). Let the electronics "warm up" for at least 30 minutes before operating the wind tunnel.
2) Record the barometric pressure and the room temperature.
3) Measure the diameter of each object. This will be our representative length, ℓ.
4) Install the flat disk model on the mini-sting force balance in the test section. Do not over-tighten the set screw!
5) Hit the button to "zero out" the balance readouts for velocity, normal force, axial force, and pitching moment.
6) After clearing the area immediately in front of the inlet and behind the exhaust, turn on the VFD (variable frequency drive) of the motor controller. By using the slider control, bring up the tunnel speed manually to 60% speed.
7) Let the flow through the test section stabilize and make a reading of the axial force on the model. Do your best to get an "eyeball average" from the digital display. This will be your drag measurement (in lbs).
8) Repeat step 7) in speed increments of 10%, up to 100% (or maximum speed).
9) Repeat steps 4) through 8) for the cup, the smooth sphere, and the "tripped" sphere models.

[9] 3D shapes are shown on the left half of the figure, and 2D shapes are shown on the right

Data Reduction

Your data reduction should involve the following calculations:

1) Calculate the reference area, S, for the models. Use the cross-sectional (or frontal) area for this area.
2) Calculate the air density in slug/ft³.
3) Tabulate your raw data for each model: the model geometry, the indicated test section velocity, and the measured drag.
4) Tabulate your calculated data for each model: the true test section velocity, the dynamic pressure, and the Reynolds number based on ℓ. You may combine the two data tables.
5) For the disk and cup models, make a separate plot of D as a function of q using the proper units. For the smooth and tripped spheres, put both models on the same plot. Fit an appropriate trendline or curvefit through your data and force it to pass through $(0,0)$ (What is the most appropriate trendline for this relationship, theoretically?). Make sure you print out the value of the slope on your plot. The value of the slope for this curvefit is equal to the product of the area and the averaged drag coefficient for the model, $\bar{C}_D \cdot S$. Using your plots, determine $\bar{C}_D$ for each model. You should review the graphics conventions to ensure your plots are properly formatted.
6) Make a table comparing the averaged drag coefficients for each model. Present the data in two ways: as a value of $\bar{C}_D$ and as a percentage of $\bar{C}_{D_{disk}}$. Compare both of these with the benchmark values presented in Figure 4; calculate the percent deviation from the benchmark where possible.

Deliverables

Although the data were gathered in teams, each write-up must be done and submitted on an individual basis. You must hand in a formal **RESULTS** write-up for this experiment, which must include the following:

- The plots required. You should present the plots within the text of your write-up.
- A final $\bar{C}_D$ data table containing the comparisons. Place this within the text of your write-up.
- Raw and calculated data tables should be appended as an appendix. This may be your hand-written results from the day of the experiment. Note that your data is effectively presented in the plots, so duplicate data tables aren't necessary unless you're going to point out the numbers.
- A sample calculation for one data point, appended as an appendix. This should match your graphical results, and may be hand-written as well.
- In the discussion of your results, you should focus on the following (broken up roughly into paragraphs):
- What measurements were made? Make reference to your data tables (even if they're in the appendices). What is presented? How did you arrive at those numbers?
- Make reference to and discuss the meaning of your plots. What is presented? What trends are observed? Why do the different shapes have different drag coefficients? By the values of the Reynolds numbers, what type of flow might you expect over these objects?
- Which shape has the highest drag coefficient? Why?
- Which shape has the lowest drag coefficient? Why?
- What is the effect of putting a wire loop on the front of the sphere? Why? Is there any significance of the range of Reynolds numbers tested?

- Your discussion of the drag coefficients should involve the relative balance between the two contributions of drag discussed in class.
- Can you estimate the <u>precision</u> of your velocity and drag measurements? In other words, how much were the measurements varying when you did your "eyeball average?" What affect does this have on the final $\bar{C}_D$ numbers?

• Table 4. Raw data table for drag coefficient experiment

Date & Time: _____ Barometric Pressure: _____

Reference Area: _____ Room Temperature: _____

Data Point No.	Model Installed	Motor Power (percent)	Indicated Speed (mph)	Drag (lbs)	True Speed (fps)	q (psf)	Reynolds Number
1	Flat Disk	0	0	0	0	0	0
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

Laboratory

6

Spheres in Freefall
Aerodynamic Drag and the Ballistic Parameter

Introduction

In the application of Newtonian mechanics, an object's displacement, velocity, and acceleration are derived under the assumption of zero aerodynamic force. In other words, only inertial and gravitational forces are considered. This assumption is the basis for the conclusion that two objects of dissimilar mass will fall at the same rate because the acceleration due to gravity is the same for both. However, this assumption is only true (in practice) if the objects are falling in a vacuum. In reality, all objects experience additional deceleration due to the action of aerodynamic resistance, otherwise known as drag.

The measurement of aerodynamic drag is crucial in predicting aircraft performance. For example, the amount of drag must be compensated by the thrust provided by the aircraft propulsion system. The drag produced by an object will be a function of its geometry and the flow properties around it. Some shapes have a tendency to produce low drag (making them suitable for use on aircraft flight surfaces) and some have a tendency to produce high drag (making them appropriate for application as aerodynamic decelerators). To understand the drag of basic shapes, this exercise will focus on dropping spherical objects having diverse sizes and weights. Some of the objects considered will be ping pong balls, golf balls, baseballs, tennis balls, street hockey balls, playground balls, and the like. The overall drag characteristics for these objects will be evaluated by estimating the ballistic parameter from the time of freefall. These tests will be performed in a location such as the north stairwell in Maury Hall.

The Drag Coefficient

The Buckingham Pi Theorem can be used to perform a dimensional analysis on the calculation of aerodynamic drag.[10] This method reveals that the drag is directly proportional to the dynamic pressure, q, and the representative area, S. As such, the equation for the calculation of drag can be written as:

$$D = C_D \, q \, S = C_D \frac{1}{2} \rho V^2 S \tag{6.1}$$

In equation (6.1), the combined constant of proportionality is called the drag coefficient and is written as C_D. It is a dimensionless number. For a sphere, the value of the drag coefficient will be between 0.25 and 1, with the specific value depending upon the Reynolds number based on the diameter of the sphere, Re_D. The representative area used for blunt bodies is the cross sectional area.

Terminal Velocity and the Ballistic Parameter

An object in freefall can be represented as a free body diagram with two opposing forces in the vertical direction. Weight acts in the direction of travel (down) and the aerodynamic drag acts opposite to it (up). The summation of forces is thus:

$$\sum F_y = ma = W - D \tag{6.2}$$

When the body achieves equilibrium, the acceleration goes to zero. This means the object has achieved its *terminal velocity* and equation (6.2) leads directly to:

$$W = D = C_D \frac{1}{2} \rho V_{term}^2 \, S \tag{6.3}$$

[10] Refer to Section 5.3 in Introduction to Flight, by John D. Anderson.

where V_{term} represents the terminal velocity. Rearranging, this results in the following relation for the terminal velocity:

$$V_{term} = \sqrt{\frac{2(W/S)}{\rho C_D}} \tag{6.4}$$

Thus, the terminal velocity is a finite number that depends on the physical characteristics of the object (W, S, and C_D) and the flow properties (ρ). Within equation (6.4) is a grouping of terms that is collectively called the *ballistic parameter*. The ballistic parameter is represented by the equation:

$$\beta \equiv \frac{C_D S}{W} \tag{6.5}$$

With this definition, the terminal velocity is now expressed as a function of the fluid density and the object's ballistic parameter:

$$V_{term} = \sqrt{\frac{2}{\rho \beta}} \tag{6.6}$$

Procedure

Follow these steps to determine the value of the drag coefficient for the different spheres:

1) Record the room temperature and the day's barometric pressure.
2) Measure the height from which you will be dropping the balls.
3) Prior to each drop, measure the object's mass and diameter. You will be provided with a digital scale and a set of vernier calipers at the top of the drop site.
4) When signaled over the radio, drop the object from the pre-measured height. The radio operator down below will count it down as, "3…2…1…drop." Upon the word "drop," release the object. The stopwatch operator will also start the time keeping at the same time.
5) When the object strikes the floor, the stopwatch operator will stop the time keeping. Then the data recorder will write down the time of freefall for that data point.
6) A person will then retrieve the object and take it back up to the top of the drop site.
7) Repeat steps 3) through 6) until at least 3 trials of each object are recorded.

NOTE: A suggested list of tasks involves 5 people manning permanent positions for the duration of the experiment. This is so that consistency can be maintained during the collection of the data. These positions are:

Lower Drop Station

Stopwatch Operator
Data Recorder (writes down all the data for the given data point)
Radio Operator (requests measurement data and performs the countdown)

Upper Drop Station

Dropper (releases the object on cue)
Radio Operator (relays the measurement data to the Data Recorder)

Team Responsibilities: These are handled by two-person teams

Selection of an object
Measuring the mass and diameter of the object
Retrieving the object and returning it to the upper station (you can meet the other person halfway up the stairwell).

Data Reduction

Your data reduction should involve the following calculations:

- Calculate the air density in kg/m³.
- For each object, calculate the average velocity of the drop by averaging all the data points for that object.
- Calculate V_{term} for each object. Assume that each object reaches equilibrium very quickly after the release point.
- Calculate β and C_D for each object.
- Calculate the Reynolds number, Re_d, for each object at terminal velocity.
- Plot V_{term} against β. Maintain the standard SI units.
- Average all the values of the drag coefficient for all objects dropped. Tabulate the minimum, maximum, average, and standard deviation for all the values of C_D.

Deliverables

You must hand in the following: a formal **CONCLUSIONS** write-up for this laboratory, including a graph and a completed data table (complete with sample calculations), and the answers to the following questions.

Questions

1) A Major League baseball has a regulation weight of 5 oz. and a circumference of 9 in. Calculate the ballistic parameter if the drag coefficient is measured to be 0.4. Calculate the terminal velocity of a baseball at Jacobs Field and at Coors Field.
2) A street hockey ball achieves a terminal velocity of 23.8 m/sec. It has a mass of 48.4 g and a diameter of 66mm. Calculate its drag coefficient and ballistic parameter if it's falling at sea level. Calculate the drag at the terminal velocity.
3) Calculate the velocity of an object using Newtonian mechanics (**HINT**: Assume it falls the same distance, but neglect the aerodynamic drag).
4) What would explain the trend you observe in the values of C_D for the different objects?
5) Does the golf ball have a drastically different value of C_D compared to the ping pong ball? Would you expect it to? Why or why not?

• Table 5. Raw data table for freefall experiment

Date & Time: _____ Barometric Pressure: _____

Drop Height: _____ Room Temperature: _____

Data Point No.	Object	Diameter (cm)	Mass (g)	Elapsed Time (sec)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
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24				
25				
26				
27				
28				
29				
30				
31				
32				
33				
34				
35				

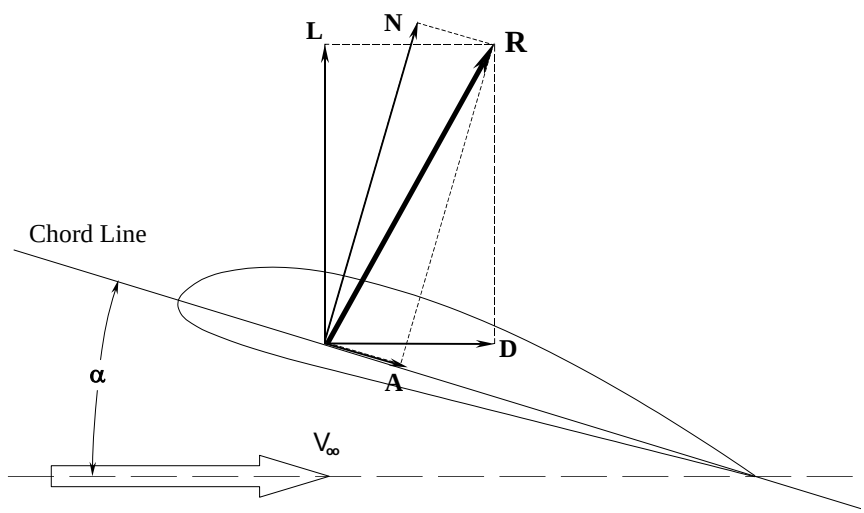
Laboratory

7

Airfoil Lift Determination
Observations of the Distribution of Pressure

Introduction

The imbalance of pressure forces over the upper and lower surfaces of a wing yields a net vertical force. This is mainly because the generation of lift creates lower pressures above the airfoil and higher pressures below. In this laboratory, we will explore how the distribution of pressure affects the airfoil lift. The results will reflect upon the importance of the leading edge region in the development of efficient lift.



• Figure 5. Forces acting on an airfoil

Airfoil Lift and the Lift Coefficient

Consider the airfoil section in Figure 5, where the angle of attack with respect to the incoming flow is labeled as α (also called AOA or the incidence angle). The freestream velocity is labeled as V_∞. The distribution of pressure around the airfoil yields a net resultant aerodynamic force; this force is labeled as R and it generally increases with α. The resultant force can be decomposed using two different orthogonal axis systems. The first of these is relative to the airfoil chord line, the imaginary line extending through the leading edge and the trailing edge. The force that is parallel to the chord line is known as the *axial force* and the perpendicular force is known as the *normal force*. These are labeled as A and N, respectively, in Figure 5.

The second orthogonal axis system is oriented with the incoming wind direction, also known as the relative wind vector. Using this system, a more convenient force decomposition involves the drag (D), which is <u>parallel</u> to the relative wind, and the lift (L), which is <u>perpendicular</u> to the relative wind. From trigonometry, we obtain the relationship between the two axis systems; we are presently concerned with only the lift. The lift equation becomes:

$$L = N\cos(\alpha) - A\sin(\alpha) \tag{7.1}$$

However, this relation can be simplified somewhat. In practice, the magnitude of N is much larger than the magnitude of A, with a ratio of anywhere from 60:1 to 130:1 over the range of this experiment. Combined with the fact that small airfoils can endure only relatively small incidence angles, perhaps only as high as 12° or so, we realize that the term $\cos(\alpha)$ is much larger than the term $\sin(\alpha)$. This leads to a fairly accurate approximation for the lift that can be easily obtained in a simple laboratory experiment using:

$$L \approx N\cos(\alpha) \tag{7.2}$$

Then, in order to calculate the lift coefficient, we need to divide the lift force by the freestream dynamic pressure, q_∞, and the wing planform area, S. If consistent units are chosen, the following equation will yield a *dimensionless* lift coefficient:

$$C_L = \frac{L}{q_\infty S} \approx \frac{N\cos(\alpha)}{q_\infty S} = C_N \cos(\alpha) \tag{7.3}$$

It can be seen that the lift coefficient depends on the so-called normal force coefficient, C_N. However, for an infinite wing, lower-case subscripts are used to designate two-dimensional section characteristics. Thus for this experiment:

$$C_\ell \approx C_n \cos(\alpha) \tag{7.4}$$

Normal Force Coefficient

Thus, to calculate the lift coefficient, we require the lift force. And to calculate the lift force, we require the normal force. Now all that is needed is an accurate measurement of the normal force, N. This can be an involved derivation, so only the principal results will be presented here. You should consult section 5.7 of your text (pp. 252-256) for more detail.

In essence, the increment to the perpendicular normal force is the difference of the pressure forces acting on differential areas on the lower and upper surfaces, respectively. The pressure force on lower surface acts in the positive direction and the pressure force on the upper surface acts in the negative direction. This is written as:

$$dN = dF_L - dF_U = p_L(b \cdot dx) - p_U(b \cdot dx) \tag{7.5}$$

Note that p_L and p_U are the lower and upper surface pressures, respectively. The area these pressures are acting on is $b \cdot dx$, where b is the span of the airfoil section and dx is the chordwise increment. Simplifying, the equation then becomes:

$$dN = b(p_L - p_U)dx \tag{7.6}$$

Dividing by the dynamic pressure and the wing area results in the contribution to the normal force coefficient. In this instance, the rectangular wing area simply becomes the product of the chord and span ($S = cb$), such that:

$$dC_n = \frac{dN}{q_\infty S} = \frac{b(p_L - p_U)dx}{q_\infty cb} = \frac{(p_L - p_U)}{q_\infty} \cdot d\left(\frac{x}{c}\right) \tag{7.7}$$

But this can be simplified further when considering the definition of pressure coefficient:

$$C_p \equiv \frac{p - p_\infty}{q_\infty} \tag{7.8}$$

Equation (7.7) is simplified by subtracting and adding the freestream pressure, p_∞, and substituting equation (7.8):

$$dC_n = \frac{(p_L - p_\infty) - (p_U - p_\infty)}{q_\infty} \cdot d\left(\frac{x}{c}\right) = \left(C_{p_L} - C_{p_U}\right) \cdot d\left(\frac{x}{c}\right) \tag{7.9}$$

To get the total normal force coefficient over the entire airfoil (from the leading edge to the trailing edge), we must integrate over the chord length. This means the value of x/c goes from 0 to 1:

$$C_n = \int_0^1 \left(C_{p_L} - C_{p_U}\right) d\left(\frac{x}{c}\right) = \int_0^1 C_{p_L}\, d\left(\frac{x}{c}\right) - \int_0^1 C_{p_U}\, d\left(\frac{x}{c}\right) \tag{7.10}$$

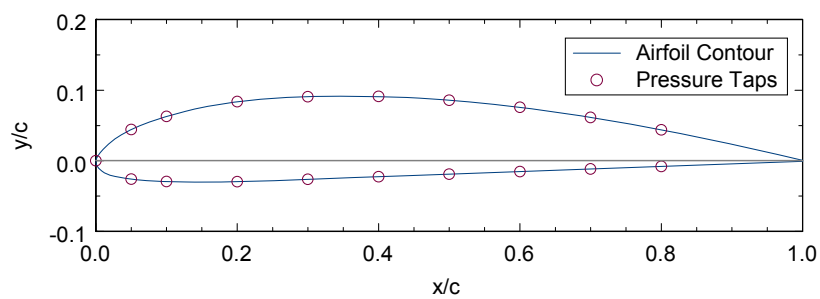
Therefore, we can get the normal force coefficient by *integrating* the plot of $C_{p_L} - C_{p_U}$ as a function of x/c. Or, more easily, we can get the area between the C_{p_L} and C_{p_U} curves. Unit cancellation shows us that if we use the dimensionless quantities for C_p and x/c, then the coefficient C_n will also be dimensionless.

The Clark-Y14 Airfoil

The airfoil used in this laboratory is one of the earliest airfoil designs, the Clark-Y14. The Clark-Y14 is a cambered airfoil with a maximum deviation from the chord line of 4.6% of the chord length. The thickness-to-chord ratio is about 0.14. These parameters are summarized in Table 7. Figure 6 shows the airfoil contour on a dimensional plot. Note how the mean line between the upper and lower surfaces is curved, with a maximum deviation of about 0.16" from the chord line.

• Table 7. Geometry details of the Clark-Y14 airfoil

Chord (inches)	3.50
Span (inches)	10.75
Thickness	14.0%
Camber	4.6%



• Figure 6. Clark-Y14 airfoil contour and pressure tap locations

The Inclined Manometer Bank

Also depicted in Figure 6 are the locations of the surface pressure taps, from which the airfoil pressure distribution will be measured. There are 18 pressure taps that are connected to a manometer bank with flexible tubing; the dimensionless coordinates of these pressure taps are listed in Table 8. The manometer bank is shown in Figure 7. Through the flexible plastic tubing, the surface pressures will be transmitted to the bank for ease of measurement. **YOU MUST PAY ATTENTION TO UNITS IN THIS EXPERIMENT**, because the manometer bank is *inclined* at an angle of 30° and thus measures a "skewed" pressure difference. In order to get a true vertical column of fluid (and thus an accurate pressure measurement), we have to apply the equation:

$$\Delta h = \Delta l \cdot \sin(30) = 0.50 \cdot \Delta l \tag{7.11}$$

• Table 8. Surface pressure tap locations

x/c	Upper Surface		Lower Surface	
	No.	y/c	No.	y/c
0.00	1	0.0000	1	0.0000
0.05	2	0.0443	3	-0.0261
0.10	4	0.0630	5	-0.0294
0.20	6	0.0839	7	-0.0297
0.30	8	0.0907	9	-0.0263
0.40	10	0.0912	11	-0.0226
0.50	12	0.0859	13	-0.0190
0.60	14	0.0758	15	-0.0153
0.70	16	0.0614	17	-0.0116
0.80	18	0.0439	19	-0.0079

In equation (7.11), Δl is the length of the *inclined* manometer column and Δh is the vertical height difference. Furthermore, the fluid in the manometer tubes is not water, but alcohol. The alcohol used has a specific gravity of 0.811, so this must be factored into the equation:

$$\Delta h_{water} = \Delta h_{alcohol} \cdot 0.811 = \left(0.50 \cdot \Delta l_{alcohol}\right) \cdot 0.811 \tag{7.12}$$

Thus we can convert the pressure measurements from units of inches alcohol to units of inches H_2O. Now Δh, which is really a pressure measurement, can be converted to the units required for the data reduction (NOTE: 1 atmosphere=406.78 inches H_2O).

However, the manometer bank is actually showing you the <u>gauge</u> pressure, not the <u>absolute</u> pressure on the airfoil surface. It is called gauge pressure because it is referenced to the atmospheric pressure, and is written as **psig** (lbs/in², gauge). This is in contrast to **psia** (lbs/in², absolute). Since the reservoir of the manometer bank is open to atmospheric pressure, the pressure indicated will be the gauge pressure. So instead of indicating p_L and p_U, it is really indicating $p_L - p_{atm}$ and $p_U - p_{atm}$. You must take this into consideration when calculating surface pressures and pressure coefficient values. To get the pressures in absolute terms (psia), convert the Δh value from in. H_2O to lbs/in² and then add the atmospheric pressure (in lbs/in²) for each data point:

$$p = \Delta h_{water} \cdot \left(\frac{14.7 \quad psi}{407 \quad "H_2O}\right) + p_{atm} \tag{7.13}$$

Helpful Note: The tops of the manometer tubes are connected to the surface pressure taps and the bottoms are plumbed into the fluid reservoir. Therefore, a <u>positive</u> deflection in the fluid column actually represents a <u>negative</u> gauge pressure, $p - p_{atm}$.

Procedure

Follow these steps to operate the 12x12" Aerolab Educational Wind Tunnel #1 for this laboratory:

1) Apply AC power to the control computer of the Educational Wind Tunnel (EWT). Let the electronics "warm up" for at least 30 minutes before operating the wind tunnel.
2) Record the barometric pressure and the room temperature.
3) Check the manometer bank to ensure that all tubes are reading zero with the air speed at zero.

4) Hit the button to “zero out” the balance readouts for velocity, normal force, axial force, and pitching moment. You will only be using the computer to set the velocity in the test section.

5) After clearing the area immediately in front of the inlet and behind the exhaust, turn on the VFD (variable frequency drive) of the motor controller. By using the slider control, bring up the tunnel speed manually to 50% speed. Under the “Setpoint” window, type in 80 mph and enable the automatic speed control by clicking the “Auto Control” button.

6) Adjust the airfoil section to zero degrees AOA. When the airspeed stabilizes, record the height of the alcohol columns on the manometer bank for tubes 1-19. Record the height of the reference tube (labeled as “ R ” on the metal strip), which corresponds to the test section static pressure, p_∞. You should notice that most of the raw pressure data will be <u>negative</u>. Note that these pressures should be recorded in the units of “inches alcohol.” Use the table on page 16 as your datasheet.

7) Repeat steps 6-7 for AOA=5°, 10°, and 15°.

8) When complete, shut down the tunnel by disabling the auto control and reducing power to 0%. Turn off the VFD of the motor controller.

• Figure 7. Alcohol manometer bank

Data Reduction

The data reduction should involve the following calculations for all the wind tunnel tests run in your class section:

- Calculate the air density.
- Convert the pressures from inches alcohol (gauge) to lbs/in² (absolute).
- To calculate the test section dynamic pressure, don't use the displayed test section velocity because it's not the true value. Instead, take the reference pressure and multiply by the following correction factor:

$$q_\infty = 0.965\left(p_{atm} - p_\infty\right)$$

- Calculate the pressure coefficients C_{p_L} and C_{p_U} from the leading edge to the trailing edge.
- For each angle tested, plot C_{p_L} and C_{p_U} against x/c on the same graph. To close up your graph, set the pressure at the trailing edge equal to the reference pressure (i.e. where x/c = 1.00, C_p = 0.00). Remember that this reference pressure is actually the test section static pressure.
- At each AOA tested, calculate the value of the normal force coefficient by determining the area between the curves. You may use the data values to calculate individual trapezoidal areas, or you may plot the data on a grid and count the number of blocks bounded by the two curves. Whichever method you chose, you must show all your work!
- At each AOA tested, calculate the value of C_n and C_ℓ. Tabulate these values.
- Compare your values with the following 2D theoretical results[11] for the Clark-Y14. These results were generated at a Reynolds number of 220,000 and a Mach number of 0.1:

- Table 9. Theoretical results for a Clark-Y14 airfoil section

α (deg)	C_ℓ
-5	-0.127
0	0.541
5	0.997
10	1.413
15	1.497

Deliverables

Although the data were gathered in teams, each write-up must be done and submitted on an individual basis. You must hand in the following deliverables to complete this laboratory:

- A formal **CONCLUSIONS** write-up for this experiment. This should be between one and three brief paragraphs in length. Remember that is should be a brief summary of what might go into a full-blown results section. Some items to consider:
- Is the method an effective experimental exercise? Why or why not?

[11] These results were obtained using the XFOIL code compiled for Microsoft Windows.

- What was the minimum percent error? What are some factors that might have affected your results?
- Can you isolate a region along the airfoil chord that is primarily responsible for the generation of lift? What is the range of x/c values?
- What was the Reynolds Number for your airfoil test? Use the chord length as the representative length in the calculation. How might this influence the flow over the Clark-Y14 airfoil?
- An appendix with your raw data table
- Plots of C_p (both upper and lower) as functions of x/c for each AOA
- A table of C_n and C_ℓ values for each AOA, and percent error from the theoretical 2D results
- Sample calculations for your data that are used to obtain your results

• Table 10. Raw data table for pressure distribution experiment

Date & Time: _____ Barometric Pressure: _____

Test Section Airspeed: _____ Room Temperature: _____

Port No.	x/c	Manometer Column Readings,[12] $\Delta\ell$ (inches alcohol)			
		α_1 =	α_2 =	α_3 =	α_4 =
R					
1	0.00				
2	0.05				
3	0.05				
4	0.10				
5	0.10				
6	0.20				
7	0.20				
8	0.30				
9	0.30				
10	0.40				
11	0.40				
12	0.50				
13	0.50				
14	0.60				
15	0.60				
16	0.70				
17	0.70				
18	0.80				
19	0.80				
"20"[13]	1.00				

[12] **NOTE**: All manometer readings should be negative.
[13] There is no pressure port at the trailing edge; this pressure is assumed to be the same as "**R**."

Laboratory

8

Flow Visualization I: Smoke Tunnel
Circulation and High-Lift Aerodynamics

Introduction

This laboratory exercise provides a physical picture of the flowfield patterns around various airfoil sections. The models include the high-lift devices of a trailing-edge flap, a boundary layer suction system, and a blown boundary layer airfoil. Lastly, the effects of circulation can be visualized around a rotating circular cylinder.

Circulation Theory

The Kutta-Joukowsky theorem introduces the theoretical concept of circulation, which is defined by Γ. This theorem has physical implications in the lift-per-unit-span of a wing section and can be implemented as:

$$\frac{L}{b} = \rho_\infty V_\infty \Gamma \tag{8.1}$$

In other words, the lift produced by a 2D airfoil section is directly proportional to the circulation around it. Thus, increasing the circulation will produce an increased lift. Circulation can be produced by rotation of a cylinder or a sphere, or it can be enhanced by changing the shape of the lifting surface (i.e., camber or thickness). This concept can be *physically* seen in the various high-lift devices analyzed in this experiment.

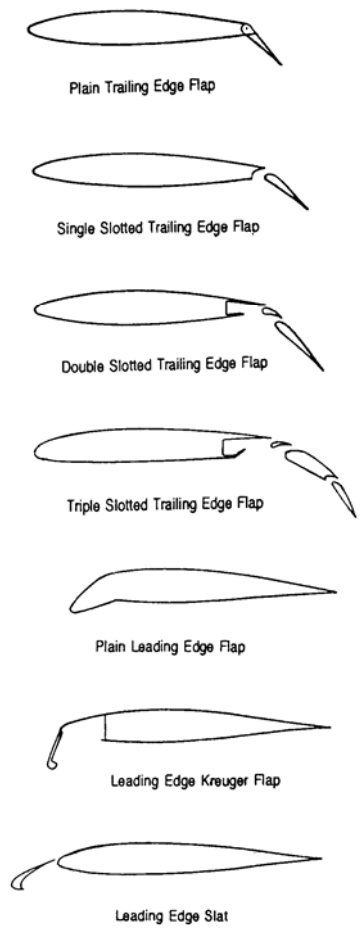
High Lift Devices and Aerodynamic Effects

In general there are three techniques for increasing the lift on an airfoil: camber line changes, area changes and boundary layer control. The various devices which implement these techniques are shown in Figure 8.

Thin airfoil theory shows that both lift and pitching moment increase with increasing airfoil camber. Trailing edge flaps and leading edge flaps use camber line changes to increase airfoil lift. Deflection of a flap increases the effective camber of the airfoil section, thus increasing the lift coefficient at a given angle of attack. Large increases in drag and pitching moment (nose down) about the aerodynamic center along with lower angles of zero lift are observed. The effects of various flap geometries are shown in Figure 9, and these configurations represent a flap that is 25% of the chord deflected at 30°.

Extendable leading edge slats and trailing edge slotted flaps are used to increase the effective airfoil/wing area. However, the airfoil/wing coefficients are still based on the original wing planform area, so large increases in lift coefficient result. Maximum lift coefficients exceeding 3.5 are possible for high lift wing configurations when considering the 2D sectional characteristics.

However, slats and slotted flaps have another, more important effect: delaying the separation of the boundary layer on the upper surface of the airfoil. In so doing, the airfoil section very effectively reaches higher angles of attack and the resultant increases in the maximum lift coefficient. A fixed slat operates the same as a slot but is different geometrically because it is a small airfoil ahead of the leading edge whereas slots are actually cut through an airfoil. In both cases high pressure air from the lower surface is accelerated through a diverging passage and is directed tangential to the upper surface of the airfoil to increase the momentum in the boundary layer. The effect is to delay upper surface separation until a higher angle of attack is reached. This increases α_{stall} and $C_{L_{\max}}$ without changing either α_{L_0} or $C_{M_{AC}}$. If a downward movement of the slat is also used, the effective camber is increased with a small increase in drag and an α_{L_0} shift. A similar effect is used with slotted trailing edge flaps.



• Figure 8. Typical wing high lift devices

Area boundary layer control is also used to either suck the low energy lower regions of the boundary layer off the airfoil surface or to re-energize these layers by actively blowing air tangential to the surface. The result is the same: delayed boundary layer separation and higher airfoil lift. These effects will be very similar to those of the slot or slat. These observations of the effects of boundary layer control are summarized in Figure 10, and may include leading edge slats or boundary layer suction. In general, wing flaps are capable of producing a greater increase in $C_{L_{max}}$ than slats or slots. Used together the effects are additive.

Procedure

Follow these steps to determine the variation of dynamic pressure with velocity:

1) Form up into teams of two or three. Read through the questions at the end so you are prepared to explore the answers.

2) Follow the instructions and precautions of the technician in operating the smoke tunnel and installing the models. Start the blower and turn on the test section lighting.

3) Start the "smoke" (the "smoke" is actually atomized water created by an ultrasonic water mister). The traces of streamlines should become immediately apparent in the tunnel. **NOTE: The ½" tubing connecting the "fog box" to the bottom of the rake in the inlet will occasionally fill up with condensed water. If this happens, simply disconnect it from the rake and drain it.**

4) Install the plain Clark-Y airfoil section. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns traced out by the smoke. Use the template drawings provided on pages 39-43. Pay

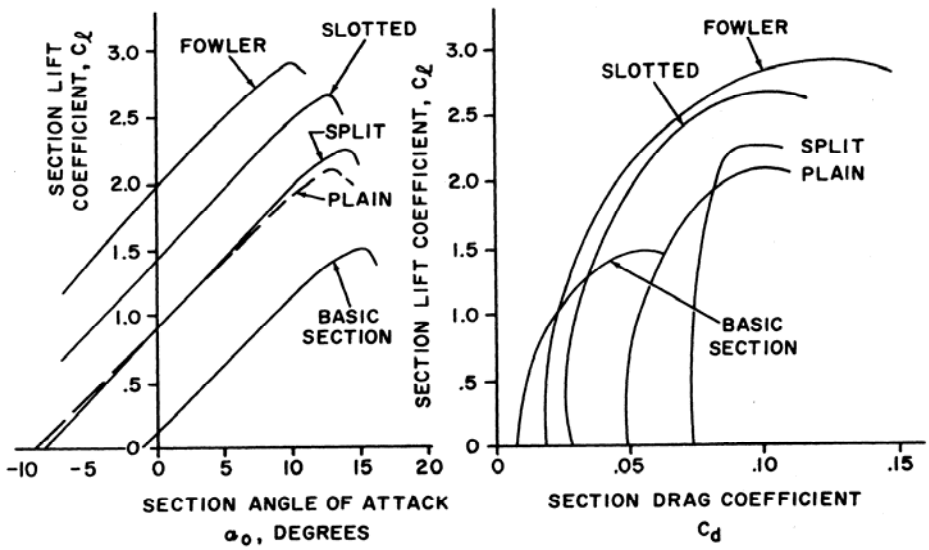
particular attention to the stagnation point and regions of flow separation (i.e., the wake). Label these on your sketches.

5) Install the flapped Clark-Y airfoil section and set a flap angle of approximately 30°. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns, as in step 4).

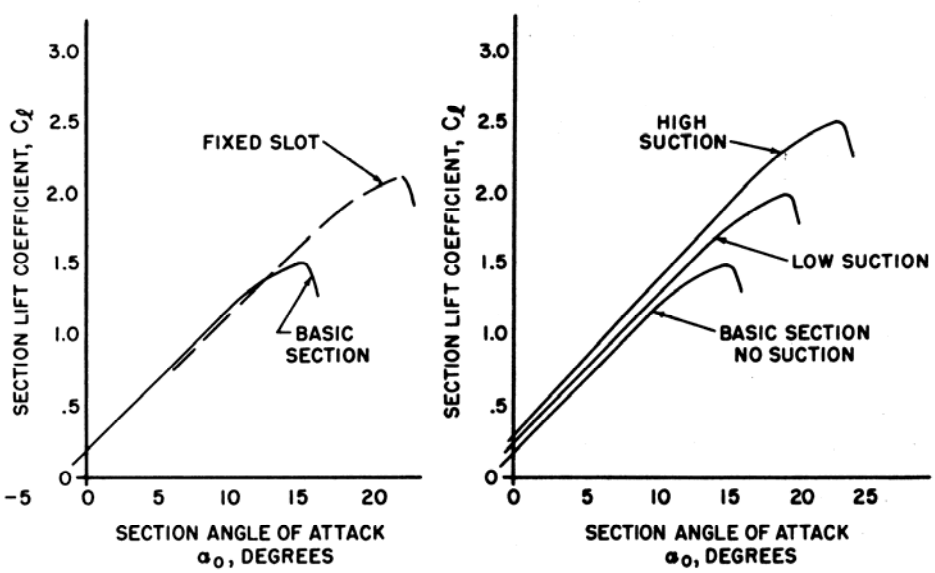
6) Install the boundary layer suction airfoil section and start the vacuum pump. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns, as in step 4).

7) Install the blown boundary layer airfoil section and start the air pump. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns, as in step 4).

8) Install the rotating circular cylinder section. Operate it at zero, low, and high rotation rates and sketch the flow patterns, as in step 4).



• Figure 9. Effects of various flap configurations



• Figure 10. Effects of boundary layer control on lift curve

Deliverables

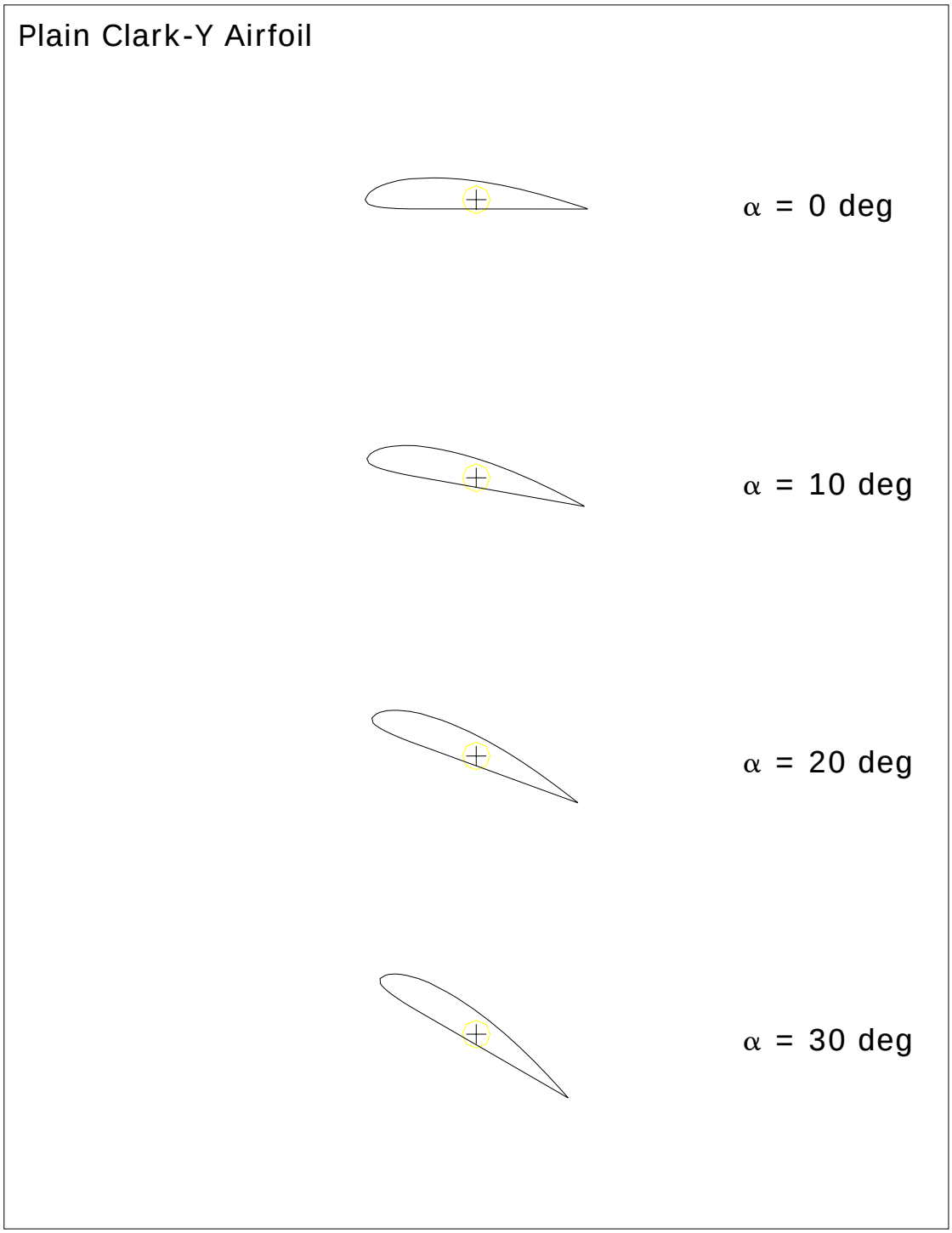
Although no formal write-up section is required for this laboratory exercise, you must hand in your annotated flowfield sketches and the answers to the following questions:

Questions

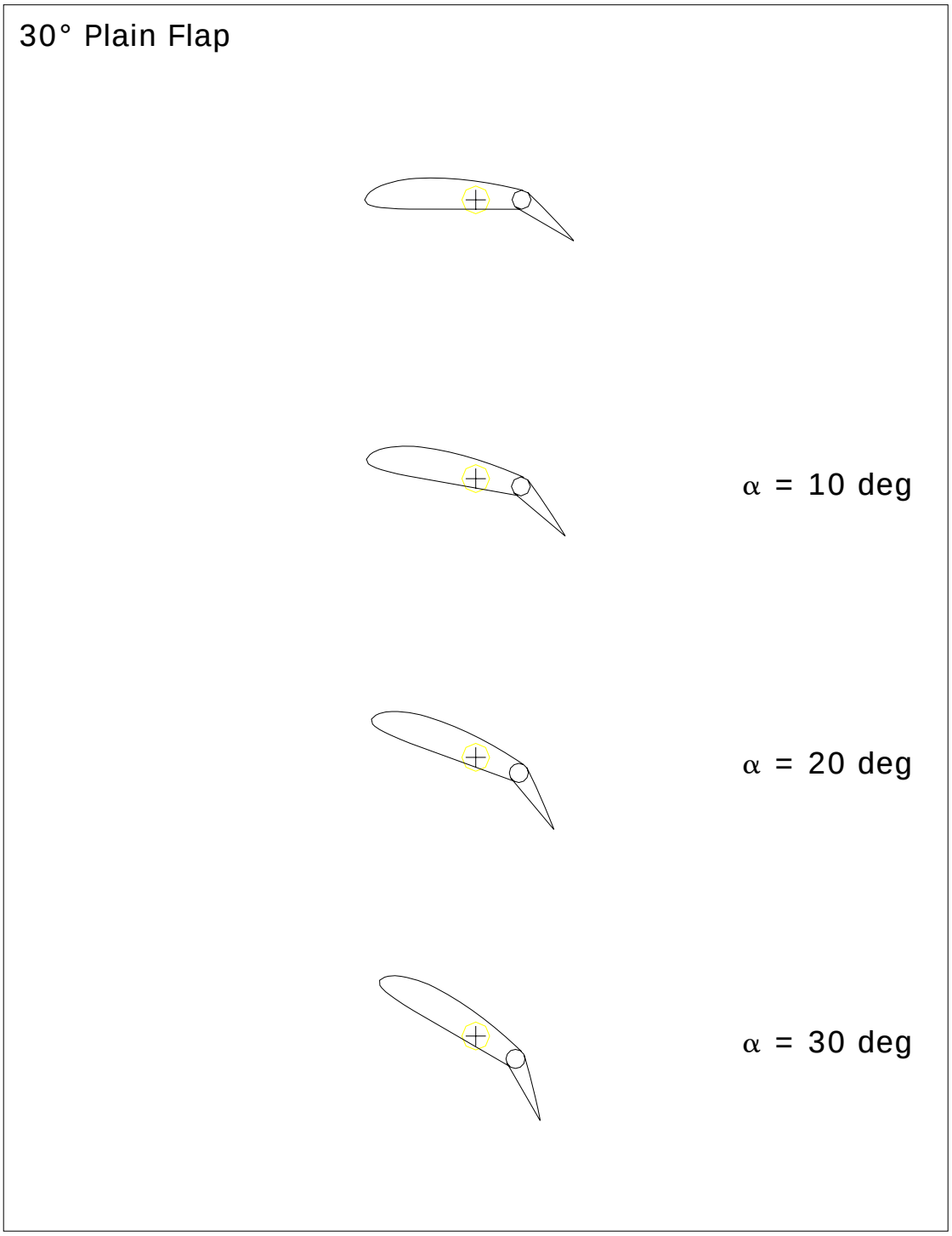
1) Do you observe stall phenomenon on the plain Clark-Y airfoil? What is the estimated stall angle? What about the flapped airfoil?

2) Do you observe stall phenomenon on the airfoil with boundary layer suction? What is the estimated stall angle? How does the wake change? What about the airfoil with boundary layer blowing?

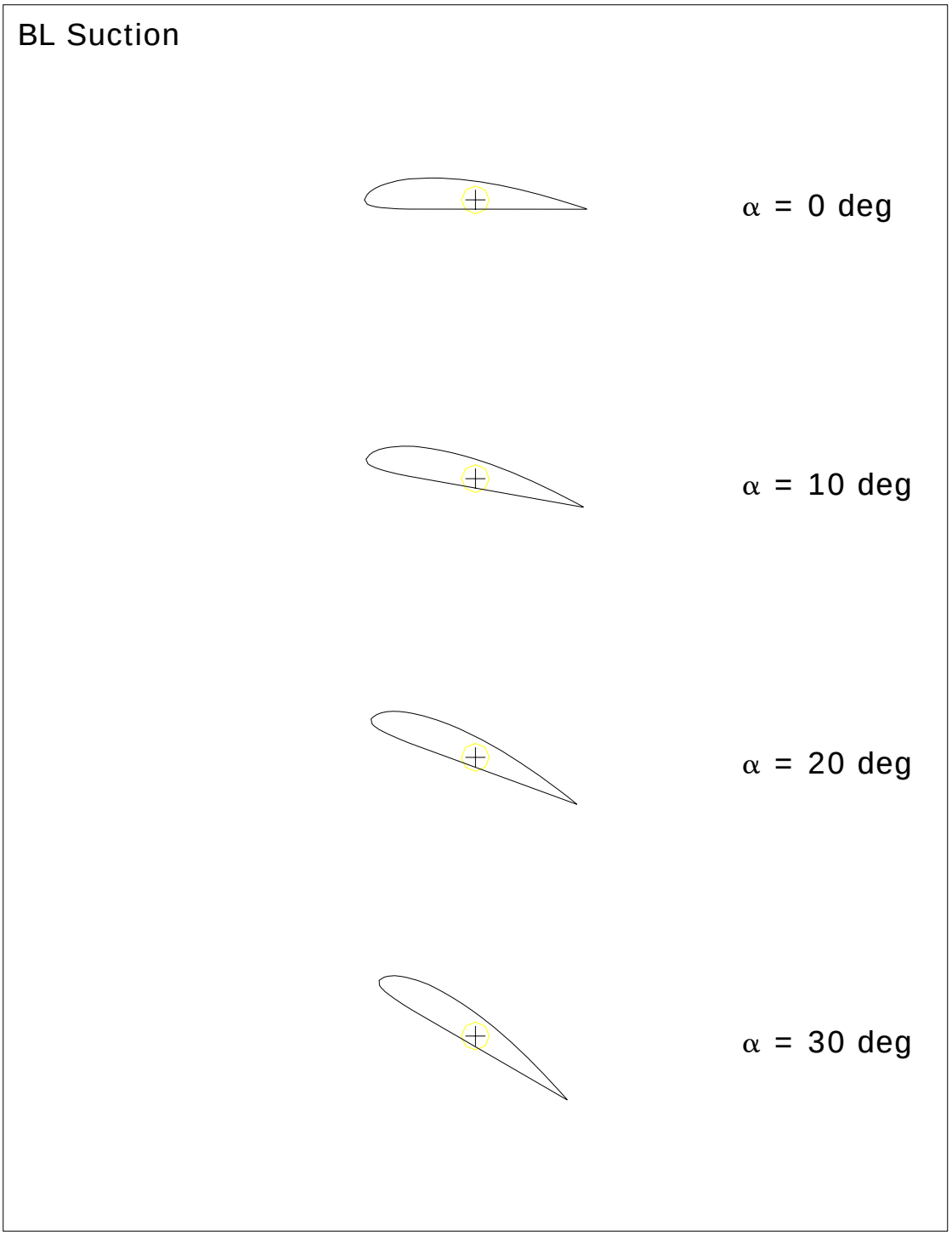
3) What does rotation do to the streamlines around the circular cylinder? What direction is the resultant force? What <u>conceptual</u> aerodynamic quantity is represented by this <u>physical</u> evidence?



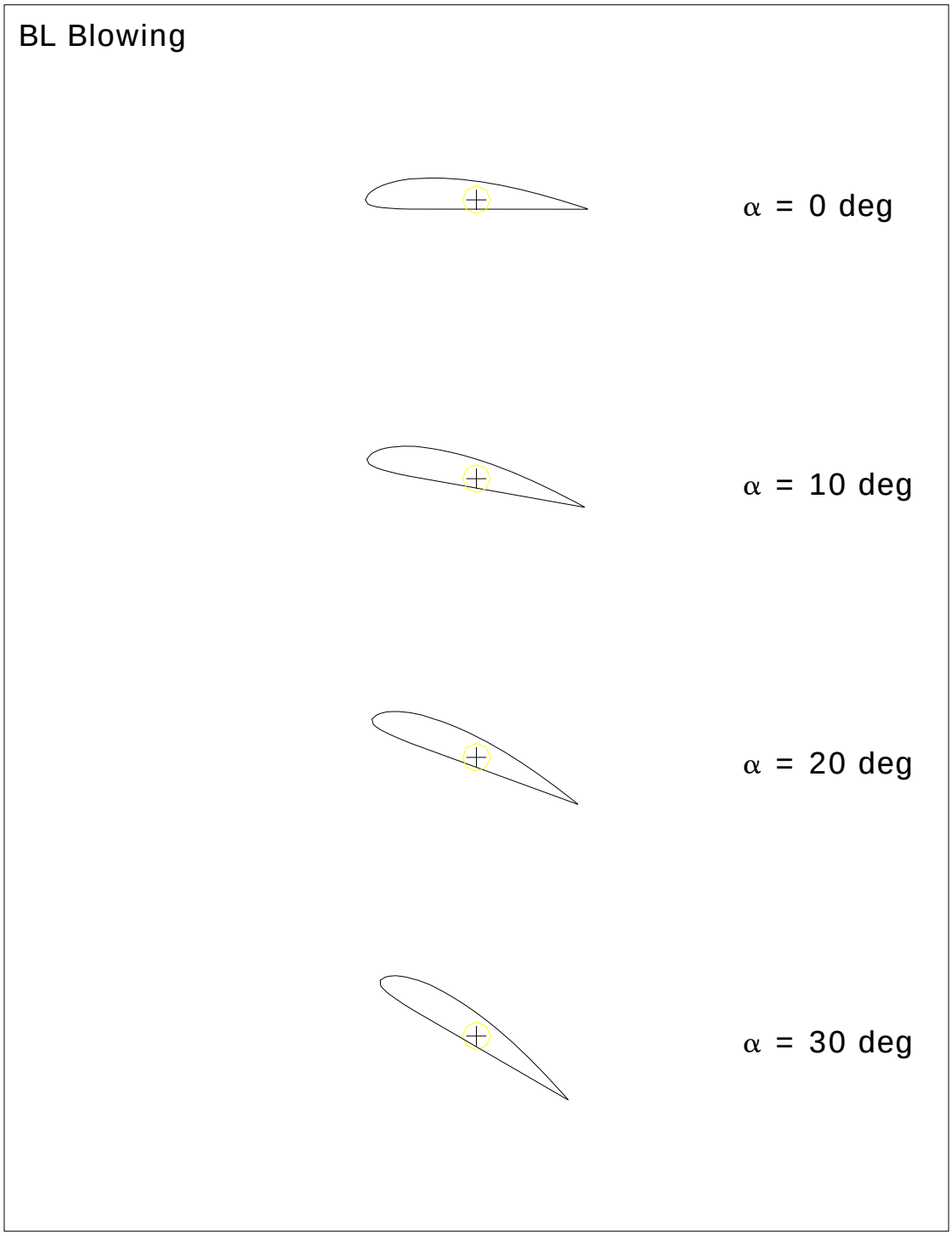
• Figure 11. Streamline patterns for the Clark-Y airfoil



• Figure 12. Streamline patterns for the Clark-Y airfoil with a plain flap



• Figure 13. Streamline patterns for the Clark-Y airfoil with boundary layer suction



• Figure 14. Streamline patterns for the Clark-Y airfoil with boundary layer blowing

• Figure 15. Streamline patterns for a circular cylinder

Laboratory

9

Flow Visualization II: Water Tunnel
Delta Wing Aerodynamics

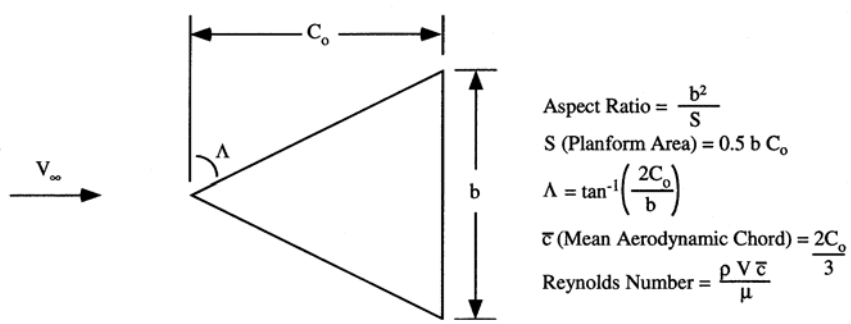
Introduction

This laboratory exercise provides a physical picture of the flowfield patterns around a sharp-edged delta wing with a leading edge sweep angle of 65°. The delta wing models an extreme example of a finite wing (aspect ratio of 1.87) and as such, clearly demonstrates the structure and function of wing tip vortices. These concepts have a direct application to the aerodynamic design of high-performance combat aircraft like the F/A-18.

The aerodynamics of delta wing planforms are significantly different from those associated with relatively straight, moderately swept wings usually designed for subsonic flight. The flowfield of slender, low aspect ratio wings, commonly called delta wings, are dominated by two leading edge vortices which form on the upper surface of the wing. The high axial velocities present at the core of these tight vortex structures produce a significant contribution.

Delta Wing Aerodynamics

The low aspect ratio highly swept triangle planform, commonly know as the "delta wing", originated with the designs of Alexander Lippisch in Germany during the 1940's. The delta wing was developed in an attempt to minimize some of the negative aspects associated with supersonic flight, most notably wave drag and compressibility effects. Some of the relevant delta wing geometric details are shown in Figure 16.



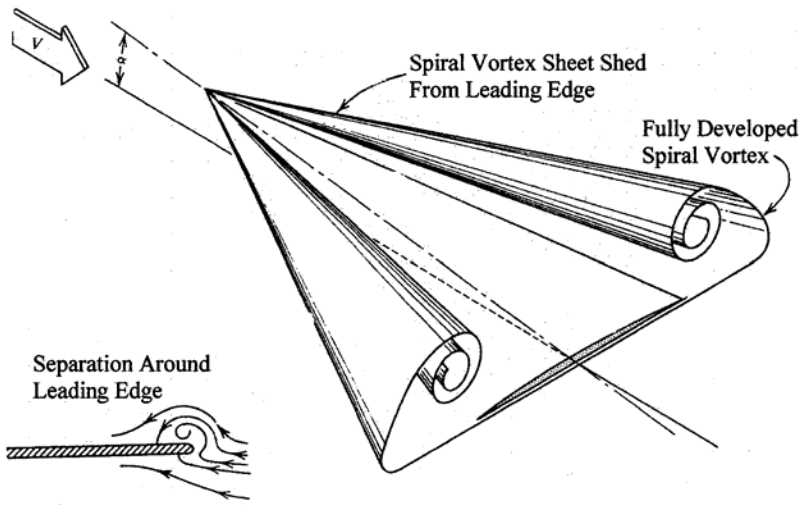
• Figure 16. Delta wing planform geometry description

Leading Edge Separated Flow

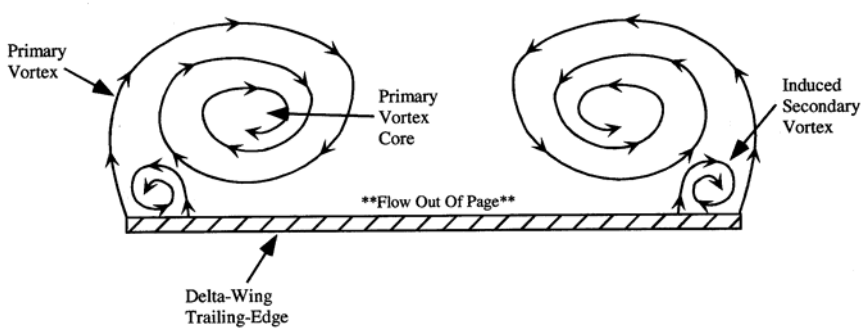
The most interesting aspect of the delta wing flowfield occurs independent of compressibility effects or Mach number. At moderate to high angles of attack (α = 5°-30°), flow separation occurs along the length of each of the leading edges, from the apex to the trailing edge. This separating shear layer (i.e., the viscous boundary layer away from the surface) results in two vortex sheets which roll up to form coherent vortices which stream aft along each leading edge. This flow characteristic is depicted in Figure 17.

For the delta wing at a positive AOA, the leading edge stagnation point lies on the lower surface of the planform. As the flow tries to negotiate the large pressure gradients associated with the sharp leading edge, it is unable to remain attached and separates from the upper surface. The separated free shear layer spirals around and reattaches to the upper surface some distance inboard of the leading edge. This roll-up occurs

along each leading edge of the planform and forms two coherent vortices, beginning at the apex of the delta. Smaller secondary vortices are also induced as a result of the primary vortex, as shown in Figure 18.



• Figure 17. Leading edge separated flow and vortex formation



• Figure 18. Leading edge vortex formation (looking upstream)

Vortex Bursting

Flow underneath the primary vortex encounters an adverse pressure gradient due to the strong rotation of the vortex. The induced adverse pressure gradient causes a secondary separation underneath the primary vortex which forms a secondary vortex whose rotation and vorticity are opposite to that of the primary vortex. The rotational velocities in the core of the primary vortices can be up to 3 times the free stream value. The high core rotational velocities (axial velocities) present in the primary vortex cores generate a low pressure on the upper surface of the planform, resulting in an additional lift force known as vortex lift. At high angles of attack the percentage of the total lift attributed to vortex lift can be upwards of 50%. The amount of vortex-induced lift increases with increasing AOA and is responsible for the nonlinear aerodynamic characteristics of a delta wing. However, it is this additional lift that enables high-AOA flight and maneuvering for high-performance combat aircraft.

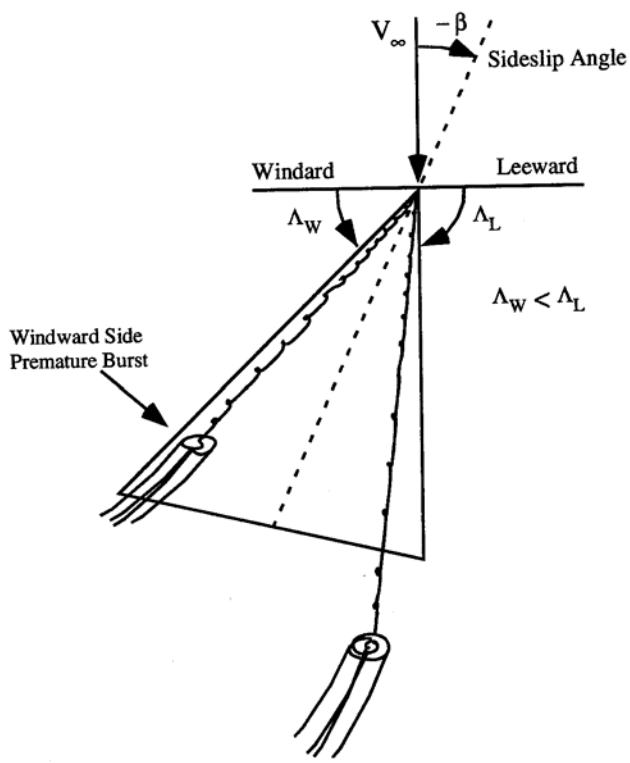
The study of vortex bursting has been an active field of research since the early 1960's. Bursting is a fundamental change in the vortex flowfield and is defined as a sudden enlargement of the vortex with an associated rapid reduction in core axial velocity. The once tightly wound, coherent vortex becomes a diffuse turbulent flow at a sufficient distance downstream of the apex, as depicted in Figure 19. If the bursting occurs over a lifting surface, the loss of the high axial core velocity results in a reduction of the vortex lift.

This reduction in lift due to the vortex bursting is analogous to a conventional wing stall due to flow separation.

There are two types of vortex bursting, a spiral type and a bubble type. At low AOA, the two primary vortices remain tightly wound and coherent from the planform apex to the trailing edge and burst somewhere aft, in the wake. As AOA increases, the burst point moves forward until reaching the trailing edge of the planform. Once the burst point reaches the trailing edge and begins to move up the body towards the apex, the delta wing is said to be undergoing stall. The movement of the vortex burst from trailing edge to apex proceeds rapidly with increasing AOA, and it slows down as the burst point nears the apex.

In addition to angle of attack effects, sideslip or yawing of the delta wing will also affect the vortex structure and burst dynamics. By yawing the planform, the side yawing into the oncoming flow “sees” a lower effective leading edge sweep angle and is termed the windward side. Conversely, the side yawing away from the oncoming flow sees a greater effective leading edge sweep and is termed the leeward side. For a given aspect ratio and AOA, the vortex burst point will move forward with decreasing leading edge sweep angle. As a result, the windward side vortex burst point will move toward the apex and the leeward burst point will move aft.

The vortices are a very useful and controllable source of lift through a large range of AOA, approximately 10° to 30°. Vortex lift provides significant maneuverability at high AOA to high performance fighter aircraft. However, these coherent, high energy, lift-producing vortices eventually undergo a breakdown called "bursting".



• Figure 19. Vortex burst modes on a yawed delta wing

The understanding of vortex burst dynamics and their behavior is of paramount importance to the designer of high performance military aircraft. Unfortunately, the burst process is highly nonlinear and no theoretical or analytical method currently exists for accurately predicting vortex breakdown on wings. Several empirical methods exist based on experimental data but none are generalized enough to accurately predict breakdown over an arbitrary design. The purpose of the delta wing experiment is to study and visualize these leading edge vortices, their behavior, dynamics and bursting through visualization.

Procedure

Follow these steps to determine the variation of dynamic pressure with velocity:

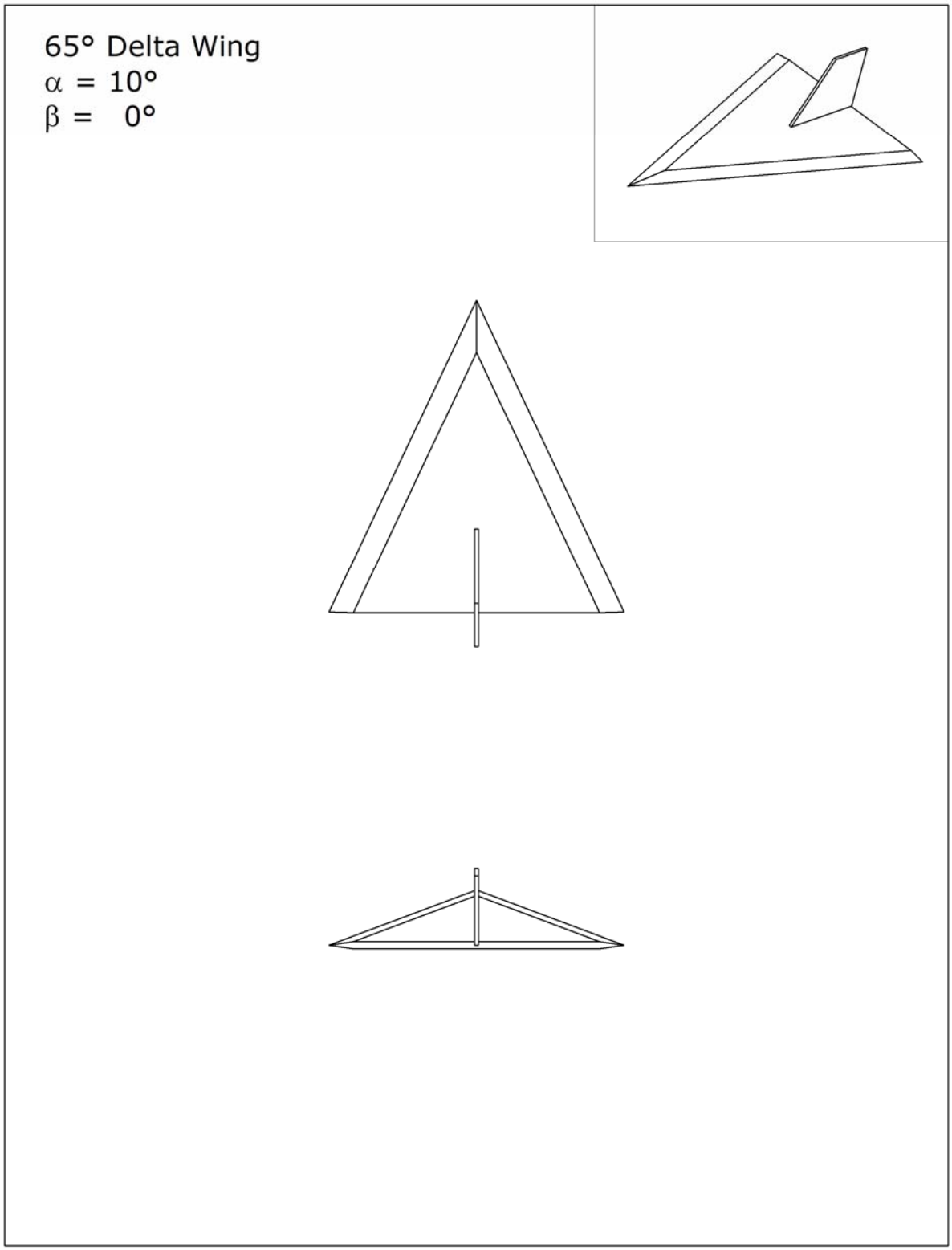
1) Form up into teams of two to four. Read through the questions at the end so you are prepared to explore the answers.
2) Follow the instructions and precautions of the technician in operating the water tunnel and positioning the model. Start the tunnel circulation pump.
3) Position the model at zero sideslip (yaw angle) and 10° AOA.
4) Make sure the air reservoir for the dye injection system is adequately pressurized and gradually open the dye lines until you see thin filaments of dye issuing out of the ports on the model surface. Sketch the flow patterns traced out by the dye streaks. Use the template drawings provided on pages 49-52. Pay particular attention to the symmetry and dimension of the vortices with respect to the model. Indicate the flow direction with arrows on your streamlines. Indicate the location of the vortex burst point.
5) Position the model to 20° AOA and repeat step 4).
6) Position the model to 30° AOA and repeat step 4).
7) Now position the model at a 10° sideslip angle and a 20° AOA and repeat step 4).

Deliverables

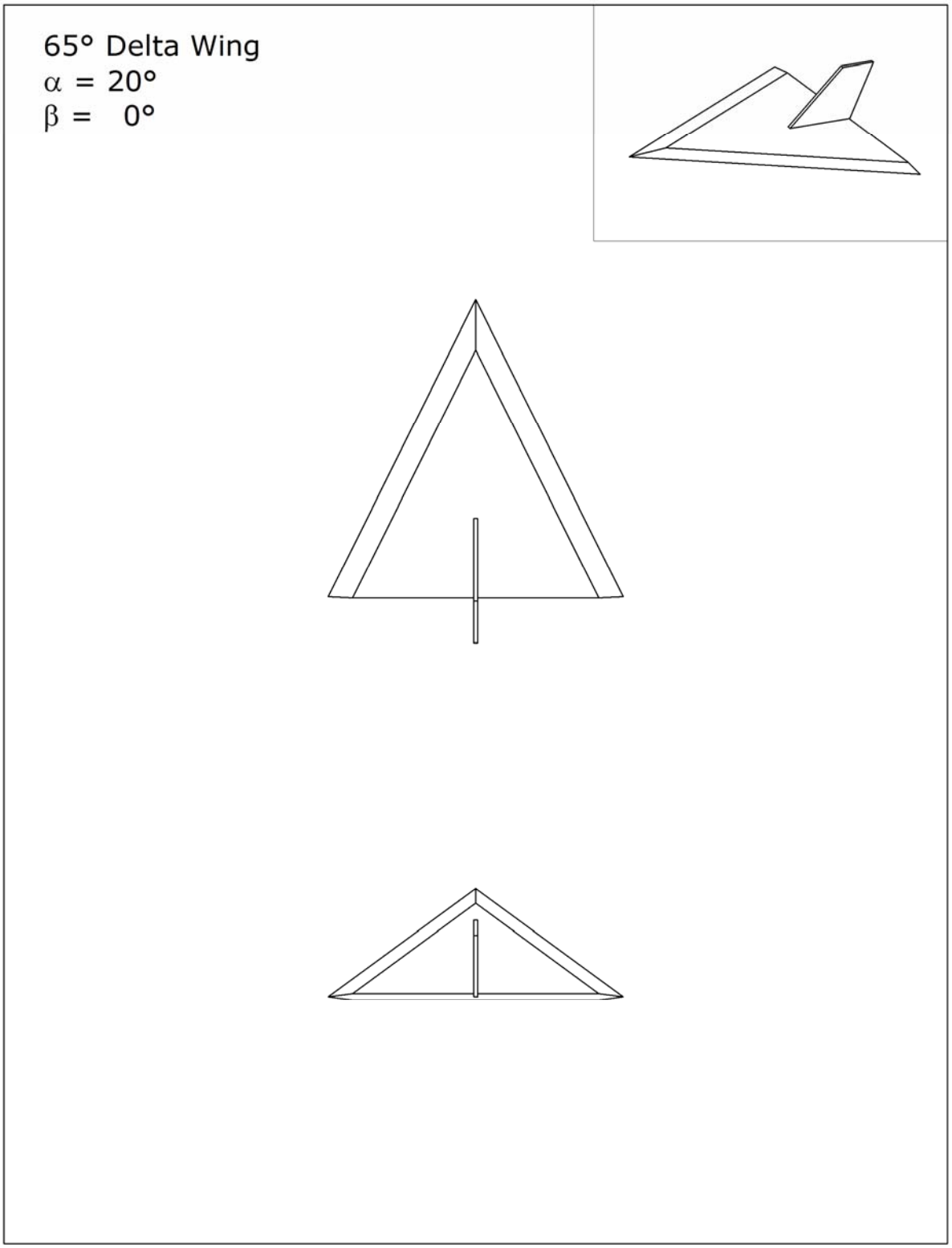
Although no formal write-up section is required for this laboratory exercise, you must hand in your annotated flowfield sketches and the answers to the following questions:

Questions

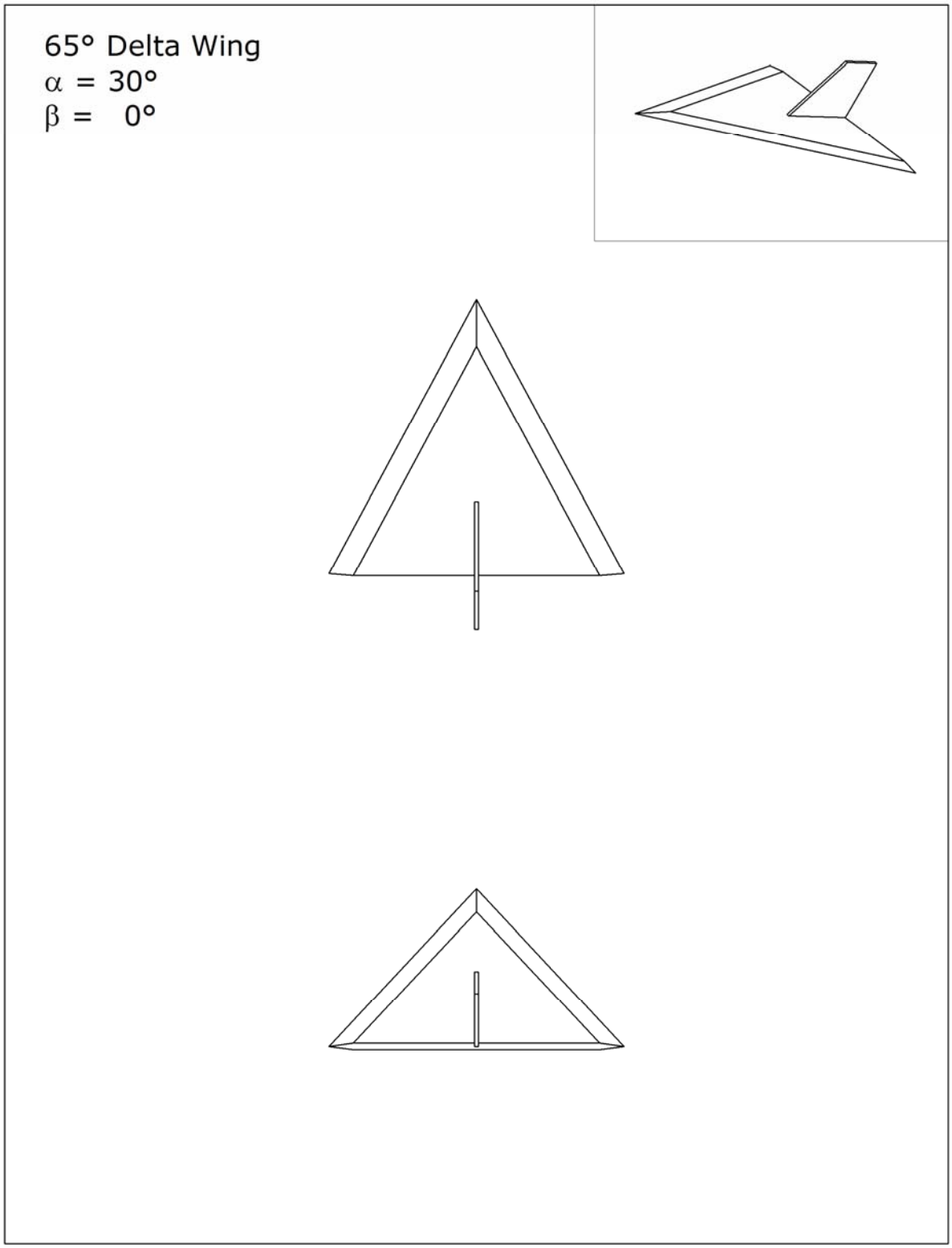
1) Under what conditions can water flow accurately model air flow?
2) What type of motion do the streamlines trace out?
3) If the delta wing is at an angle of attack, what must the wing be producing?
4) The motion of the streamlines, combined with the fact of question 3), is physical evidence of what conceptual aerodynamic phenomenon?
5) Does the wing stall? Explain. How is “stall” manifest in the streamlines?
6) At “stall,” what happens to the aerodynamic phenomenon from question 4)?
7) How does sideslip affect the streamlines?
8) What effect do the vortices have on the wake behind the delta wing at high AOA?



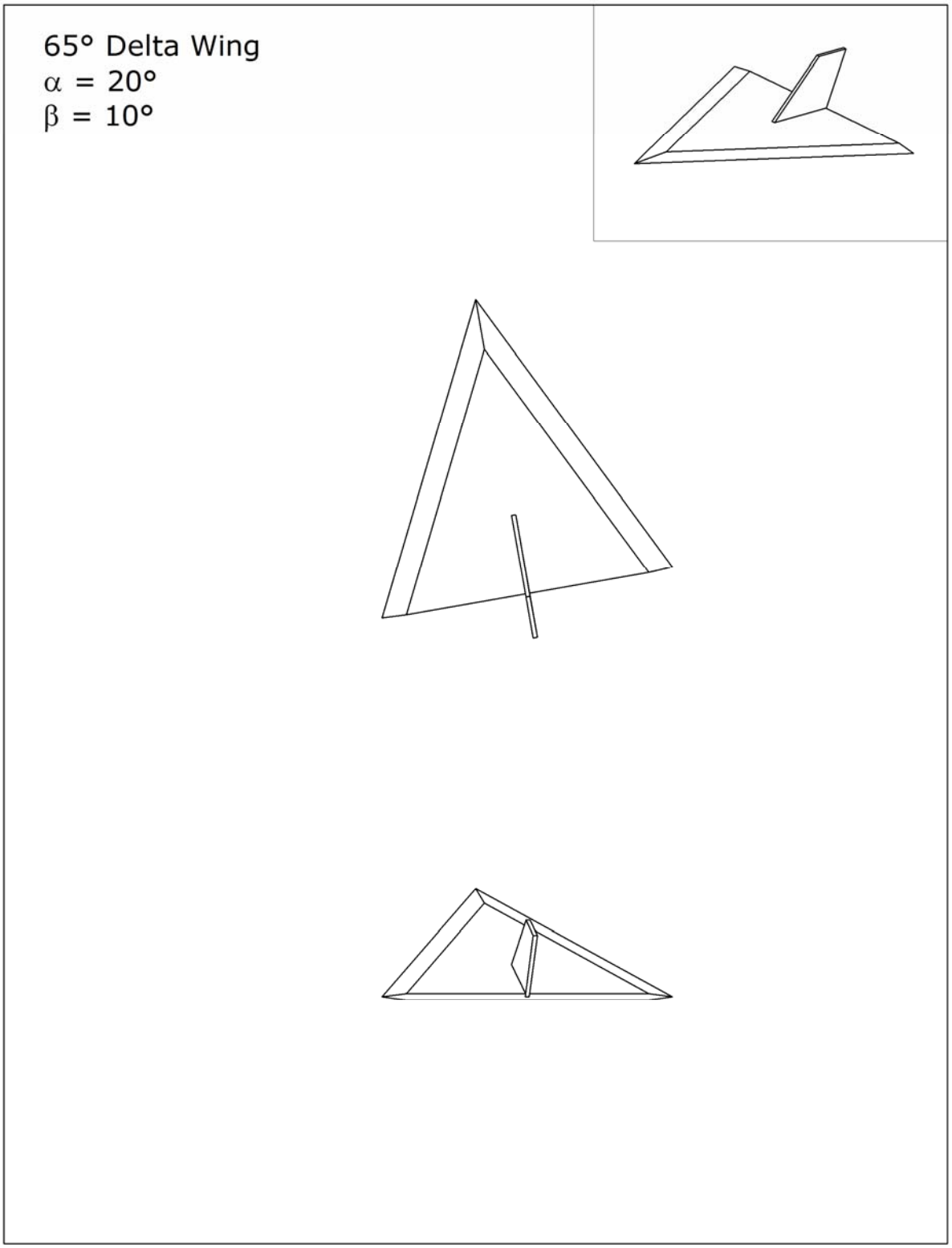
• Figure 20. Streamline patterns for a delta wing at 10° AOA



• Figure 21. Streamline patterns for a delta wing at 20° AOA



• Figure 22. Streamline patterns for a delta wing at 30° AOA



• Figure 23. Streamline patterns for a delta wing at 20° AOA and 10° yaw

Laboratory

10

Glider Performance
Performance Analysis and Flight Testing of a Thermic-18 Glider

Introduction

The purpose of this experiment is to predict and validate full-scale performance characteristics of a Thermic-18 glider using experimental wind tunnel techniques. To accomplish the purpose, this effort is divided into two parts, which will be conducted during two different laboratory periods:

Wind Tunnel Testing of a Thermic-18 Glider Model. Data will be collected using a 2X-scale metal glider model installed in the USNA Eiffel Wind Tunnel. The model is to be mounted on the sting balance and tested at various angles of attack and airspeeds.

Flight Testing of a Thermic-18 Glider. Full-scale balsa wood gliders will be fabricated and flown in Alumni Hall. The distances and average velocities for each flight will be determined.

Part A. Wind Tunnel Testing of a Thermic-18 Glider Model

The wind tunnel data will be acquired using an internal strain gauge balance (shown in Figure 24) that is installed on a sting mounting system. The sting system allows for pitching and yawing the model during a wind tunnel run. When measuring aerodynamic forces using this type of balance, the lift, L, and drag, D, cannot be measured directly.

• Figure 24. Typical 6-component internal strain gauge balance

Glider Lift and Drag Determination

The sting balance can only measure the local *normal force* (perpendicular to the sting) and the *axial force* (parallel to the sting). These forces are denoted by N and A, respectively. The values for L and D can be determined from trigonometry using the sting angle of attack, α:

$$L = N\cos(\alpha) - A\sin(\alpha) \tag{10.1}$$

$$D = N\sin(\alpha) + A\cos(\alpha) \tag{10.2}$$

Balance Tare Corrections

However, before the normal and axial forces from the balance can be used, they must be corrected to account for the weight of the model and any small voltage offsets in the electronics. This procedure is known as obtaining the *balance tare*. In other words, we want the balance to read zero load at zero velocity.

The balance tare must be measured at all the AOA values we plan on testing because shifts in the sting will produce shifts in the balance output. This effect is more pronounced for pitch than for yaw. So, to obtain the corrected values for the normal and axial forces, we must subtract the tare measurements from the “raw” balance measurements using the following equations:

$$N = N_{raw} - N_{tare} \tag{10.3}$$

$$A = A_{raw} - A_{tare} \tag{10.4}$$

Please refer to Figure 5 on page 27 for clarification.

Wind Tunnel Procedure

Follow these steps to test the 2X-scale glider model in the USNA Eiffel low speed wind tunnel:

1) Record the ambient temperature and atmospheric pressure.
2) **BEFORE TURNING ON THE FAN**, record sting tare data for AOA, normal force, and axial force. Start with the sting position at +20° AOA and decrease to -20° in decrements of 2°. Record the values for α, N, and A at each point (Table 11 on page 58 has been provided for your raw data). This is your balance **TARE DATA**.
3) NOTE 1: The AOA value is changed on the data acquisition computer and the sting will automatically pitch when activated. Be careful to enter the proper angle because a mistake may lead to tunnel and/or model damage. Do not change model orientation when someone is working on the model!
4) NOTE 2: The sting force measurements are automatically recorded when the TAKE DATA button is depressed. The **normal force** is recorded as "**Lift**" and the **axial force** is recorded as "**Drag**." Do not mistake these for the actual lift and drag measurements; they must be transformed using the trigonometric relationships!
5) Start the wind tunnel and set the speed to V_∞ = 40 mph, as indicated on the digital readout on the tunnel. Record the dynamic pressure (in inches of alcohol) as displayed on the slant manometer.
6) Perform an *Alpha Sweep:* Increase the AOA from -20° to +20° in increments of 2°. At each angle of attack, wait for the forces to stabilize for several seconds (by watching them fluctuate on the monitor), and then press the TAKE DATA button. Record the values for α, N, and A at each point (use Table 11 on page 58 as before). This is your balance **RAW DATA**.
7) NOTE: At each AOA value, you will need to slightly adjust the fan speed to keep the test section velocity constant.
8) Set the model to +6° AOA.
9) Perform a *Reynolds Number Sweep:* Vary the test section velocity from 30 mph to 70 mph in increments of 10 mph. Record the values for V_∞, N, and A at each point (use Table 12 on page 59 for your data).
10) Measure the root chord and wingspan of the model. Its wing area is **83.04 in^2**.

Wind Tunnel Data Reduction

The data reduction for the wind tunnel testing phase should involve the following calculations. You will be required to show these results to your instructor prior to conducting the flight test phase.

1) Calculate the air density.
2) Calculate the true airspeed in the test section for each run condition using the dynamic pressure. Note that the dynamic pressure is in units of inches alcohol, so you must convert using the following: 502.2 in. alcohol = 406.8 in. H_2O = 1 atmosphere.
3) Calculate the Reynolds number for each run condition. Use the mean aerodynamic chord as the reference length.

4) Calculate the *corrected* balance data for N and A at each AOA by subtracting the corresponding tare values from the raw data.

5) Convert N and A into L and D at each AOA.

After reducing your data, plot the following:

6) C_L as a function of α

7) C_D as a function of α

8) C_D as a function of C_L

9) C_D as a function of C_L^2

10) L/D as a function of α

11) L/D as a function of Re

From these plots, and using the equations for gliding flight, determine the following quantities:

12) Lift curve slope, a

13) Parasite drag coefficient, C_{Do}

14) Oswald efficiency factor, e

15) Maximum L/D ratio

16) AOA required to achieve maximum L/D ratio

17) Ideal glide angle for maximum range, θ_{ideal}

Part B. Flight Testing of a Thermic-18 Glider

For steady, level flight it is acceptable to assume that $L = W$ when conducting performance analyses. However, for gliding flight, this is inappropriate since an un-powered aircraft cannot maintain its altitude. Thus we introduce the glide angle, θ, which has a <u>positive</u> magnitude when measured <u>below</u> the horizon. Now the lift required for flight is a function of this angle:

$$L = W \cos\theta \tag{10.5}$$

$$\tan\theta = \frac{1}{L/D} \tag{10.6}$$

From this equation it becomes obvious that the minimum glide slope occurs when the glider is flying at the maximum L/D ratio. Using the launch height, h, and the glide range, R, equation (10.6) can be rewritten more simply as:

$$\frac{L}{D} = \frac{1}{\tan\theta} = \frac{R}{h} \tag{10.7}$$

Flight Test Procedure

The full-scale balsa wood gliders will be flight-tested in Alumni Hall. They will be launched from the balcony above the entrance tunnel (right behind the USNA crest) and below section R at the northeast end of the arena. Follow these steps to flight-test your gliders:

1) Carefully build your Thermic-18 glider according to the instructions on page 59. Use the templates for the wing and tail planforms as shown, with the straight edge as the leading edge. Remember that extra glue will add extra weight and complicate your balancing task.

2) Record the atmospheric pressure and ambient temperature. If a thermometer is not available in Alumni Hall, estimate the room temperature.

3) Record the height of the balcony from which you will be throwing your gliders. Add the approximate height above the floor from which you will be launching your gliders.

4) Determine the mass of your glider **BEFORE** your first flight using the gram balance provided.

5) Before attempting your first flight from the balcony, make several tosses from the floor to practice your technique and to assess your glider balancing. Make a smooth, slightly downward motion with your arm to launch the glider. Do not throw it too hard, because a velocity of around 10 mph is all that is required for flight. If you throw it too hard, the glider will climb upward, pitch to a high AOA, and likely stall. If you throw it too slow, it will nose over and dive, picking up speed until flight velocity is achieved.

6) You must add clay ballast to the nose of your glider to balance it properly along the longitudinal (pitch) axis. Chances are, your glider will initially pitch up and stall, perhaps resulting in a "porpoising" flight path. This occurs because the center of gravity is too far aft causing the glider to trim out at a high lift coefficient that is beyond the capability of the thin wings. Thus, airfoil stall results. If the CG is aft of the neutral point, then the glider will be longitudinally unstable and generally not airworthy. If too much clay is added, the CG will be too far forward causing the glider to trim out at a low lift coefficient. Thus, the glide ratio will be less than optimal and the glider will not achieve a very long range. In this latter case, the glider will fly more like a lawn dart than an airplane.

7) Make careful observations about how your glider responds during the initial flights, paying particular attention to the rolling and yawing tendencies. It is imperative to keep your glider on a relatively straight flight path. You may need to balance your glider along the lateral (roll) axis to prevent rolling off the intended flight path. To do this, add a small amount of clay to the wing tip that drops off. Another technique is to add small ailerons made out of tape. Adjust as necessary to keep a wings level flight attitude. Or, if your glider has yawing problems, fabricate a small rudder out of tape. Adjust it as necessary to prevent a "fish-tailing" deviation from the intended flight path.

8) Once your glider is reasonably balanced and is flying straight, make a few tosses from the balcony. Record the flight distance along the floor (from the balcony to the point where the glider touches down) using a tape measure and the flight time using a stopwatch. And, if the glider mass changes, measure the new mass. A data sheet is provided (Table 13 on page 60) for your trials.

9) After obtaining a few good trials with your glider, continue adding mass to the nose and record its glide performance. It is possible that moving the CG slightly more forward will result in better glide characteristics.

Flight Test Data Reduction

The data reduction for the flight test phase should involve the following calculations FOR EACH TRIAL. You will be expected to include these results in your final draft of the lab report.

1) Calculate the air density in Alumni Hall.

2) Determine the average glide slopes.

3) Calculate the corresponding **actual** L/D ratios from the glide slopes.

4) Determine the average flight velocities using your time and distance data.

5) Calculate the lift coefficients required to fly at the observed flight velocities.

6) Using the wind tunnel results, determine the approximate AOA values required to achieve the calculated lift coefficients. What is the corresponding L/D ratio that would be **predicted** using the wind tunnel data?

7) Calculate the percent error between your actual and predicted L/D ratios.

8) What is the glide velocity if your glider was trimmed to fly at the maximum L/D? Use your wind tunnel results to support your answer.

9) What is the terminal velocity of your glider? Assume it is plummeting straight down with zero lift generated. Use your wind tunnel results to support your answer.

Deliverables

You must hand in the following: a **FORMAL REPORT**, complete with the eight required sections (cover page, abstract, introduction, background theory, experiment setup and procedures, results and discussion, conclusions, and appendices).

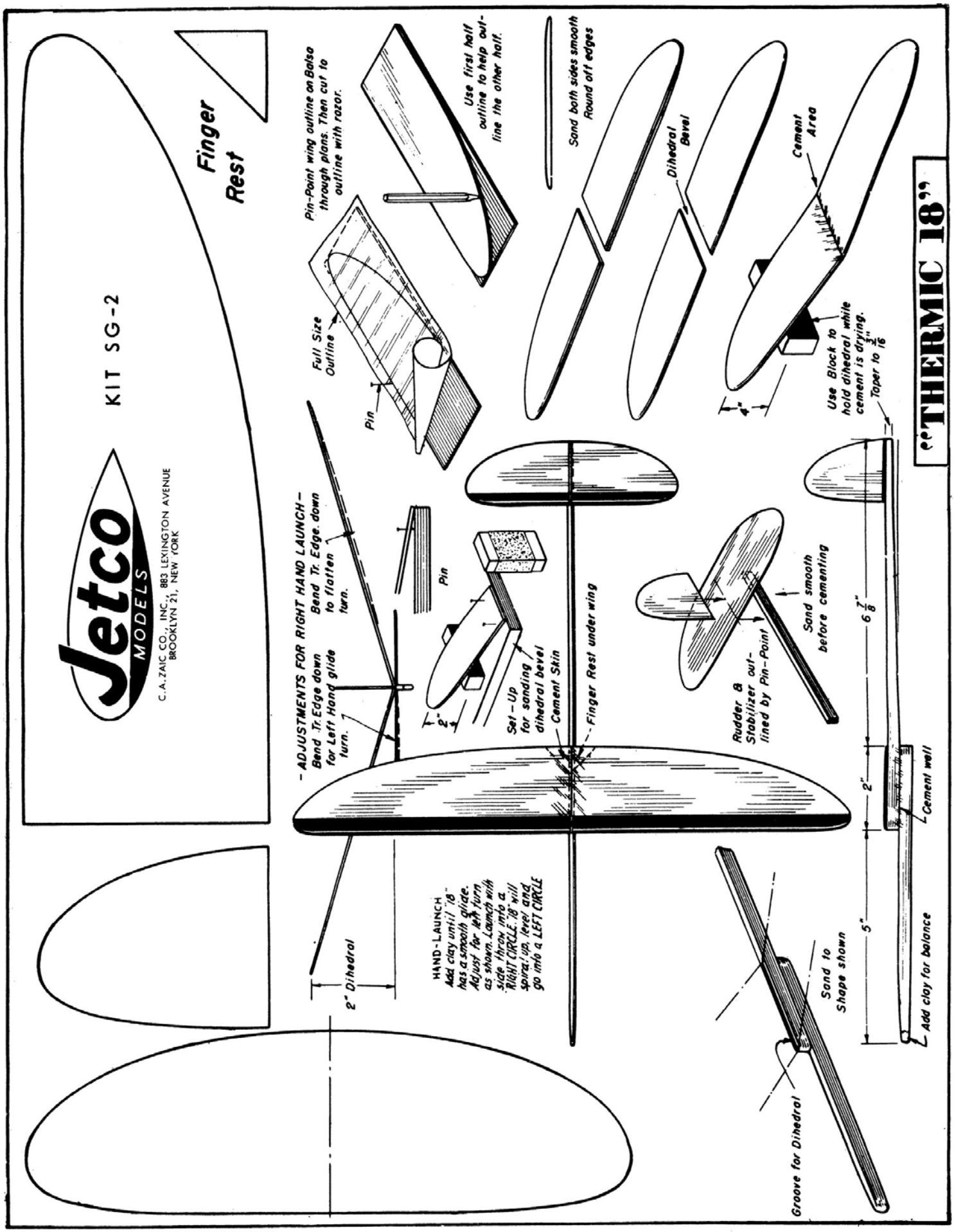
• Table 11. Glider Wind Tunnel Data: Alpha Sweep

Test Date: _____ Indicated Airspeed (mph): _____

Barometer (in. Hg): _____ Dynamic Pressure (in. alcohol): _____

Room Temp (ºF): _____

Sting AOA (deg.)	Balance Tare Data (wind off)		Balance Raw Data (wind on)	
	Normal Force, N (lbs)	Axial Force, A (lbs)	N (lbs)	A (lbs)



• Figure 25. Build plans for the Thermic-18 glider

• Table 13. Glider Flight Test Data

Test Date: _____ Barometer (in. Hg): _____

Height of Balcony (feet): _____ Room Temp (ºF): _____

Height of Launch Point above balcony (feet): _____

Trial Number	Glider Mass (g)	Flight Distance (feet)	Flight Time (sec)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Appendix

A

Conversion Factors

To be written.

Appendix

B

Technical Writing Guidelines
Preparation of Formal Technical Reports

Components of a Formal Technical Report

This is a summary of what goes into a formal technical report. All students should refer to the Aerospace Engineering Report Writing Manual for specific guidance on report writing. Some of the important points will be summarized here. The formal technical reports you turn in shall consist of the following elements: A cover page, front matter, the body of the report, references, and appendices.

Cover Page

Use the cover sheet formatted in the Microsoft Word template for a technical report.

Front Matter

Following the cover page, there is an assortment of "front matter." This material includes the abstract, table of contents, and several lists of information.

Abstract

The abstract should not exceed 200 words, even for a relatively long paper. It should be written last, but it must appear first in the report as a single paragraph. It should be an overall summary (not an introduction!) and complete in itself. Readers should not have to read the paper to understand the abstract. Avoid using too many acronyms or symbols. Keep it mostly text. The abstract should contain the following points, and can be written in four sentences at a minimum:

- A statement of the engineering problem (what the whole work is all about)
- An explanation of the approach used to solve the problem (analytical, experimental, design technique, device improvement, testing scheme, etc.)
- The principal results (summarize the newly observed facts)
- What the principal results mean (brief conclusions of the experiment or argument discussed in the paper)

Table of Contents

Make sure "Table of Contents" doesn't show up in your table of contents.

List of Figures

This list shows all the figures in the report and their respective page numbers.

List of Tables

This list shows all the tables in the report and their respective page numbers.

List of Symbols

This list tabulates all symbols (English and Greek), abbreviations, and acronyms that appear in the report.

Body

This is the text of the actual report. It should include four major components. These would be chapters in a large, formal report or section headings in a small, informal report. For formal laboratory reports, use the former construct. These sections are summarized:

Introduction

Consider this to be independent of the abstract and write it as if the latter never existed. Include the following points:

- The background of the report (e.g., What is the motivation and/or the applicability of the study? This is the "Why" for the study, and should tie it in with relevant aircraft, observed phenomena, or published work).
- The purpose and objectives (i.e., the specific "What" and "How" for the study. What types of tests are being done?).
- Background theory used in the report. Give only the equations used in data reduction and to explain certain phenomena or trends that occurred in the experiment. The assumptions involved must be well stated. Number your equations so you can refer to them later in the text.

Experimental Setup and Procedure

Describe the setup and outline the procedure undertaken during the experiment. Include pictures or sketches when they would help your description. This should include the model, the wind tunnel (or other facility), supporting relevant equipment, and instrumentation.

Results

This section shall represent the major element of the report, and should be about half of the total number of pages. A good presentation and discussion of the results will yield a good grade. A bad one will drop the grade considerably. So, be alert! The results should be discussed in a logical sequence by referring to each individual figure or table. The graphs and tables should be numbered and captioned accordingly. Reference every figure and table in the report. Any figure or table included in the report and not referenced in the Results section will be a liability to the writer, and that figure or table will be ignored. This may reduce the grade substantially. The discussion of the results must represent a critical assessment of the project. Any deviations of the experimental method from theoretical predictions must be explained and justified. The errors resulting from these comparisons should be assessed and quantified which should give you reasons for rejecting or accepting the experimental results. You must present your experimental error as a deviation from the listed data. The uncertainty of your measurements is as important as the measurements themselves. **TRUE ENGINEERS ARE VERY CRITICAL OF THEIR WORK.**

Conclusions

Summarize what you have accomplished by emphasizing the important results obtained, and whether you have accomplished all the objectives set out for the project mentioned in the Introduction. You shouldn't have anything new to say in the Conclusions. Critique your own work if there are deficiencies. Include recommendations to accept or reject the results and to improve the methodology of the project. BE CREATIVE. Do not be afraid to express original ideas as long as they make good engineering sense.

References

Any external source that was used in the preparation of the work should be cited. This could include background theory or other published experimental data. Include any web sites that were accessed.

Appendices

Appendices may contain sketches, tables, figures, sample calculations, and data if it is not convenient to place within the text. Examples of this would be raw data, or the sampling of data plots that is not directly addressed in the Results section. Also include any MATLAB scripts that were used to reduce your data. Each appendix is assigned a letter.

Appendix

C

Technical Graphics Guidelines
Preparation of Plots, Tables, and Equations[14]

General Preparation

Like all aspects of technical writing, the preparation of plots, figures, tables, and other graphics elements is expected to portray professionalism and clarity of communication. Even if your text is lucid and well-written, your report will be considered of poor quality if your graphics are ill-prepared or ambiguous. Therefore, all graphics included in your technical writing, regardless of the format, shall abide by these common-sense guidelines.

First Things First

If you are using Microsoft Excel to prepare your plots, you must take note. This is because the "default" scatter plot in Excel is a terrible format to use, violating almost every rule for preparing plots. Therefore, you must invest a significant amount of time to change the formatting and thus the look of your graph. In particular, Excel defaults to the following 11 things that are completely unacceptable with regards to technical data presentation:

1) The background is non-white. This quickly runs your printer dry and, more importantly, can make it difficult to see details on your plot. Change the background to white.
2) The plot area is framed by a gray border. This should be black, to clearly define the plotting area. Alternatively, this can be eliminated altogether (i.e., axes lines only on the plot).
3) The graph area is framed by a black border. This should be eliminated because it is unnecessary.
4) There are gridlines. These should be removed because they detract from the plot details and trends. Instead, include tick marks along your axes to demark the major and minor increments.
5) The legend squeezes out usable plot area. If you don't need a legend, then don't use one. If you need one, overlay it on a non-critical part of the plot area.
6) The legend text is ambiguous. You must give the data series meaning.
7) The title squeezes out usable plot area. Eliminate this. Every plot is captioned in a technical report, so a plot title is extraneous. This is usually true for PowerPoint presentations, as well.
8) The "automatic" axis limits and increments are usually poor representatives for the data selected. Change these using the guidelines on page 69.
9) The data points are connected with a "smoothed line." This is the phoniest aspect of Excel! Note how the smoothed line apparently predicts a false maximum at x = 8. If you use a line, then just "connect the dots" with straight line segments because this preserves the true trend.
10) The symbols are usually too small. Furthermore, the symbols and lines are usually color-coded in such a way that photocopying makes the data series seem ambiguous. Follow the guidelines on page 70 to select the symbol size, shape, and coloring.

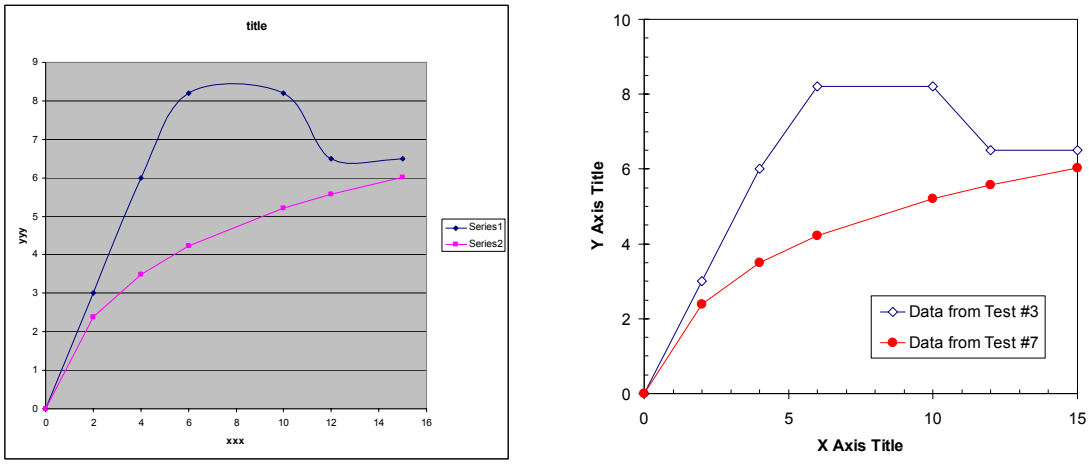
[14] Compiled from USNA's *Report Writing Handbook* (adapted from the USNTPS handbook, *The Write Stuff),* dated August 1999; USNA's *Technical Report Writing Guide* (adapted from USAFA guidelines and prepared for students in the Astronautics Track); and W.H. Mason's unpublished *Applied Computational Aerodynamics* (http://www.aoe.vt.edu/~mason/Mason_f/CAtxtTop.html), Appendix C.

11) The font is usually far too small. Once reduced to fit within the document, these fonts can be unreadable. Make the fonts larger.[15]

Excel Examples

The problems with Excel are illustrated in the two examples shown in Figure 26. The graph on the left uses all of the unacceptable Excel default formats. It is terrible as a scientific figure and will receive zero credit in a technical report. By contrast, the graph on the right shows the same data with all of the Excel problems corrected. This results in an acceptable presentation of the data. You should carefully study the differences between these two plots if you will be using Excel to plot your data.

If you will be regularly using Excel to prepare your plots, then you should consider creating a custom template of your own default formats. This can be accomplished by setting up a properly-formatted scatter plot and then accessing (from the standard Excel toolbar) Chart > Chart Type > Custom Types. Then you can select from "User-defined" chart types to add your own customized default chart. When you hit the "Add" button, it will save the current plot in your list of chart types. Make sure to click the "Set as default chart" button to complete the task. From now on, every graph will default to the formatting you defined.



• Figure 26. An unacceptable Excel plot (left) and a satisfactory one (right)

General Guidelines for Figures and Tables

These guidelines relate to the general use of figures and tables in technical writing:

1) The category "figure" includes graphs, charts, illustrations, photographs, diagrams, or schematics. Figures are numbered and captioned below the figure. The only time a title or caption appears above the figure is in a presentation slide.

2) The category "table" involves data arranged in tabular form. Tables are numbered and captioned above the table.

3) Orient the figure or table so that it is read in the same orientation as a page of text. Large illustrations may be rotated so that the top of the figure is along the left margin of the page (Note: this is upside-down compared to the landscape output from a printer).

4) Figure and table captions should be brief, but descriptive. Avoid lengthy captions with too much detail. Avoid using abbreviations or symbols in the caption text, unless is it absolutely necessary. The caption should all be on the same line, with normal capitalization (avoid all caps). **The caption must remain with the table or figure, not on the previous/next page!**

[15] Besides, your instructor may have less-than-perfect eyesight!

5) Annotate the table or figure with reference information relating to the data. This could be the test article model and/or serial number, the test Mach and Reynolds numbers, the material used, etc. Use annotation to make it clear what is being presented, but don't be redundant with the figure caption. Refer to the graphs in this document for examples of how to annotate figures.

6) The table or figure should appear close to the place it is referenced in the text, with the following priority:

   a. On the same page following the first reference, or
   b. On the same page, visible from the reference point, or
   c. At the top of the following page, or
   d. In an appendix.

7) Every table and figure <u>must</u> <u>be</u> <u>referenced</u> in the text. If it's not, then it doesn't belong in the report. The exception is material that appears in the appendices. In this case, the figures or tables can be referred to in bulk (e.g., "Appendix B includes the raw data plots for the lift coefficient.").

8) If the table or figure is not your own, you <u>must</u> cite its source! Do this at the end of the caption.

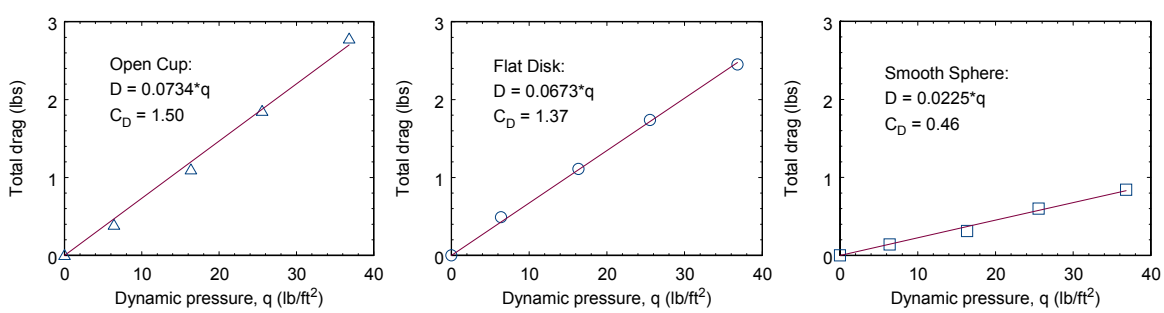
9) Figures and tables are numbered consecutively using Arabic numerals (e.g., "Figure 1," "Table 2," etc.). They should also appear in the report consecutively. A separate numbering sequence shall be used for figures and tables.

10) Figures and tables in the appendices are numbered consecutively using Arabic numerals preceded by the appendix letter (e.g., "Figure A.1," "Table B.2," etc.).

11) Use an appropriate number of significant digits in numerical information presented in figures and tables. This extends to reference information, axis labels, and legends.

Formatting Plots

When comparing several plots showing the same type of data, it is preferable to include all data series on one set of axes, but it is not always possible or practical. One huge plot may become inundated with too much information. In this case, make separate graphs but make them as uniform as possible. Make all plots the same size with the same axes limits using consistent symbols, lines, and/or colors. Sometimes, this means that some of the graphs will have a lot of seemingly wasted plot area. However, this is acceptable because it allows for instantaneous "eyeball" comparison between the different plots. See Figure 27 for an example of uniform scaling between several plots.



• Figure 27. An example of uniform axis scaling for comparison purposes

Proper Scales and Increments

It is important to select the proper scales and increments when setting up plotting axes. In particular, you should pay special attention to the major and minor tick mark increments along each axis. You should follow the so-called "1-2-5 rule." This rule basically states that the smallest division on a plot's axis must be easily read. This is accomplished by creating axis divisions and subdivisions, as indicated by major and

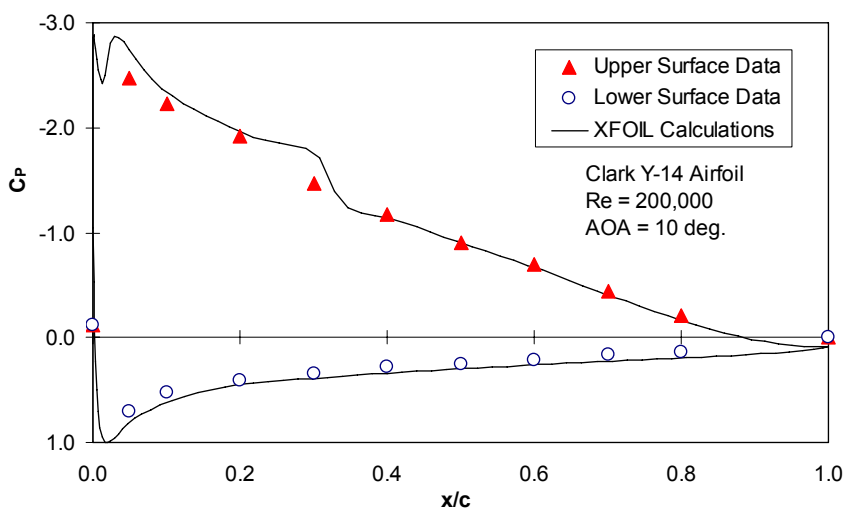
minor tick marks, that are separated by an order of magnitude of 1, 2, or 5 (i.e., 1, 2, or 5 x 10^n). By following this rule, data can be easily interpolated between tick marks. Some good examples of major and minor tick mark increments are 10, 0.2, 50, and 0.001. Some poor choices are 40, 25, 0.125, and 60, because they do not follow the 1-2-5 rule.

When setting up a graph's plotting limits, you should use common sense. The limits should include the range of interest without too much extra space (the exception is when you have a series of identical plots, with varying data). It is common to hold loosely to the 1-2-5 rule when setting up axis limits.

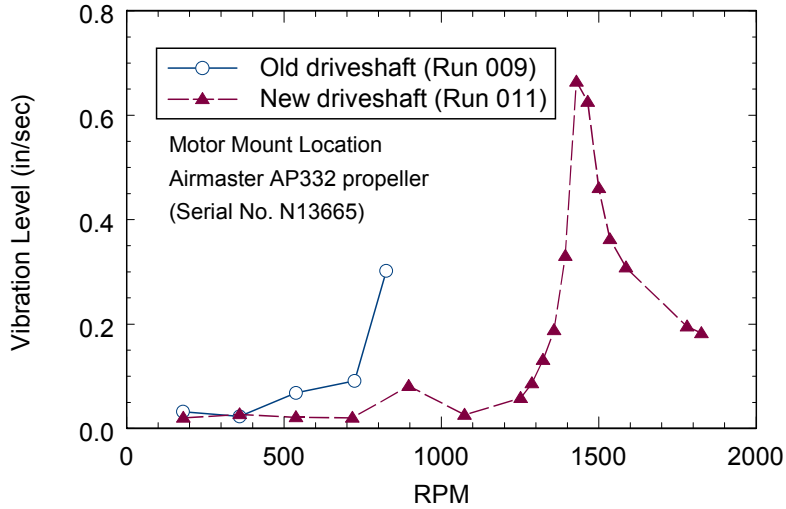
Selection of Symbols and Lines

The use of line/symbol combinations can signify a lot about your data. Proper use will help facilitate quick comparisons and make conclusions clear. Follow these guidelines to help you:

- The choice for symbol/line/color combinations should be consistent throughout the report or presentation. For example, if lift coefficient data for the NACA 0012 with zero flaps is represented by red, filled triangles connected by a solid line, then maintain this combination throughout the rest of the plots: drag polar, pitching moment coefficient, and L/D ratio.
- Maintain a consistency in the ordering of the data, as presented in the plot legend. Keep this order throughout a series of data plots. And if possible, select an ordering that roughly mimics the data in the plots (i.e., the data series on top, in the middle, and on the bottom should be reflected in the legend in the same orientation).
- If experimental data is being compared to theoretical calculations (including CFD or simulation results), use the accepted convention: experimental data is indicated by symbols (no lines) and theoretical data is indicated by lines (no symbols). The legend should also clearly discriminate the two data series, as is shown in Figure 28.
- If plotting complicated data, you might want to "connect the dots" to clarify the trends, even if multiple series of experimental data are included. In this case, it may be useful to change the line type as well: solid, dashed, dotted, etc. See Figure 29 for details.



• Figure 28. A plot comparing experimental data (symbols) with theoretical results (line)



• Figure 29. Plotting complicated experimental data for comparison

The Use of Color

The most important aspect to remember when selecting symbol/line combinations is that the color may not be transmitted accurately. This is especially true if the report is photocopied, during which a beautiful, color-coded chart or plot may be quickly reduced to an ambiguous mass of similar-looking symbols and lines (i.e., "junk"). Excel is especially good at auto-selecting color schemes that all look the same after photocopying.

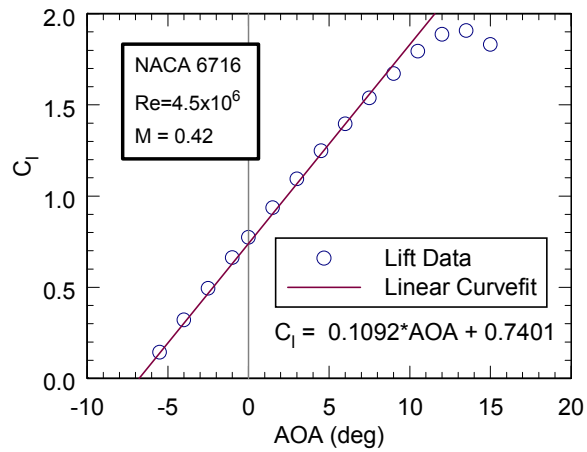
In short, it is permissible to use color in reports and presentations, but your results, analysis, and conclusions **SHOULD NOT BE TOTALLY DEPENDENT** on an accurate color facsimile of the figure. In other words, follow these basic guidelines to distinguish your data in other ways:

- Alternate between open and filled symbols for alternating data series.
- Alternate between dark hues and medium hues. As an example, magenta photocopies as a medium gray color. Avoid using the lightest colors like yellow and cyan, because these won't show up on a photocopy at all.

Data Trends

When plotting experimental data, only use a trend line (or curvefit) that accurately represents the theoretical trend! This means that the "smoothed line" function in Microsoft Excel is completely inappropriate for scientific and engineering plotting, because it represents no physical aspect of the data.

As an example, consider experimental lift coefficients plotted against the angle of attack for an airfoil. Suppose you are required to determine the lift curve slope and then interpolate the function to get α_{L_0}. It makes no sense to fit a quadratic trendline through the data, even if the nonlinear stall region is included. The theoretical relationship between lift coefficient and AOA is linear at low-to-moderate angles of attack, so a linear curvefit should be used. If you're using an Excel linear trendline, make sure to create the trendline only from the data points that are in the linear region. Figure 30 shows the proper use and format of a linear curvefit (or trendline) and how the information can be presented on the plot. Remember that if you use the wrong data points to determine something like the airfoil lift curve slope, then all your subsequent results and conclusions are in error!



• Figure 30. Proper use of linear curvefit information

In some situations, the linear trendline may differ from the linear theory, so make sure you present the context of the problem appropriately. A trendline uses the acquired experimental data to create a best-fit linear function through the points; it only requires the original set of data. Linear theory involves another data series representing the theoretical relationship (in other words, a second dataset). Therefore, the slopes of these two elements may differ; do not confuse the two.

Formatting Tables

Tables are used to present the numerical value of data for comparison and/or calculation. The purpose of a table is to present a more-inclusive presentation of the data than is discussed in the text. In other words, one or two critical data points might be discussed in detail in the text, but the table shows all 8 data points. Table 14 depicts an example of a data table.

• Table 14. A properly-formatted data table.

Balloon Weight Component Measurements

C (in)	Volume (ft^3)	$W_{envelope}$ (lb)	$W_{payload}$ (lb)	W_{total} (lb)
-	0	-	-	-
66.75	2.91	0.1004	0.0886	0.1890
80.60	5.12	0.0715	0.2684	0.3399
92.00	7.61	0.1003	0.3815	0.4818
99.10	9.51	0.0986	0.4930	0.5916
110.70	13.26	0.1094	0.7618	0.8712
116.25	15.35	0.1048	0.8918	0.9966
-	20	-	-	-

Follow these general guidelines when preparing a data table:

1) Consider if a graph is better suited to present your data.

2) You should use “open table” formatting. In other words, there is no box around the whole table. There are also no horizontal lines except to delineate the column headings. Lastly, the columns are all separated by vertical lines.

3) Tables should be clear, concise, and easy to read. Do not include too much information in one table. Sometimes, two smaller tables are better than one large one.

4) Don’t leave blank cells in a table. Use dashes to represent omitted data.

5) Tables may be used to present raw data. These tables should be included in the Appendix.

6) Tables represented reduced data can be included within the body of the report. If this data is already represented by a graph, you may want to consider putting the table in the Appendix.

7) Include units in the column or row headings.

Formatting Equations

It is expected that equations are included in most technical reports or presentations. Because they usually require a little more preparation than typing characters at the keyboard, they are considered with the graphical elements of a technical report. There are only a few basic guidelines for properly using equations:

1) Use an equation editor (e.g., MathType). These are usually built into word processing applications. DO NOT type out equations using text and symbols (i.e., -, +, *, /, ^, etc.).

2) Keep the equation all on one line, if possible.

3) Every equation should be referenced in the text. If it’s not, then it shouldn’t be in the report.

4) You should number your equations with Arabic numerals. If possible, place the equation number on the same line as the equation, aligned with the right margin. In Microsoft Word, this is impossible, so put it on the next line and right-justify it.

5) Define symbols immediately following the equation unless they are already defined in the List of Symbols.

An example of Bernoulli’s equation should appear all on one line in a report, like this:

$$p_t = p_s + \frac{1}{2}\rho U_\infty^2 \qquad \text{Equation 1}$$

…or like this:

$$p_t = p_s + \frac{1}{2}\rho U_\infty^2 \qquad (13.1)$$

Alternatively, the equation and label can be staggered on two separate lines, like this:

$$p_t = p_s + \frac{1}{2}\rho U_\infty^2$$

Equation 2

…or like this:

$$p_t = p_s + \frac{1}{2}\rho U_\infty^2$$

(13.2)

Appendix

D

Technical Writing Samples
Elements of a Formal Technical Report

Examples

The selected examples shown here are technical writing samples that are based on Laboratory Exercise 2.

Example Abstract

The present work seeks to investigate the buoyancy phenomenon as described by Archimedes Principle. Experimental results were obtained for the net lifting force of several helium-filled balloons, ranging in diameters of 18-37 inches. Comparisons were made with theoretical calculations based on Archimedes Principle. The results validated the linear relationship between the lift and the volume of the envelope over the range of 0.12-0.97 lbs net lift. Comparisons between the theoretical and the experimental values were within approximately 6 percent at most. Therefore, theoretical results can be used to accurately predict the net lift of lighter-than-air vehicles.

Example Introduction Section

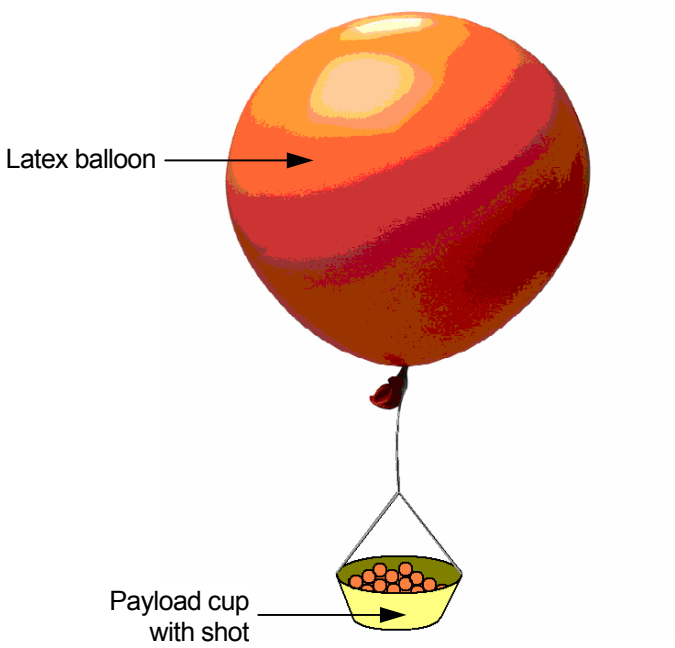
To be written.

Example Experimental Setup and Procedure Section

The experimental determination of buoyancy involved helium balloons and a weight balance procedure. The equipment, instrumentation, and experimental method are summarized in this section.

Equipment

The balloons used were made of latex and capable of inflated diameters of up to 36-40″. The latex envelopes weighed approximately 0.1 lb each. Each balloon was attached to a cup that could be loaded with a balancing payload weight. The payload weight typically consisted of a quantity of copper shot (i.e., airgun BB's). This setup is depicted in Figure 31.



• Figure 31. Experimental apparatus for measuring buoyancy

Instrumentation

The primary instrumentation involved length and weight measurement. The circumference of each balloon was measured with a 120″ tailor's tape measure. The weight of each balloon component was obtained using an analytic pan balance (maximum capacity = 0.7 lb).

[This would be a sufficient treatment of the instrumentation used in this particular experiment. Normally, the Experimental Setup section might include a diagram and/or additional specifications of the instruments used.][16]

Experimental Method

To obtain theoretical and experimental measurements of buoyancy, each balloon was first inflated with helium to an actual inflated diameter of 20-37″. After the balloons were tied off, the mean circumference was determined using a number of different cutting planes through each inflated balloon, to account for the non-spherical shape.

Then the payload cup was attached and loaded with shot until buoyancy equilibrium was achieved. Occasionally, small bits of paper were added to trim out the total vehicle. After the equilibrium was achieved, the envelope and payload were weighed. When the payload weight exceeded the capacity of the balance, it was subdivided into quantities of less than 0.7 lbs.

Example Results Section

The results are presented for the determination of lifting capacity for 9 aerostatic vehicles. The procedure of Section 3 *[this would be the Experimental Setup section]* was followed to fill the balloons with helium and secure the envelopes. From an average circumference for each balloon, the volume was determined. This volume, which was in the range 3–14 ft³, was then used to calculate the theoretical lifting capacity based on equation 5 of Section 2 *[this would be in the Theory section]*. The density of the helium was calculated by assuming that the pressure and temperature inside the envelope were at ambient conditions (1013mb and 20°C, respectively). Experimental determination of the lifting capacity was made by balancing out the

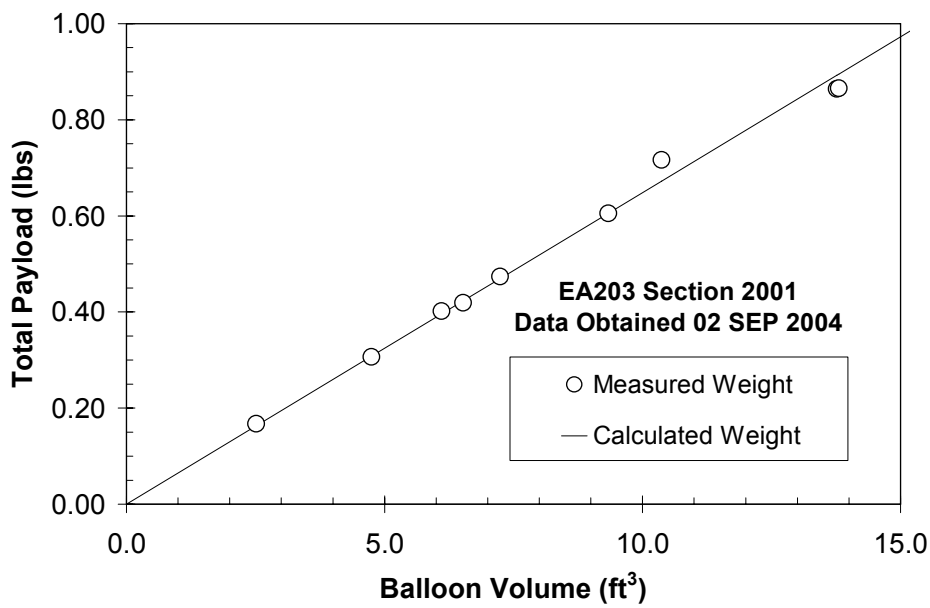
[16] These parenthetical comments are for reference only and should not be included in a technical report. It is common and acceptable practice to refer to previous sections of a report.

buoyant force with weights. These total measured payloads varied from 0.2–0.9 lbs. A summary of these calculations and measurements is shown in Table 15.

• Table 15. Calculated weights of aerostatic vehicles

Balloon Volume, ft³	Measured Weight (Total Payload), lbs	Theoretical Weight (Lift), lbs	% Error
2.51	0.167	0.163	2.5
4.75	0.306	0.308	0.5
6.11	0.402	0.396	1.5
6.52	0.419	0.423	0.9
7.24	0.474	0.470	0.8
9.34	0.606	0.606	0.0
10.37	0.716	0.672	6.5
13.77	0.864	0.893	3.2
13.80	0.866	0.895	3.3

The lifting capacity results are graphically presented in Figure 31. This figure shows the total payload of the aerostatic vehicle plotted against the enclosed volume of each balloon. Both theoretical and experimental results are presented. It is clear from the plot that the predictions for lifting capacity should follow a linear relationship. The slope of this line is proportional to the differential in density between the enclosed helium and the displaced air (equation 5). The experimental data points closely follow the linear relationship, with a maximum error of 6.5%. The average error for all nine balloons is far below this at 0.4%. With such good agreement between theory and experiment, it is clear that lifting capacities of helium aerostatic vehicles can be accurately predicted using these methods.



• Figure 32. Lifting capacity of aerostatic vehicles

Sources for error[17]

In the present experiment, there were a few sources for experimental error. First, the oblateness of the inflated balloons challenged the assumption that the envelope volume was spherical. This assumption was used to calculate the volume from the average circumference. The actual circumference measurements were relatively accurate, estimated to be within ±¼″. Second, obtaining the maximum weight lifted depended on having a leak-proof envelope and achieving equilibrium. The balloon tested by the author showed no signs of leakage. However, equilibrium was difficult to achieve, as slight air currents in the room cause the balloon to drift up or down, even at the same loading condition. The weight measurements were displayed with four digits of accuracy, but the recorded values are precise to within ±0.0002 lb.

Example Conclusions Section

The present work shows that Archimedes Principle has been accurately applied to calculating the net lifting force of helium-filled balloons. The theoretical trend, a linear relationship between buoyant force and the volume of the envelope, was precisely modeled in the experimental data, with an average error of 0.4%.

In summary, the following conclusions can be drawn from this experiment:

- The linear relationship between the lift and the volume was validated.
- The results apply to the range of balloons tested, volumes of 3–14 ft^3 and total weights of 0.2–0.9 lbs.
- Maximum experimental error was 6.5%.
- These conclusions demonstrate that the theoretical results obtained from Archimedes Principle can be used to accurately predict the net lift of lighter-than-air vehicles. The predictions can be applied to the preliminary sizing of aerostatic vehicles, blimps, airships, or hybrid air vehicles.

[17] **NOTE:** If you list "human error" as a source of experimental error (a common misconception for pre-engineering students), then you didn't do the experiment carefully enough, and it should be re-done! You can always estimate the precision to which you obtained your measurements.

Appendix

E

Expectations of Submitted Work

Preparation of Homework, Laboratory, and Project Assignments

To be written.

Appendix

F

Aerospace Engineering Problem Solving
A Systematic Approach

Introduction

Before getting into the specifics of our approach to solving basic engineering problems, let's talk a little bit about philosophy. Here in the Aerospace Engineering department at the Naval Academy, you will be exposed to a wide variety of problems designed to test your understanding of course material and to teach you how to apply the principles you're learned to real-life engineering efforts. Some things to think about:[18]

1) Problem solving is the most effective route to proficiency in engineering – lots of problems.

2) The real world of engineering is not a series of neatly stated exercises. At some point, the student must face the fact that the analysis of a problem may require considerable time, outside study, and imagination. Imagination in the sense that real problems are not completely stated or specified, that the statement of the problem must be completed based on the judgment of the individual student.

3) The end product is not necessarily a number that is right or wrong. There may be more than one method of approach or solution to the problem presented. Further, solutions may require extensive numerical computation or even iterative procedures. Computers are generally used for those types of solutions.

4) An engineering analysis must not only present answers to specific questions, it must also provide a clear guide to the thought processes by which the answers were obtained. Further, it must provide a meaningful discussion of the implications of the answers.

Problem Solving Procedure

Having said all that, you will now be given a step-by-step procedure, illuminated with an example, to solving many typical engineering problems. You should look at this as a sort of template for organizing your work, finding a solution, and then presenting it properly. You will be expected to follow this or a similar logical, well-documented approach when submitting assignments in Aerospace Engineering courses.

Systematic Approach to Solving Engineering Problems

1. Read and understand the problem. Don't waste any time trying to answer the **WRONG** question!

2. Determine <u>exactly</u> what parameter or parameters the problem is asking for (See number 1).

3. Think about what information is relevant to the sought-after result and why. This will help you determine whether the givens in the problem are necessary and/or sufficient to solve it.

4. Collect all the given data including that which is known by extension (i.e. information from charts, tables, etc.)

5. Draw or sketch a picture of the problem and identify the variables. Label pertinent aspects of the diagram.

[18] From a course handout provided by Professor D. F. Rogers, Aerospace Engineering Department, USNA, 1964-2003.

6. Establish which fundamental principles apply. Write down any equations that might be useful in solving the problem. Do not begin to "crunch numbers" until you're satisfied that you have captured all the pieces of the puzzle.

7. Develop an approach and the logic necessary to implement a solution. If a computer program is required, develop an algorithm that can be used to write the code.

8. Once the code is written for computer problems, perform a hand calculation with simple data to ensure that the program functions as it should.

9. Perform a sanity check on the solution. Are numerical results of an order of magnitude that makes sense?

10. Make sure your results are clear, well-identified and properly labeled.

Sample Problem Solving Exercise

The problem statement is:

An aircraft is flying at 25,000 feet pressure altitude at M = 0.7. It has a gross weight of 32,000 pounds, a wing loading of 42 pounds/square foot, and an average chord length of eight feet. The airplane has a total surface or wetted area of 1400 square feet and is similar in shape to an F-8 Crusader (equivalent parasite area = 18.2 square feet). Find the thrust required for steady, level flight.

Applying the method:

1. Read and understand the problem. Assuming you've read the problem in its entirety, be sure you understand all the information either asked for or provided in the words. For example, what's wetted area? What's equivalent parasite area? Why does it matter what the airplane looks like? If there's anything you cannot readily and immediately work with, research it.

2. Determine exactly what it is you're looking for. In this problem, you are asked to find the thrust required for steady, level flight. Actually, steady and level are additional information which could go under the givens outlined in part 4. Steady means the airplane is neither accelerating nor decelerating and level means it is not climbing or descending. From our knowledge of physics (see sample writeup), we can conclude that for this specific case, the thrust required is exactly equal to the drag. Therefore, what we are actually looking for is the overall drag of the aircraft for the given conditions.

3. Think about what information is relevant to the sought-after result and why. For example, in this problem you are given wetted area and an idea of how clean the airplane is (looks like an F-8). This information is normally used to determine equivalent parasite area (f) using an appropriate chart. Since you are given an exact value for f, you can conclude that these pieces of information are superfluous and set them aside initially. You may find later that they are useful but such an examination will help simplify the problem up front.

4. Collect all the known relevant data including that which is known by extension (i.e. from charts, tables, etc.) In this simple problem, most of the information you need to get a solution is provided directly. The rest should be available from a familiar resource. For this problem-

Given directly:

a) The vehicle is an airplane, not a blimp, not a missile, etc.
b) Pressure altitude = 25,000 feet
c) Mach number (M) = 0.7
c) Weight (W) = 32,000 pounds
d) Wing loading (W/S) = 42 pounds/square foot

e) Chord length (c) = 8 feet
f) Equivalent parasite area (f) = 18.2 square feet

By extension:
a) From a chart of the standard atmosphere, we can obtain the following information for a pressure altitude of 25,000 feet (English Engineering units since those are what is used to define the problem)-

1) Density (ρ) = .001065 slugs/cubic foot
2) Pressure (p) = 785.31 pounds/square foot, 5.45 pounds/square inch
3) Temperature (T) = 429.53 degrees R

Some standard atmospheric tables contain values for the speed of sound (a) which is usually required in a problem that involves Mach number. If your table does not, it can easily be calculated later. We'll do that in this problem.

5. Draw a picture if appropriate and identify the pertinent variables. (straightforward, see sample writeup)

6. Establish which fundamental principles apply. Write down equations that may be useful in solving the problem. Always use standard terminology and standard symbols where appropriate. If you use something nonstandard, make sure you define it. In this case what we are looking for is the drag (D) which we know is defined by:

$$D = \frac{1}{2}\rho V^2 S C_D \qquad (1)$$

where ρ = local air density, V = flight velocity of the aircraft, S = wing area, and C_D = drag coefficient. We've already determined the density so to calculate the drag we have to find the remaining three parameters.

a) Velocity (V) – We are given Mach number so we can use the following additional relationship to calculate the velocity:

$$V = M * a \qquad (2)$$

where a = the local speed of sound. Since we did not get a speed of sound value from the atmospheric table, it must be calculated using the following relationship:

$$a = \sqrt{\gamma R T} \qquad (3)$$

where γ = the ratio of specific heats for air (1.4), R = the specific gas constant for air (1716 foot-pounds/slug-degree R), and T = the absolute temperature which we determined in part 2. That takes care of velocity.

b) Wing area (S) - Given the weight of the aircraft and the wing loading, the wing area can easily be determined:

$$S = \frac{W}{W/S} \qquad (4)$$

c) Drag coefficient (C_D) will require a bit more work. Starting with the drag polar which is an expression for the overall drag coefficient of the airplane (the two terms on the right represent parasite and induced drag coefficients respectively):

$$C_D = C_{D_o} + \frac{C_L^2}{\pi A \mathrm{Re}} \qquad (5)$$

where C_{Do} = the parasite drag coefficient, C_L = the lift coefficient, AR = the wing aspect ratio, and e is the wing efficiency factor (usually about 0.8). Immediately, we see that we have a few more things to calculate:

1) Parasite drag coefficient (C_{Do}) is often determined using the following expression:

$$C_{D_o} = \frac{f}{S} \qquad (6)$$

where f and S are already known for this problem.

2) Lift coefficient is calculated as follows:

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} \qquad (7)$$

where L = the lift of the airplane which in steady, level flight is equal to the weight (W), a given parameter in the problem.

3) Aspect ratio (AR) – This is the ratio of the span (b) to the average chord length (c) of the wing. Since we know the wing area (S) and the average chord length, we can calculate the span and then the aspect ratio:

$$b = \frac{S}{c} \qquad AR = \frac{b^2}{S} = \frac{b^2}{cb} = \frac{b}{c} \qquad (8, 9)$$

We have now gathered all the equations required to solve this problem and have yet to punch a single calculator button.

7. Develop an approach and the logic necessary to implement a solution. In the previous step, we began with an equation for the parameter that the problem asked for, namely the thrust required or drag, and worked our way down through various equations that were required to determine values in preceding ones. By breaking the problem down in such a manner, we were able to reach a point where all required values are either known or calculable with the equations previously introduced. The solution logic is then simply to plug values into those equations in some logical order thereby ultimately arriving at a value for the desired parameter. The enclosed sample writeup clearly shows the process. Not all problems are this straightforward however you should try to approach every problem this way.

If a computer program is required to answer the problem (usually in cases where the same calculations must be performed repeatedly many times) then this step would consist of developing an algorithm from which computer code may be written. Algorithm development and programming are introduced as elements of EA308, Engineering Analysis. For this problem, only one set of calculations is necessary therefore writing a program is not required.

8. For those problems for which code is required, a step-by-step hand calculation should be performed with simple data to ensure that the logic is sound and that the program leads to the correct result. (Not necessary here)

9. Once the solution is determined, perform a sanity check to make sure that your answer makes sense. In this problem, the result will be a value for thrust required or drag in pounds of force (lbf). Given an aircraft with a gross weight of 32,000 pounds and assuming a lift-to-drag ratio of about 10 (a good ballpark value for most airplanes), you would expect your result to be on the order of 3200 pounds or so. If your answer is around 100 pounds, it should clue you in that you've made a mistake - likewise, if your answer is several

hundred thousand pounds. A large part of engineering work involves analysis and evaluating whether or not results are good and valid. This step helps develop that capability.

10. Make sure your results are clear, well-identified, and properly labeled. Always indicate your final answer with a box. In this case, your answer should be something like:

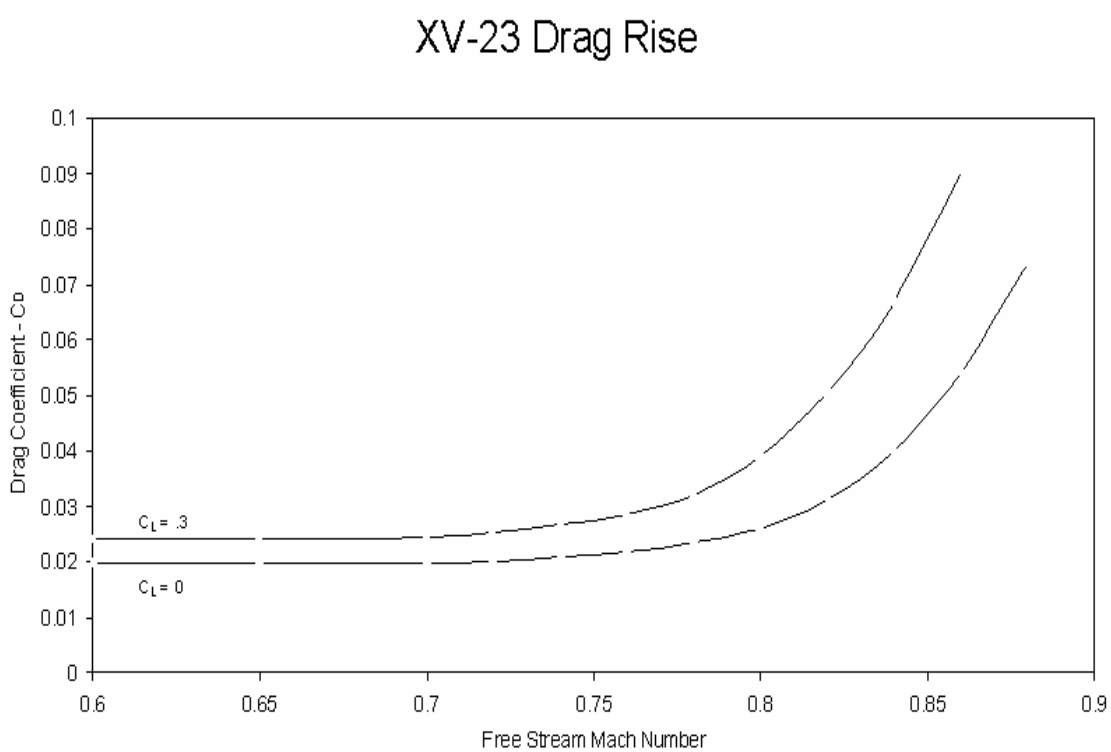
$$T_{req} = 5086.4 \text{ lbf (or just plain lb)}$$

Never forget to include the units for your answer. Without them, the answer is wrong!

Additional considerations:

1. Always be mindful of units. It is imperative that you understand which units are compatible in an equation and which are not. For example, the lift and drag equations require that density be expressed in units of slugs per cubic foot when forces are expressed in pounds, velocity in feet per second and wing area in square feet. Using pounds-mass (lbm) per cubic foot will result in a disastrously wrong answer. Likewise, the values of constants (R, C_p, C_v, etc) vary depending upon the units. Know which values are appropriate for the problem at hand. When in doubt, you should perform a dimensional analysis to ensure that units are accounted for and match across the equation. It is helpful to book keep units as you go through the various calculations. A mismatch of units will clue you in that you're made a mistake. (See sample writeup)

2. If a problem requires a plot or graph, make sure it is properly scaled, labeled and annotated. There should be a title, each axis should have a label which includes the appropriate units and different data sets should be identified. An example is shown below.



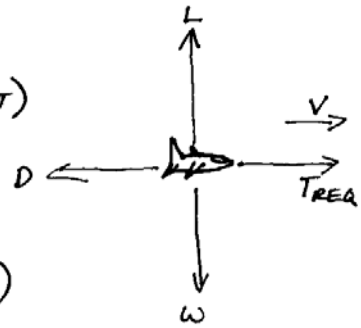
SAMPLE PROBLEM

GIVEN:

(SEE HANDOUT)

FIND:

(SEE HANDOUT)



(DIAGRAM)

FUNDAMENTAL PRINCIPLES

$T_{REQ} = D$

$D = \frac{1}{2}\rho V^2 S C_D$

$V = M \times a$

$a = \sqrt{\gamma R T}$

$S = \frac{W}{W/S}$

$C_D = C_{D_0} + \frac{C_L^2}{\pi AR e}$

$C_{D_0} = \frac{f}{S}$

$C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$ $\quad L = W$

$AR = \frac{b^2}{S}$ $\quad b = \frac{S}{c}$

SOLVE:

$$S = \frac{W}{W/S} = \frac{32{,}000\ \cancel{LB}}{42\ \cancel{LB}/FT^2} = 761.9\ FT^2$$

$$b = \frac{S}{c} = \frac{761.9\ FT^{\cancel{2}\,FT}}{8\ \cancel{FT}} = 95.2\ FT \quad \text{(VERY BIG!)}$$

$$AR = \frac{b^2}{S} = \frac{(95.2\ \cancel{FT})^2}{761.9\ \cancel{FT^2}} = 11.9$$

$$a = \sqrt{\gamma R T} = \left(1.4 \times 53.3\ \text{FT-LB}/\text{LBM-°R} \times 32.2\ \text{LBM}/\text{SLUG} \times 1\ \text{SLUG-FT}/\text{LB-S}^2 \times 429.5\ °R\right)^{\frac{1}{2}} =$$

$$1016\ \text{FT}/\text{S}$$

$$V = M \times a = (0.7)(1016\ \text{FT}/\text{S}) = 711\ \text{FT}/\text{S}$$

$$C_L = \frac{W}{\frac{1}{2}\rho V^2 S} = \frac{32{,}000\ \text{LB}}{(.5)(.001065\ \text{SLUG}/\text{FT}^3)(711\ \text{FT}/\text{S})^2(761.9\ \text{FT}^2)} \times 1\ \text{SLUG-FT}/\text{LB-S}^2 = .156$$

$$C_{D_0} = \frac{f}{S} = \frac{18.2\ \text{FT}^2}{761.9\ \text{FT}^2} = .024$$

$$C_D = C_{D_0} + \frac{C_L^2}{\pi AR e} = .024 + \frac{.156^2}{\pi(11.9)(0.8)} = .0248$$

$$D = \frac{1}{2}\rho V^2 S C_D = (.5)(.001065\ \text{SLUG}/\text{FT}^3)(711\ \text{FT}/\text{S})^2(761.9\ \text{FT}^2) \times .0248 \times 1\ \text{LB-S}^2/\text{SLUG-FT} =$$

$$5086.4\ \text{LB}.$$

$$\boxed{T_{REQ} = D = 5086.4\ \text{LB}}$$