AE2610

Welcome

Here you will find the lab manuals for all experiments that will take place this semester. Navigate to the appropriate experiment on the left-hand menu. You can export each experiment as a PDF if you want a copy for your records, or to print as a hard copy. Also, bookmark this page on your smartphone or tablet as well as your PC/laptop as a handy guide during your lab session.

Note that this semester is the first-time we are rolling out Gitbook to deliver the manuals, so please let your TA or Instructor know if there are any typos, or suggested improvements...

Best of luck for the semester!

Rijke Tube

Objectives

This laboratory introduces the measurement of periodic fluctuating properties and acoustic oscillations. In addition, this experiment involves measurements in a reacting flow produced in a Rijke tube, pulse combustor. Piezoelectric transducers are used to monitor the acoustic pressure fluctuations, while radiation emitted by the flame and detected with a photomultiplier tube provides a qualitative measure of the chemical reaction rate or heat (chemical energy) release rate. Furthermore, students will be exposed to the use of rotameters for fluid flowrate measurements.

Note: All
experiments with combustion are potentially hazardous. Please follow all the precautions that need to be taken and which are outlined in the section on safety considerations.

Background

Pulse Combustors and Rijke Tube

In a pulse combustor, the combustion intensity and, therefore, the (chemical) heat release rate fluctuate periodically with time. The resulting pulsed heat release causes the pressure in the combustor to oscillate in time, i.e., like a sine wave. In addition, a fluctuating, acoustic velocity generated by the pulsations is superimposed upon any mean flow rate. These fluid mechanical oscillations, in turn, can reinforce the heat release fluctuations. These three effects, namely heat release, pressure and velocity oscillations are, thus, coupled and feed on one another. The strength of the oscillations thus grows until this “acoustic driving” is balanced by the acoustic losses in the combustor.

Such a combustor has many advantages. For example, the combustion intensity is increased because of the better mixing between fuel and air. In addition, heat transfer to the wall is increased since the oscillating acoustic velocity component strips away the otherwise insulating boundary layer. Finally, the pulsations tend to push the combustion products out of the exhaust. In contrast, a steady combustor creates venting by convection of the hot exhaust through a chimney, which means that a significant part of the heat (up to 30%) must remain in the exhaust and is, therefore, lost.

The pulse combustor used in this experiment is a Rijke tube, named after its Dutch inventor. It consists basically of a long, vertical tube open at both ends with a source of heat release, e.g., a burner or a heating wire, placed at roughly one quarter of its length from the lower end. If a tube with two open ends is acoustically excited, it acts like an organ pipe. Thus the pressure in the pipe will vary with time.

In general, we can take the pressure at any point and decompose into a time-averaged component ($\bar{p}$) and a time-dependent component (p'),

$$p(t) = \bar{p} + p'(t)$$

(1)

For our case, where the pipe is resonating, we get a standing acoustic wave inside the pipe. The wavelength λ of the acoustic wave is twice the pipe length [1] (see Figure 1).

> [1] Actually, this is true for the fundamental (axial) mode. The pipe can also resonate in harmonics of the fundamental mode (each having a frequency that is an integer multiple of the fundamental frequency).

The frequency f of the wave is related to the wavelength by the relation

$$f = a/\lambda = a/2L$$

(2)

where a is the speed of sound. For an ideal gas, the speed of sound is given by:

$$a = \sqrt{\gamma RT}$$

(3)

where γ is the specific heat ratio, R is the specific gas constant, and T is the gas temperature. A one-dimensional *standing* acoustic pressure wave can be described by the expression

$$p'(x,t) = A(x)sin\omega t$$

(4)

where the **acoustic pressure** p' sinusoidally fluctuates in time. $A(x)$ is the local amplitude of the pressure fluctuation at position x along the length of the combustor, and ω is the fluctuation frequency (e.g., radians/second). Note that for this standing wave, *the spatial variation of the acoustic pressure is independent from the temporal variation.*

Due to the boundary conditions at the ends of the pipe, the standing pressure wave has **nodes**, defined by $A(x) = 0$, at the open ends of the pipe and an **anti-node**, a maximum amplitude, at the center of the pipe. It can be shown that the acoustic velocities are 90° out-of-phase with the acoustic pressures. Thus the velocity has a node at the pipe center and anti-nodes at the open ends.

As shown in Figure 1, the pressure and velocity amplitudes in the lower half of the tube are on the same side of the axis. In the upper part of the tube, on the other hand, they are on opposite sides. It can be shown that **if heat is added** 1) *in phase with the pressure oscillations* and 2) in a part of the tube *where velocity and pressure amplitudes are of the same sign*, the fluctuating heat release will drive the pressure oscillations. In other words, if heat is added near the middle of the lower half of the pipe the combustor will pulse. In a way this can be regarded as a cycle. The heat addition induces the pressure oscillations that in turn cause velocity oscillations. The pressure and velocity oscillations cause oscillations in heat release, which once again drive the pressure oscillations, and the cycle continues.

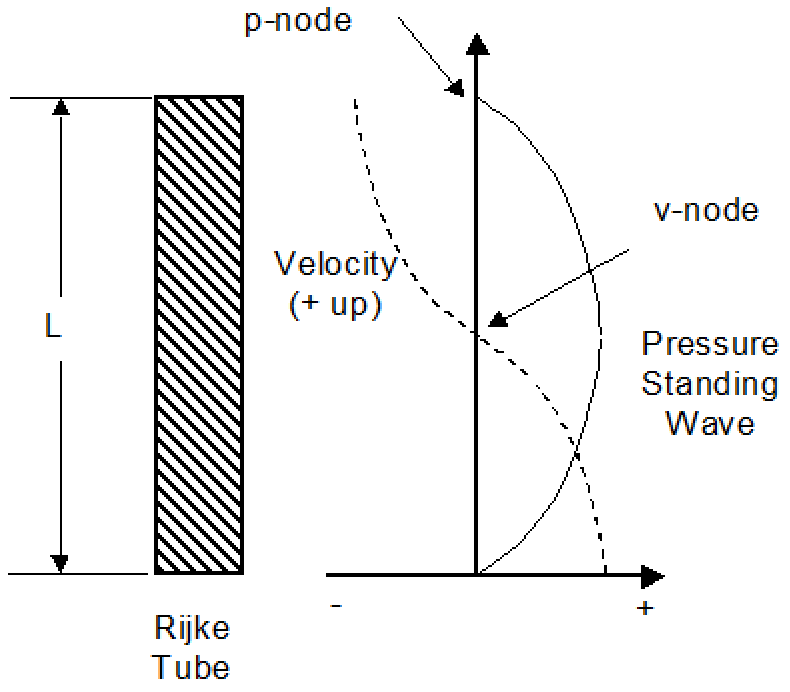


Figure 1. Schematic of standing wave in Rijke tube (note: the wavelength, $\lambda = 2L$)

A schematic of the actual combustor is shown in Figure 2. The lower end of the tube is open to the atmosphere while the upper end connects, via a large decoupling chamber, to an exhaust pipe in the ceiling. The decoupler acts like a muffler while still simulating an open end at the top of the pipe. Quartz windows are fitted into the curved wall of the pipe around the center of the lower half of the Rijke tube. Through these the flame can be observed and the radiation measurements can be carried out. A propane-fired burner can be translated by remote control up and down inside the lower half of the tube. The position of the burner can be measured using a scale attached to the tube. The buoyancy produced by the hot combustion products causes an upward draft in the tube upon which the acoustic velocity fluctuations may be superimposed. The burner is ignited using a spark.

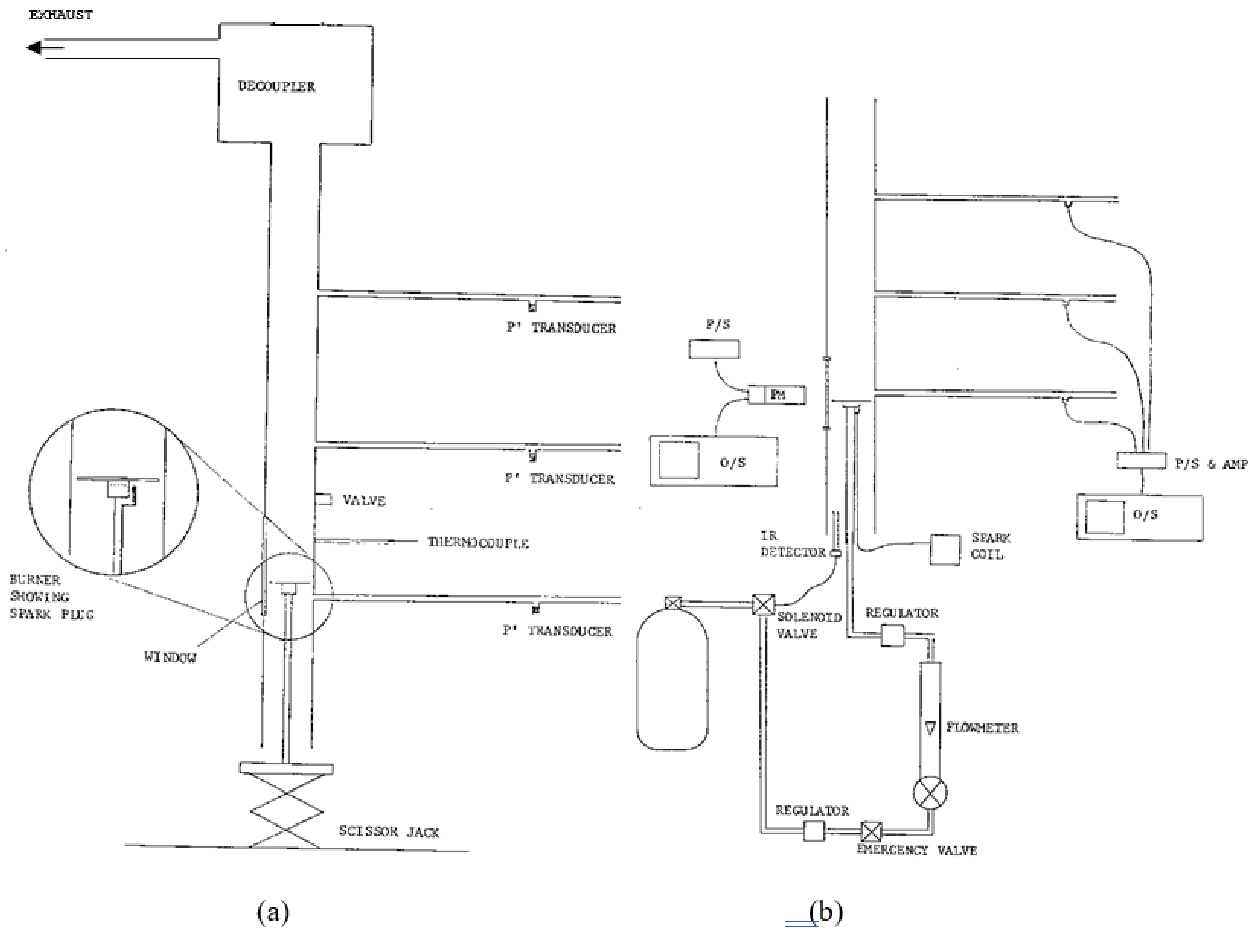


Figure 2. RIJKE tube: (a) tube/combustor schematic, (b) hook-up schematic.

Three acoustic pressure transducers are fitted to the Rijke tube near its center and near the centers of the upper and lower halves of the tube (Figure 2a). An optical detector (photomultiplier) behind an interference filter is mounted opposite one of the windows. The outputs from the photomultiplier and the pressure transducers are amplified and can be connected either to an oscilloscope or a computer data acquisition system. The fuel flow rate is measured using a rotameter. The pressure in the flowmeter is measured using a pressure gauge, while the temperature is assumed to be room temperature. Study Figure 2b and become familiar with it.

Instrumentation for Measurements

Pressure Measurements

The oscillating pressures in the pulse combustor will be measured using piezoelectric pressure transducers. This sensor portion of the transducer (Figure 3) is a small cylinder with a diaphragm on one end. The diaphragm covers a small piece of quartz or crystalline material. When the crystal experiences a stress on the diaphragm, it produces (or absorbs) *a current* that is proportional to the strain. This is known as the **piezoelectric effect**. The diaphragm is flush-welded to the case and acts as a cover for the crystal rather than as a sensing element. The output signal of the combined system is proportional to the strain, and thus the stress, applied on the crystal. For a piezoelectric pressure transducer, the stress is induced by the gas pressure on the diaphragm.

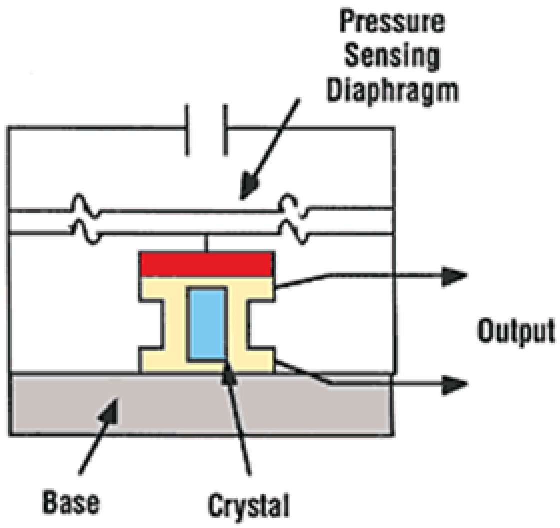


Figure 3. Schematic of piezoelectric pressure sensor (from “Pressure Measurement: Principles and Practice,” sensorsmag.com/articles/0103/19/main.shtml).

Thus piezoelectric sensor is something like the strain gages you used in previous labs, in that is also responds to strain. Electrically, the piezoelectric transducer resembles a capacitor, which can source or sink current. So, piezoelectric pressure sensors do not require an external excitation (i.e., power) source and are very rugged. The sensors however, do require charge amplification circuitry. Therefore the crystal output is connected to an electrostatic charge amplifier that generates a high level (millivolts), low impedance, DC voltage output signal. This voltage signal is directly measured by our DAQ system and thereafter must be converted to an actual pressure reading. To do this we use the calibration as shown in Figure 4, which is calculated by the manufacturer who applies known pressures to the transducer and observes the corresponding voltage output. This mapping being so linear is no coincidence; transducers are commonly designed to have linear responses so that a simple conversion can be made across the entire range of the transducer's range of operation.

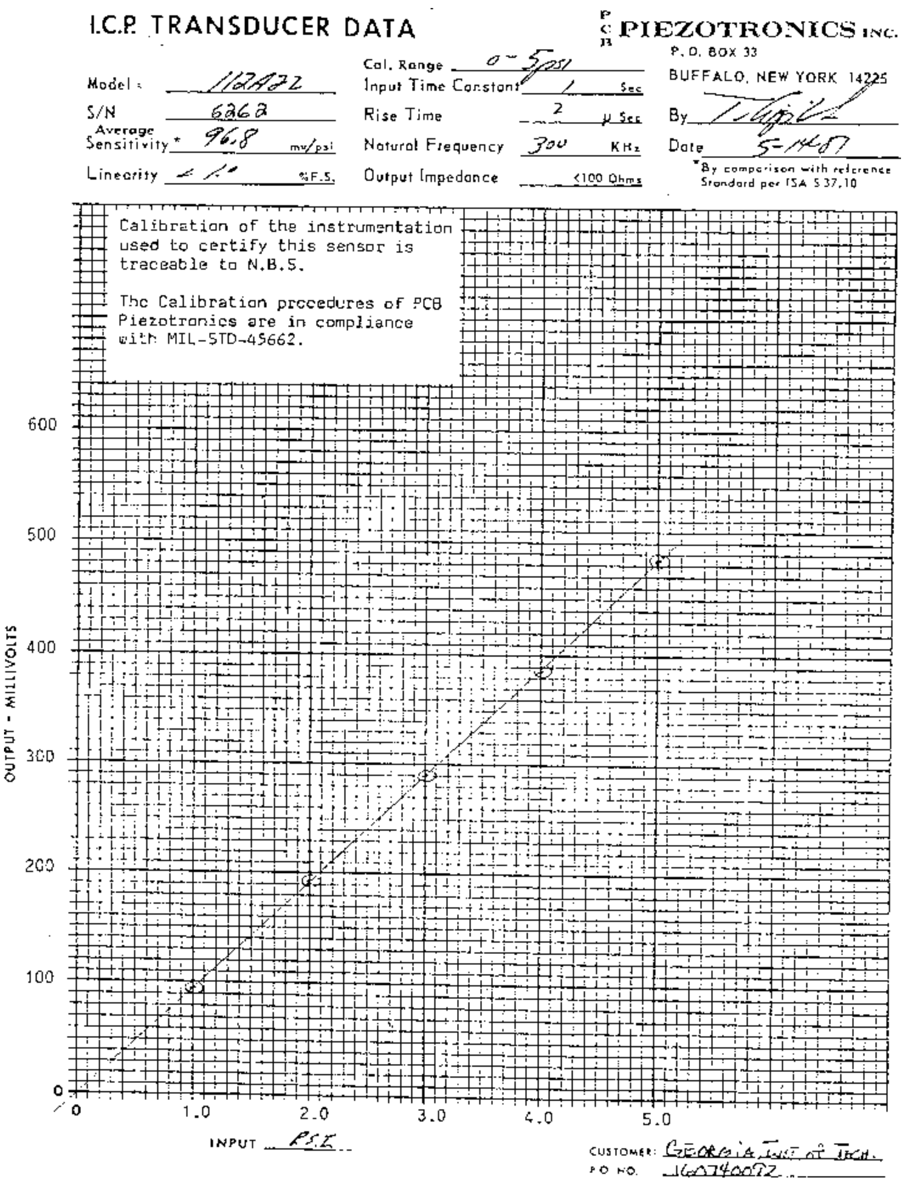


Figure 4. Pressure transducer calibration

These transducers have very fast response times (e.g., 1-10 μ sec) and will, therefore, be able to follow the fluctuating pressure signals. However, they are also susceptible to shock/vibration induced strains, and they are very temperature sensitive. Thus we cannot mount them directly to the combustor wall, which will heat up during operation of the combustor. Instead, the transducers are mounted in a semi-infinite tube configuration shown in Figure 5. This removes the sensor from the hot wall. The long PVC tubing leading from the transducer to atmosphere prevents any pressure wave reflections from the end of the tube that may affect the frequency response of the transducer. Because the piezoelectric transducers have a very rapid time response, we can connect them to time-resolved recording devices (e.g., oscilloscopes or computers) and generate power and phase spectra. [2]

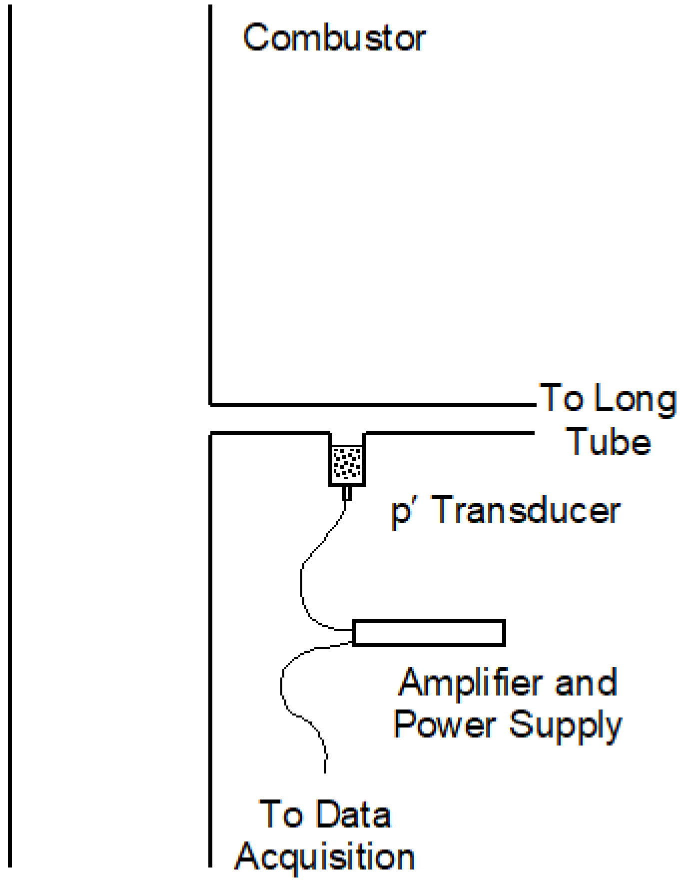


Figure 5. Schematic of pressure transducer mounted in semi-infinite tube configuration.

[2] A power spectrum is a graph of signal power (amplitude squared) versus frequency. Large single peaks indicate the signal is primarily composed of a single sine waves at the peak frequencies. The phase spectra shows the relative phase at each frequency.

Reaction Rate Measurements

The intensity of the combustion process, that is the rate at which fuel is consumed (the "reaction rate") and energy is released, can be monitored optically. During the combustion of hydrocarbon, the fuel reacts with the oxygen in the air to form carbon dioxide and water. However, this reaction does not occur in one step. Instead, a number of intermediates chemical species (radicals) are formed that have very short lifetimes before being destroyed in the next steps of the reaction process that lead to production of CO2 and H2O.

Examples of these intermediates are OH, CH, H, O and HCO. Since these radicals have unpaired electrons ("unsatisfied bonds"), they tend to be unstable and react very quickly, a process during which they are consumed. It has been shown that much of the light emitted by a flame's reaction zone comes from radicals that are produced by a chemical reaction that leaves them with an electron in a high energy orbital. This high energy state tends to decay to a lower, equilibrium energy state through molecular collisions and, to a lesser extent, by emission of radiation (light). This process, chemical creation in an excited state followed by emission of light, is called **chemiluminescence**. The chemiluminescence is *roughly* proportional to the rate at which the reaction proceeds. Since the combustion process is exothermic, i.e., chemical bond energy is converted to thermal energy or heat, chemiluminescence is qualitatively proportional to the heat release rate (energy per unit time, i.e., power). A number of optical techniques have, therefore, been developed to detect flame radiation. These optical techniques also have the advantage that no foreign object, or probe, that would interfere with the chemical reaction by catalysis or quenching has to be introduced into the flame. Furthermore, these optical techniques have very fast response times.

The technique to be used here makes use of the fact that most of the radicals emit light in very specific ranges of wavelengths (or "colors"). In particular, OH chemiluminescence occurs mostly in the range 306-311 nm (1 nm = 10-9 m), which is in the ultraviolet region of the radiation spectrum. In our experiments, the fluctuations in heat release rate are measured by passing the light emitted by the flame through an interference filter onto a photomultiplier. The interference filter allows light only in a small band of wavelengths (around ~305-315 nm in our case) to pass while the photomultiplier converts this light into an electric current that can be measured. The interference filter consists of a quartz substrate, as opposed to standard glass that does not transmit ultraviolet light, on which a number of different, thin metallic coatings have been deposited in such a way as to reject all but the narrow range of wavelengths.

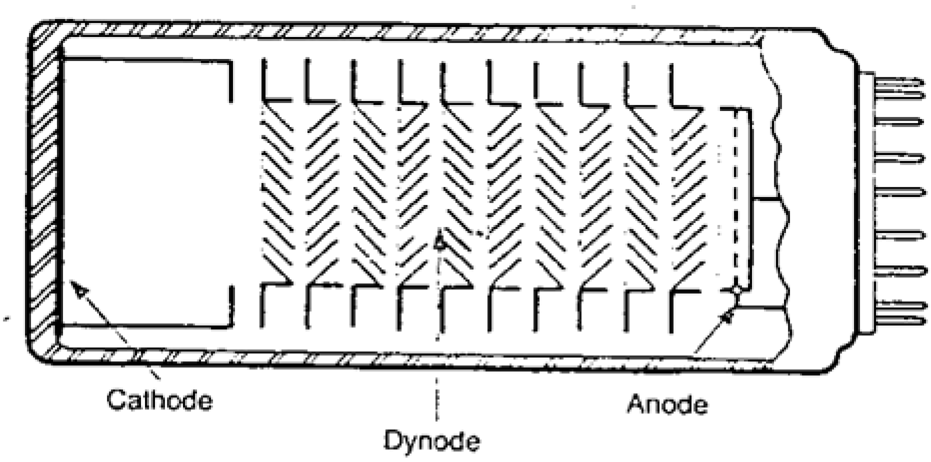


Figure 6. Schematic of a photomultiplier.

The photomultiplier consists of a photocathode, a series of charged screens or dynodes and an anode collector enclosed in an evacuated glass or quartz tube as shown in Figure 6. A high voltage (approximately 600 Volts) is applied between the cathode and anode while the dynodes are biased to intermediate voltages with a chain of resistors (the "dynode chain"). If photons are incident upon the photocathode, a proportional number of electrons are liberated (the **photoelectric effect**). These photoelectrons are then accelerated by the large voltage difference towards the (positive) anode. As these fast and accelerating electrons pass through or strike the dynodes, they liberate additional electrons that also accelerate towards the anode. After a number of dynodes, the original number of electrons has grown many times. Thus the original photons produce a small flow of electrons (a current!) that is amplified; hence the name photomultiplier. The number of electrons liberated per incident photon, which depends upon the work function of the cathode material, is referred to as the quantum efficiency h. In fact, the number of electrons emitted per photon is usually less than one, with h often below 15%. The amplification factor depends upon the number of dynode stages (typically between 7 and 11) and the applied voltage. Together, they determine the overall gain of the photomultiplier tube. Since the work function of the cathode materials is wavelength (color) dependent, different tubes with different cathode materials are used for different applications. The output from the photomultiplier tube, which is a current, is passed through a resistor, and the resulting voltage (drop) is measured. As with the pressure data, the photomultiplier output can be connected to the oscilloscope or computer.

Procedure

Safety Considerations

As with any combustion experiment **safety is a primary concern**. The fuel line is fitted with a manual shut off valve, pressure regulators and a remotely controlled solenoid valve. The fuel flow rate has been preset with the pressure regulators which are locked.

Please **DO NOT** attempt to change their settings. The ignition circuit has been designed so as to switch on the solenoid valve and the spark simultaneously. This will prevent the build up of propane in the tube which might lead to an explosion. *If ignition does not occur within 10 seconds the system, including the fuel flow, will shut down*. Any propane remaining in the tube should then be flushed out with the compressed air provided **before** pushing the reset button and attempting to relight. An infrared detector mounted on the floor monitors the flame. If the flame is extinguished it will shut the solenoid valve in the fuel line.

You may want to shut down the combustor by pushing the red button if you anticipate a longer delay between consecutive tests. The tube can get hot during operation, so **do not** touch it. Be sure to turn off all manual valves after all your tests are completed.

1. Determine the length of the Rijke tube, and the distances of the upper and lower pressure transducers from the central transducer.

2. Connect the upper (PU) and middle (PM) pressure transducers to the oscilloscope channels 1 and 2 (5 ms/div and 50 mV/div, set to AC coupling). The “Invert” button for channel 2 should be in the OUT position. Be sure that the thermocouple is retracted. Flush the tube with air. Position the burner using the remote control so that you can see it through the upper part of the large window (at ~6" based on the scale attached to the combustor) and ignite by pushing the black button. Continue to hold down this button for ~5 seconds after ignition. Make sure the heavier float in the rotameter is at the correct position (190-200) and the gage pressure at the rotameter exit is near zero.

3. Observe the pressure traces corresponding to the upper (PU) and middle (PM) pressure transducers on the oscilloscope and take notes. Also observe and make notes about the flame shape. Is there a flame below the burner plate?

4. Now, lower the burner to the 0" station and repeat step 3.

5. Remove the PM transducer from the oscilloscope and replace it with the PMT output and change sensitivity to 2V/div. (AC coupling). Observe and compare the pressure and PMT traces.
   Connect each of the pressure transducer outputs to the multimeter and read off the rms voltage values. (There will be some fluctuation of the rms with time, so try to get an average). The upper and lower pressure transducers are spaced 18 inches on either side of the central transducer.

6. Connect the pressure transducer and photomultiplier outputs to the four channels of the computer data acquisition system. Connect the sensors as follows:
   1. channel #0 is the photomultiplier,
   2. channel #1 is the upper pressure transducer (PU),
   3. channel #2 is PM,
   4. channel #3 is PL

7. Launch the LabView Rijke VI
   1. For **real-time visualization mode** (without saving) make sure you set the save flag to "Do not Save" **before** executing the VI with the **run continuously** button. You should be verifying all data looks good in this mode before saving.
   2. For **saving mode** stop the VI and change the save flag to 'Save' before executing the VI with the **run once** button. If you hit run continuous by mistake with the save flag activated it will try and save over and over, in which case hit cancel and then quickly hit the stop button before it tries to save again.

8. Acquire 1 or more data sets with the computer. Each time you acquire data, the computer will store the rms voltages, peak frequencies and associated phases for each of the channels. It will also store the power spectrum for each channel.

9. Open the valve at the back of the tube wall. Listen. Observe the flame and repeat step 7.

10. Close the valve and make sure the pulsations resume.

11. Raise the burner to the 2" station and repeat step 7.

12. Raise the burner slowly until the pulsations cease. Record the location where this happens and observe the flame shape when the pulsations cease. Repeat step 7.

13. Lower the burner slowly until the pulsations begin again. Record the location where this happens.

14. Shut down the burner using the stop button.

Data to be Taken

1. Rijke tube length and distance between pressure transducers.

2. Observations of the flame and transducer traces at the various burner locations described in the steps above

3. Burner location where pulsations cease.

4. Computer data acquisition results at 0” (valve closed and open conditions), 2”, and pulsation cessation.

Data Reduction

1. Take the rms voltages corresponding to the three pressure signals as read by the computer and convert them to dB values (see “Conversions and Properties” section below). Use the attached calibration curve for all three transducers. The calibrations are similar enough for this to be close to correct.

2. Use the length of the Rijke tube to estimate its resonance frequency assuming the gas in the tube is air with a specific heat ratio of 1.4.

3. Determine the relative phase of the pressure and radiation signals by calculating difference between each signal and the signal from the middle pressure sensor (PM).

Results Needed For Report

At a minimum, report the following results from the quantitative measurements that you carried out.

1. The frequencies and amplitudes (in dB) for the 3 pressure signals, and the frequency and rms of the PMT signal. At the four conditions (burner location and valve position) required in the Procedure. Include your estimated tube resonance frequency.

2. The relative phase angles of the peak frequencies of the three pressure signals and the PMT signal at the 0” burner location.

Conversions and Properties

1. The sound pressure level (SPL) of an acoustic pressure field is given by

$$SPL(dB) = 20\,log_{10}\left\{\frac{p_{RMS}}{p_{RMS_{threshold}}}\right\}$$

   where dB refers to decibels, p_{RMS} is the root-mean-square fluctuation of the pressure field and $p_{RMS_{threshold}}$ is the nominal rms pressure fluctuation that corresponds to the “threshold of human hearing.” This threshold value is standardized at 2 x 10-4 dynes/cm2 (or 2.0 x 10-5 N/m2 = 2.0 x 10-5 Pa = 2.9 x 10-9 psi).

2. The heating value of propane is 2,563 BTU/SCF, where SCF is the **standard** cubic feet of propane, i.e., the volume of propane in ft ^{3} at **standard** conditions.

Helicopter

Objectives

The primary objective of this experiment is to introduce the student to the measurement and response of a dynamical system. The experiments will occur on a tandem-rotor helicopter model connected to a pinned, swivel arm with a counter weight. Optical shaft encoders sense the motions of the helicopter model. During the experiment, we will calibrate the thrust control (voltage) input to the DC motors that control the rotors. Then we will measure the response of the system, specifically elevation, to various thrust inputs. Finally, the system response will be compared to a dynamical model of the helicopter.

Background

Dynamical Systems

A dynamical system is one in which the effects of an action do not achieve their impact immediately; the dynamical system evolves with time. The time evolution of the system depends both on the time-history of the external input(s) to the system and the properties of the system itself. Dynamical systems exist in many fields and applications:

- When a pilot changes the throttle (thrust) setting, the vehicle's velocity changes only gradually – but the lighter the vehicle, the faster it can reach the final velocity
- When a cook puts something in the oven, its temperature does not rise to the oven temperature instantly – and larger items heat more slowly than smaller dishes
- When a company lowers the price of a product, the impact on the product's sales (and the company's stock) can take months to evolve – and that one input is not the only thing that effects the revenues (or stock price).

This way of looking at a system is in contrast to static approaches. For example in the previous labs, you looked at the response of a system to an external input: strain response of a system to a given stress, or lift on a wing as a function of angle-of-attack and wind speed. In those instances, however, we did not consider any rate issues; we assumed there was a unique (unvarying) relationship between the inputs and outputs of the systems. This was because we ensured that the rate at which we applied the changes to the inputs (or how long we waited to acquire the data) was much slower (or longer) than how fast the system took to reach a ***steady-state***, i.e., how long it took to stop changing.

A powerful way to understand or predict the behavior of a dynamical system is through mathematical models. The models include variables that describe the current state of the system, the ***state variables***, and the things driving the system, i.e., the ***external inputs***. For example, we can look at a point mass that is free to move, the state variables would be: position ($\vec{x}$), velocity ($\vec{v}$) and acceleration ($\vec{a}$), with three components of each if the mass can move in three dimensions. As you learned in physics for simple 1-d motion, these variables are not independent, i.e., $a = dv/dt$ and $v = dx/dt$.

As an example of how one develops a model, we begin with a simple mass m pushed by an external force and constrained to move in one dimension. In this case, the motion of the mass is governed by Newton's Law, i.e.,

$$F_{external} = ma = m\frac{d^2x}{dt^2} \Rightarrow m\ddot{x}(t) = F_{external}(t)$$

Eq. 1

where the notation .. represents the second derivative with respect to time. Now consider what happens if we add a spring that anchors the mass to a wall. Some of the force applied to the mass may now have to compress or expand the spring. You probably also learned in physics that the spring force can be modeled by Hooke's Law (Eq. 1),

$$m\ddot{x} = F_{external} + F_{spring} \Rightarrow m\ddot{x}(t) + kx(t) = F_{external}(t)$$

Eq. 2

We can also add another device, called a damper, that produces a force that always opposes the motion of the mass – and the opposing force is proportional to the velocity, i.e.,

$$F_{damper} = -bv = -b\dot{x}$$

where b is the damping coefficient and $\dot{}$ means a first derivative with respect to time. Now including all the forces acting on our mass, we have

$$m\ddot{x}(t) = b\dot{x}(t) + kx(t) = F_{external}(t)$$

or equivalently:

$$\ddot{x}(t) + \frac{b}{m}\dot{x}(t) + \frac{k}{m}x(t) = \frac{F_{external}(t)}{m}$$

(3)

This differential equation models the dynamics of what is known as a spring-mass-damper system, which is illustrated in Figure 1. This simple system represents a number of real systems; for example, the suspension systems used on cars combines springs and shock absorbers (dampers). Similarly, an electrical circuit composed of a capacitor, inductor and resistor in series has the same dynamics. Moreover, this simple system displays behaviors that are also seen in more complex systems, like our helicopter model. For example, if we remove the damper from the system, i.e., set the damping constant to essentially zero, the mass would continuously move back and forth as the spring is repeatedly compressed and expanded. On the other hand if the damping was very high, it would be very hard to move the mass quickly. Also note that the coefficient of the last term on the left side (k/m) has units of $1/s^2$ or a frequency squared.

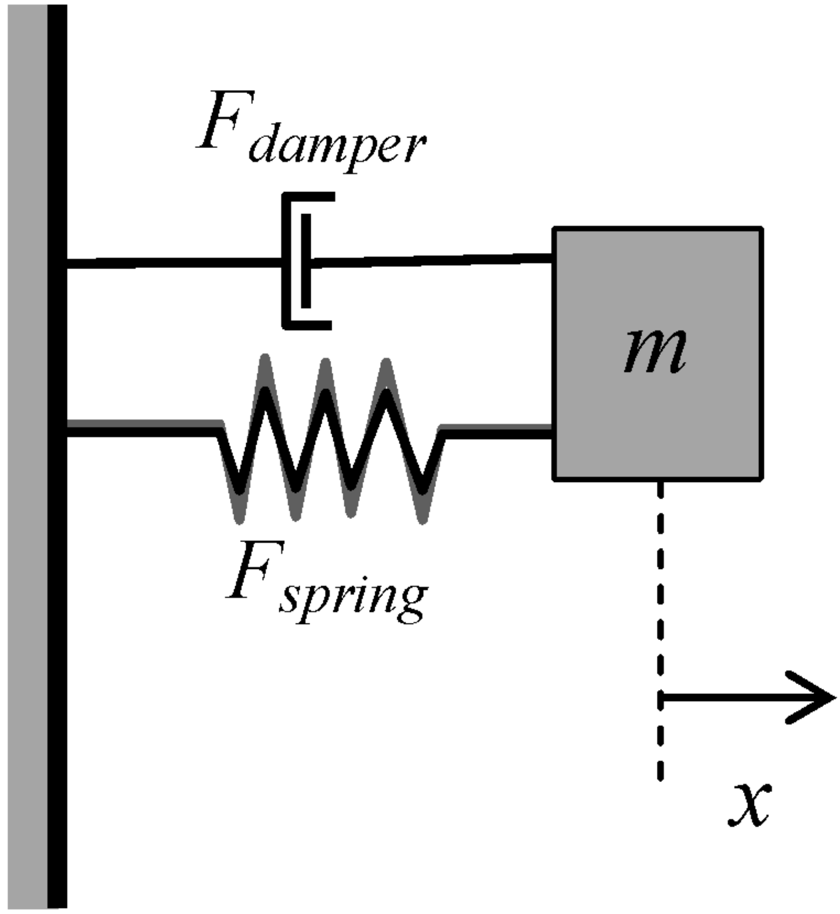


Figure 1. Schematic of one-dimensional spring-mass-damper system.

3-DOF Helicopter Model

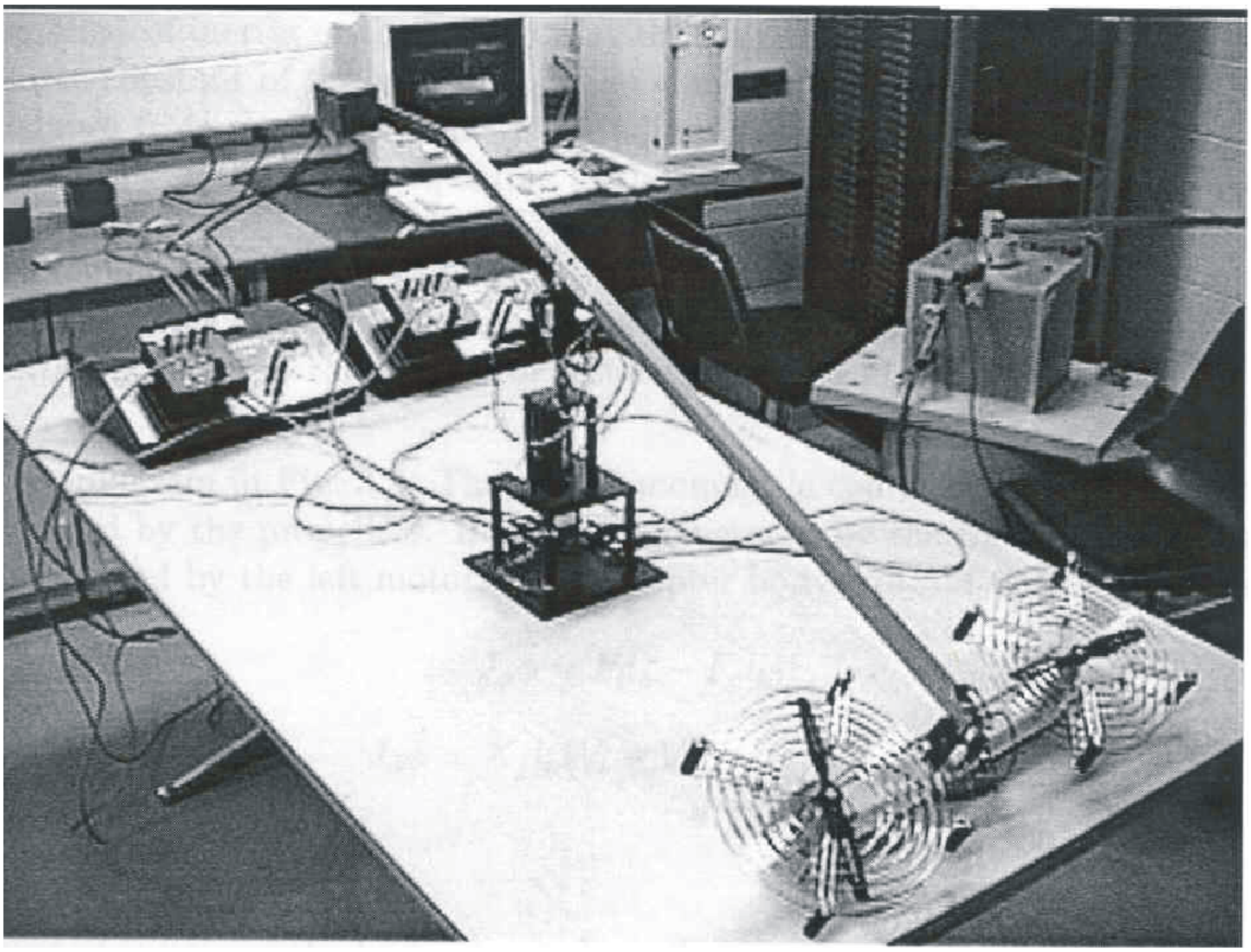


Figure 2. Photograph of Quanser 3 degree-of-freedom helicopter mechanism in GT lab.

The 3 degree-of-freedom (DOF) helicopter mechanism used in this experiment is shown in Figure 2. The 3-DOF helicopter consists of a base upon which an arm is mounted (see Figure 3). The arm carries the helicopter body at one end and a counterweight at the other. Two DC motors with rotors mounted on the helicopter body generate a force (which we will call **thrust**) based on the voltages applied to each of the motors. The portion of the thrust generated by the rotors that is in the vertical direction can cause the helicopter body to lift off the ground, because the arm is held by a pin-type connector. The purpose of the counterweight is to reduce the power requirements on the motors. The standard counterweight location is normally adjusted such that applying about 7-8 V to the motors results in hover with the arm in a horizontal position.

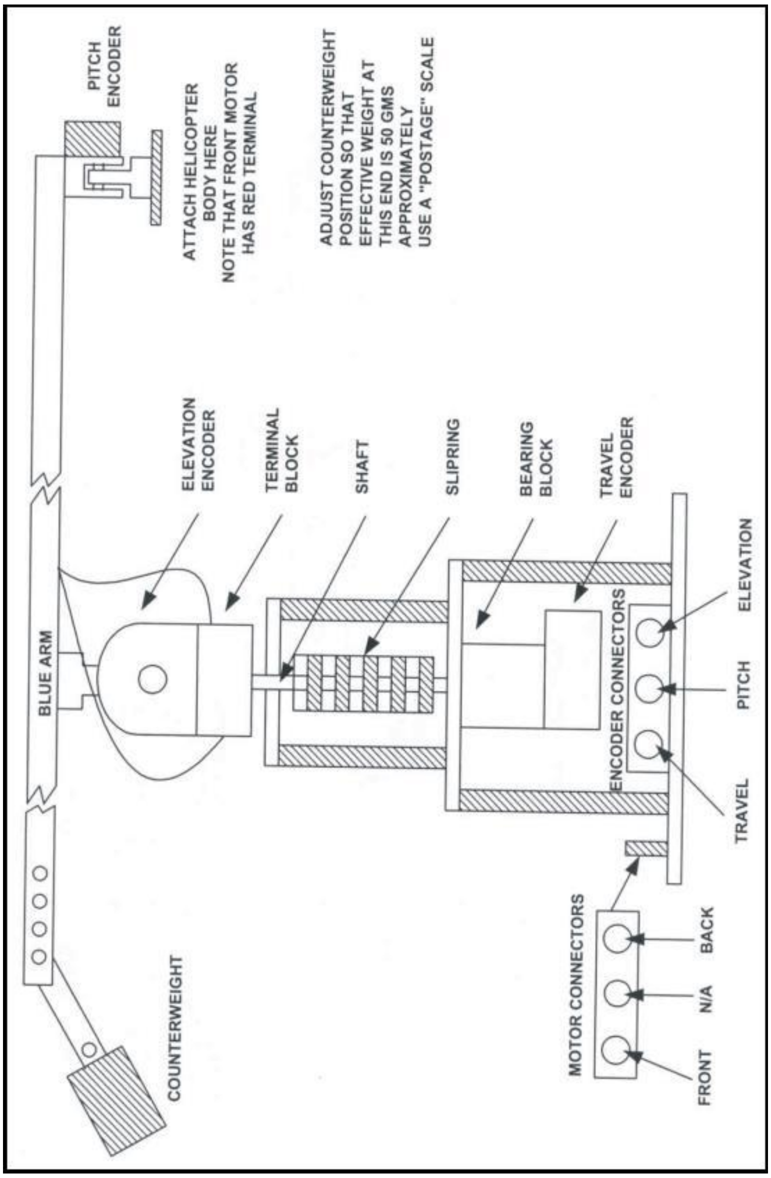


Figure 3. Schematic of 3-DOF helicopter mechanism.

The whole arm can **pitch**, which allows the elevation of the model to change, and it can also travel (yaw) in an azimuthal direction around the central swivel shaft. Optical encoders mounted on these axes allow for measuring the pitch and travel of the model. The helicopter model is mounted at the end of the arm as shown in Figure 4, and the helicopter body (or essentially the arm between the rotors) is free to roll about the arm. A third encoder measures this roll angle. All electrical signals to and from the main swivel arm are transmitted via a slip-ring with eight contacts, thus eliminating the possibility of tangled wires and reducing the amount of friction and loading about the moving axes.

In this experiment, the two rotors will be driven by a **control system** with a Matlab/Simulink™ interface that will use feedback control to keep the model from traveling/yawing or from rolling. Thus, you will *consider only the pitch* (or elevation) and total *lift* (produced by both rotors) as a function of time.

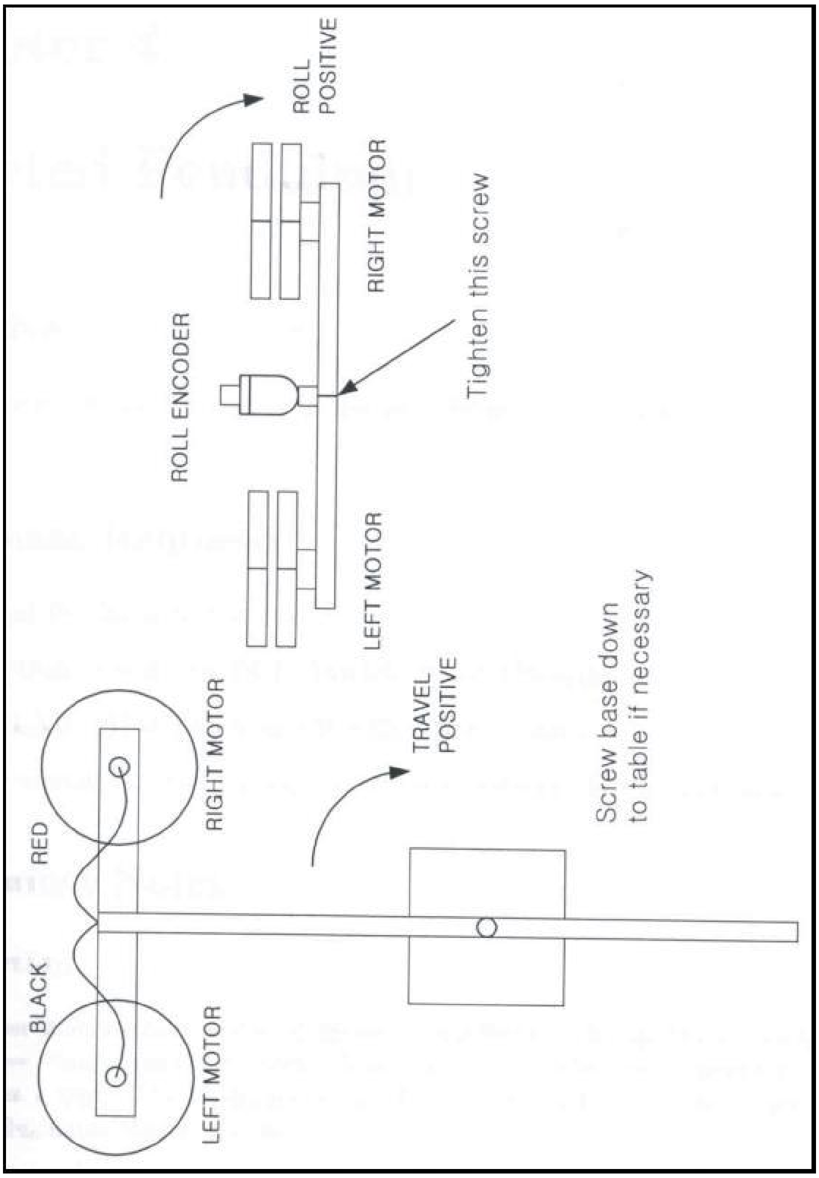


Figure 4. Main parts of the 3-DOF helicopter mechanism (looking from the back and top).

To determine the steady-state condition of our helicopter model, we can examine a *static* moment balance on the arm. From Figure 5, we can see that the model will not change its pitch angle θ (or equivalently the elevation of our model helicopter) when the moments about the pinned arm are balanced, i.e.,

$$F_{cw} l_b - F_h l_a + F_T l_h = 0$$

This expression incorporates the assumption that the mass of the lever arms are negligible. We can then solve for the thrust force produced by the rotors/fans,

$$F_T = \frac{F_h l_a = F_{cw} l_b}{l_h}$$

(4)

When the thrust produced by the rotors satisfies Eq. (4), the helicopter will have the correct thrust to hover at the given pitch angle. If we change the thrust, the helicopter will have a new steady-state hover condition; after changing the thrust, however, it will take some time for the helicopter to get to the new steady-state pitch/elevation.

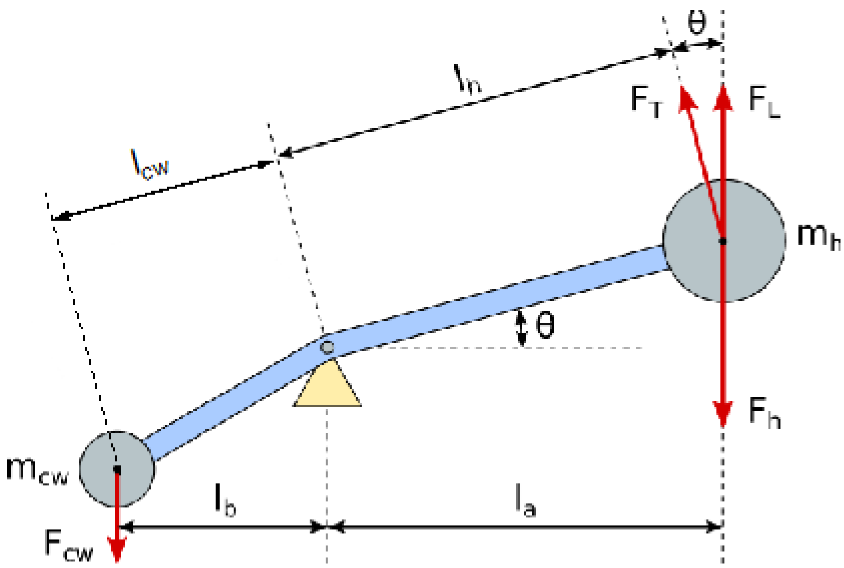


Figure 5. Free body diagram for helicopter model, with mcw=counter weight mass, mh=helicopter model mass, lh= arm length from arm's pin location to the center-of-mass of helicopter "body", FT=thrust force, FL=lift force.

You will be running three different experiments on the helicopter model.

1. Calibrating the motor control voltage, i.e., determining the thrust produced by a given motor control voltage.

2. Measuring how the system responds when its controller is told to move the helicopter to a given pitch angle (~20°), but with different levels of system damping.

3. Measuring how the system responds when you provide a thrust control input that is a sudden increase in thrust that stays constant (also known as a *step input*).

In addition, you will be using Matlab to simulate the dynamics of the helicopter mode for comparison to your experimental data.

l_h	$0.63\ m$
m_{cw}	$1.87\ kg$
$\frac{F_h l_h - F_{cw} l_{cw}}{l_h}$	$0.445\ N^*$

Table 1. Helicopter parameters (see Figure 5 for parameter definitions). Based on “flight” configuration for lab (not calibration configuration).

Optical Shaft Encoders

The motions to be measured in this experiment are all related to the rotational motion of a shaft. Thus the Quanser system employs shaft (or rotary) encoders to measure the pitch, travel and roll of the helicopter model. Generally, a shaft encoder converts an angular position to an analog or digital output. While there are a number of electro-mechanical approaches employed in encoders, the most common employ either magnetic or optical sensors to read the shaft motion, with the latter more common, especially in high resolution encoders. These types of systems have replaced older electronic potentiometer-based systems.

Optical shaft encoders typically rely on the rotation of an internal code disc that has a pattern of opaque lines or shapes imprinted on it. The disc is rotated in a beam of light, e.g., from a small LED, and the pattern of dark and light regions on the disc act as shutters, blocking and unblocking the light in systems based on transmission, or strongly and weakly reflecting the light (see Figure 6). For high resolution, the disc is divided into many segments, typically in concentric rings. Internal photodetectors sense the alternating intensity of the light and the encoder's electronics convert the pattern into an electrical output signal.

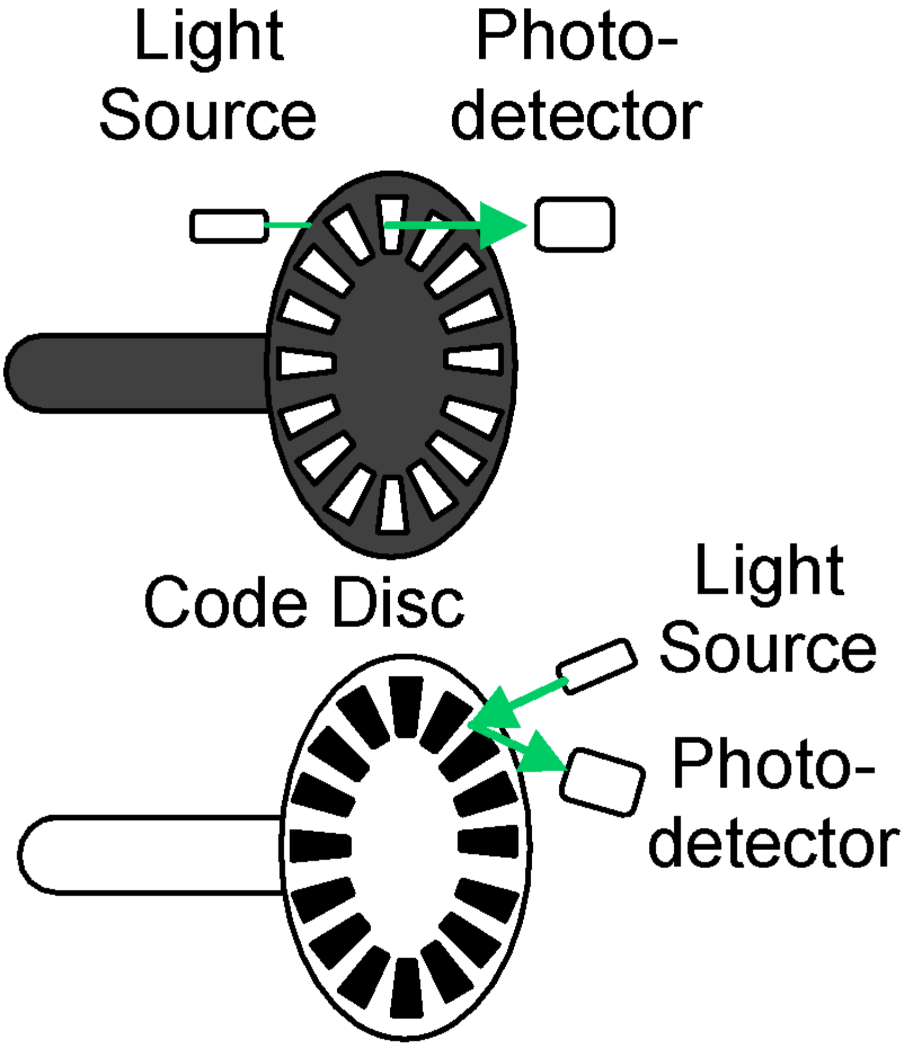


Figure 6. Schematic of basic transmissive (top) and reflective (bottom) approaches used in standard optical encoders.

There are two basic types of encoders: absolute and relative (also called incremental). An absolute encoder returns an exact position, or an angle in a rotary encoder, relative to a fixed zero position. An incremental encoder provides information on the instantaneous movement of the device, which can be converted to speed, distance traveled or position relative to an arbitrary initial state. Absolute encoders are necessary if a particular angular position must be known or retained, independent of when the encoder was powered on. Most other applications can employ an incremental encoder. Absolute encoders provide a output with a unique code pattern that is derived from independent tracks on the encoder disc which correspond to individual photodetectors and represents each position. Incremental encoders are simpler and provide information about the instantaneous motion of a rotating shaft by determining how many and/or how fast the alternating disc patterns go by.

Procedure

Although some of you will not be performing the lab yourself, it is important that you read these procedures carefully as you will need to understand them so that you may write a complete lab report.

Calibration of rotor motor control voltage

1. Make sure the counterweight is connected to the endmost attachment hole (the hole farthest from the helicopter); we will call this hole 1. (This is the flight configuration)

2. Measure the moment arm ("horizontal" distance, e.g., l_{cw} in Figure 5) between the arm's pivot point and the location of holes 1, 4 and 7, where you are going to place the counterweight (hole 4 would be the 4th hole from the end).

3. Turn on both PA-0103 Power Modules for the helicopter.

4. On the control computer, begin the Simulink software by double-clicking on the *C:\AE 2610\Helicopter 2610\Helicopter_Thrust_Identification.slx* file. This opens a Simulink window showing the controller bock diagram. Note, it may take a few seconds after Matlab starts for the window to pop up. Click the **Build Model** button to generate the code required to run the controller. Look in the Matlab command window and wait for the status to indicate the model is downloaded to target; the controller is now ready to run. Navigate back to the block diagram window and set the **run time** to 45 seconds (in the editable text box).

5. Have someone support the arm of the system (on the helicopter side of the center support) to keep the helicopter level (at the horizontal position); THEN click the **Connect to Target** button in the menu bar, followed by clicking the the **Run** button . Once the rotors have starting turning, you can let go of the arm. The person running the

computer should watch the timer and warn the person catching the helicopter to be ready.

1. If the helicopter does not hover at the horizontal position, you may have to do this step again, but this time hold the helicopter a little higher than the horizontal position.
2. If you get an error message when you hit run, you will need to go back and click Build Model again and do this step over.

6. Double click the voltage output module (green) to show a plot displaying the rotor motor input voltage as a function of time. Click the **Autoscale** button to resize the plot. Pink values show the filtered and averaged motor voltage.

7. In the command window enter the following commands (note Filename1 and Filename2 are names you pick):
   1. ```
      csvwrite('Filename1.csv',motor_voltage_f)
      ```
   2. ```
      csvwrite('Filename2.csv',time)
      ```

   This saves the filtered motor voltage and time values to a your chosen filename. Make sure that the two filenames are different. Check that the data has been saved, and the file can be opened, and then move the file to your group's folder.

8. Move the counterweight to the second location and **repeat steps 5-7**. When you remove and reinsert the bolt back in the counterweight, make sure to do this without stripping the threads. It will help if you hold the counterweight firmly against the arm while you are unscrewing and screwing the bolt.

9. Move the counterweight to the third location and repeat **steps 5-7**.

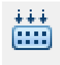
10. Close the block diagram window - but **DO NOT save the model when prompted**.

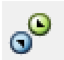
11. Make sure the counterweight is replaced in hole 1.

Response of helicopter/controller for different damping levels

1. Using the current folder window in Matlab, open the *Helicopter_Damping_Ratio.slx* file. In the command window enter: `Kd = #` where # is a value that determines the

damping of the system (a higher value corresponds to more damping). The first time you do this, pick a value in the range 30-50.

2. Click the **Build Model** button  to generate the code required to run the controller. Look in the Matlab command window and wait for the status to indicate the model is *downloaded to target*, the controller is now ready to run. Navigate back to the block diagram window and set the **run time** to 45 seconds.

3. As before, keep the helicopter horizontal/level THEN click the **Connect to Target** button  , and then the **Run** button  . Let go of the arm once the rotors begin turning. The controller is going to move the helicopter to a positive pitch angle (~20°), hold it there for a short time, and then return it to zero pitch for a short time until the run is over. REMEMBER to have someone ready to catch it when the time is up.

4. Double click the green **voltage display** and **pitch display** modules to see how they each vary with time.

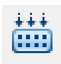
5. Save the following variables/data: *motor_voltage_f, time,* and *theta*.

6. Enter a new value of Kd in the range 70-100, and **repeat steps 14-16.**

7. Close the block diagram window - but **DO NOT save the model when prompted.**

Response of the helicopter to step input to motor voltage

1. Open the *Helicopter_thrust_input.slx* file. In the command window, enter `T = #` where # is a value between 0.2 and 0.4. Then enter `Kv = 19.23` .

2. Click the **Build Model** button  to generate the code required to run the controller. Look in the Matlab command window and wait for the status to indicate the model is *downloaded to target*, the controller is now ready to run. Navigate back to the block diagram window and set the **run time** to 60 seconds.

3. As before, support the arm to keep the helicopter horizontal/level, click the **Connect to Target** button and then click the the **Run** button . Let go of the arm once the rotors begin turning. REMEMBER to have someone ready to catch it when the time is up.

4. Save the following variables/data: *motor_voltage_f, time*, and *theta*.

Data To Be Taken

1. Lever arm distances for the counterweight positions.

2. Motor control voltages required to produce horizontal hover for three locations of the counterweight.

3. Measurement of the helicopter’s pitch and thrust control voltage versus time for two damping values.

4. Measurement of the helicopter pitch and thrust control voltage versus time for the step rise in the thrust control voltages.

Data Reduction

1. Using a modified moment balance like Eq. 4, find the **thrust force** required to produce horizontal hover for each of your counterweight locations.

2. Use a regression analysis (e.g., a least-squares fit) to find a relationship between the lift force and the motor control voltages.

3. Convert your measurements of pitch angle and control voltage versus time to helicopter elevation and thrust versus time.

Simulation Procedure

Consider a model of our helicopter system governed by the following equation of motion

$$J\ddot{\theta} = F_L l_a - F_h l_a + F_{cw} l_b - k_x\theta - k_d\dot{\theta}$$

where in addition to the forces acting on the helicopter discussed above we have added two frictional forces. First there is a frictional proportional to θ through the coefficient k_s , and second there is a friction proportional to $\dot{\theta}$ through the coefficient k_d .

1. Manipulate the equation of motion above to solve for $\ddot{\theta}$ in terms of the quantities $F_T, F_{cw}, F_h, l_{cw}, l_h, J, k_s, k_d, \theta, \dot{\theta}$. Do not forget that some quantities such as l_a, l_b and F_L are related to the system parameters through θ .

2. Implement this equation of motion into the *Helicopter_ode45_Starter.m* Matlab file which was provided where the ode is solved using the **ode45** function in Matlab. (Hint: it is useful to open the Matlab documentation for the **ode45** function to learn how to implement the ode).

3. Plot your pitch in degrees versus time for both the simulation and the experimental data.

4. Adjust the parameters k_d and k_s until you get a relatively good fit to the experimental data. (The fit must not be perfect, just close enough).

Results Needed For DATA Report

1. A plot of thrust as a function of voltage, and the linear relationship between the thrust and the motor control voltages.

2. A plot of the helicopter experimental applied thrust and its elevation as a function of time for the two damping cases.

3. A plot of the helicopter experimental thrust and its elevation as a function of time for the step input.

4. Two plots comparing the helicopter experimental elevation and the Matlab simulated elevation as a function of time for the step input. The first plot should use the standard values of $k_s = 0.2$ and $k_d = 0.1$. The second plot should use your adjusted k_s and k_d values.

5. Comment on how k_s and k_d influence the model predicted response of the helicopter system.

Subsonic Wind Tunnel

Objectives

The primary objective of this experiment is to familiarize the student with measurement of aerodynamic forces in a wind tunnel. A six-component sting balance will be used to measure forces and moments on a rectangular (two-dimensional) wing with an adjustable plain flap. In addition, the student will become acquainted with the operation of a subsonic wind tunnel, including use of a Pitot-static probe and pressure transducer to measure wind speed.

Georgia Tech's Harper Wind Tunnel, on the ground floor of the Guggenheim Building. Photo credit: Rob Felt

Photo credit: Rob Felt

Background

Aerodynamics of a Wing

Forces and Moments

In general, a body moving through a fluid is subject to three force and three moment components. The primary force components on an aerodynamic body, and in particular a wing, are lift and drag. Lift is the force component that is perpendicular to the oncoming flow direction, and drag is the component parallel to the flow (see Figure 1). Lift is generally considered positive when in a direction “upward” (opposing gravity), while drag is normally positive in the flow direction (i.e., tending to slow down the body). The third component is the called the side force. For objects symmetric about the side force axis and moving straight into the flow, there should be no side force. Side forces on a wing usually come about when an aircraft is turning or not flying into the wind.

The three moments are: the pitching, roll, and yaw moments (see Figure 1). The pitching moment is around an axis parallel to the direction of the side force, and would act to change the pitch or angle of attack (a) of the lift body. The roll moment is around an axis in the drag direction, while the yaw moment acts around the lift axis. For most wings flying into the wind, the pitching moment is the dominant component. It is customary to define the pitching moment about the aerodynamic center; the point at which the pitching moment does not vary with lift coefficient, i.e., angle of attack.

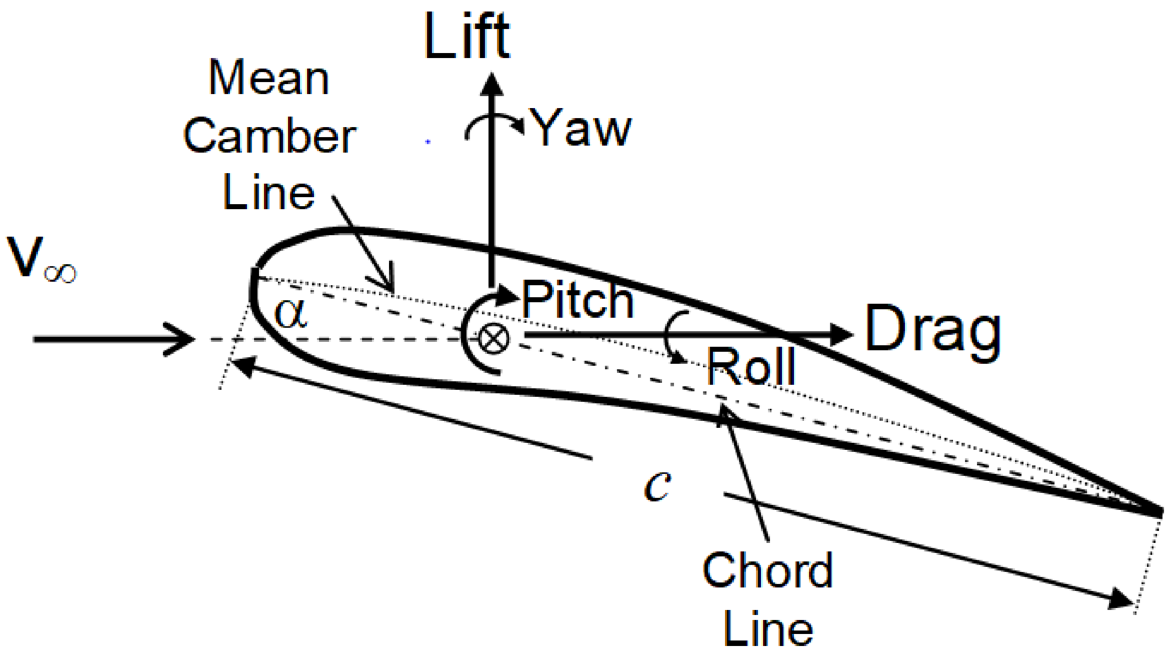


Figure 1. Some of the force and moment components on an airfoil. The angle of the attack (α) is shown between the chord line and the flow direction.

The magnitudes of the aerodynamic forces and moments depend primarily on the shape of the body, the speed and orientation of the body with respect to the fluid, and certain properties of the fluid. For a rectangular wing, lift primarily depends on the curvature (camber [1]) of its cross-section, the angle of attack, the flow speed, and the density of air. The shape of the wing's cross-section is known as an airfoil.

The thin airfoil inviscid flow model [2] (also called "thin airfoil theory") predicts that lift increases with increasing positive (concave downward) camber or with rearward movement of the location of the maximum camber. In a "real" viscous airflow, this is also true at moderate angles of attack. Thus, the maximum value of the lift coefficient attainable with any airfoil increases with increasing camber. This is of great benefit, since the higher the maximum lift coefficient the lower the stalling speed. Also, the effective camber of an airfoil can be varied by deflecting a segment of the airfoil such as a flap or aileron. It may be shown that, for a given amount of deflection, the change in lift coefficient is larger if the deflection occurs at the trailing edge rather than at the leading edge. Hence, flaps and ailerons are fitted at the trailing edge of an airfoil or wing. Additionally, thin airfoil theory predicts that the aerodynamic center of an airfoil is located one-quarter of a chord length behind its leading edge.

The rectangular wing used in this experiment (see Table 1 for dimensions) is fitted with a plain trailing edge flap. Aerodynamics forces on the airfoil will be measured as a function of wing angle of attack and flap deflection angle. The lift results will show if increased flap deflection has the expected effect, while the drag results will show whether an increase in lift at a fixed angle of attack by means of a flap deflection is accompanied by any corresponding drag change. If there is a drag increase this is not necessarily a disadvantage. For example, during landing the higher engine power required to compensate for the drag increase will minimize engine acceleration time in the event of a missed approach.

Dimension	Value (inches)
Span	18.25
Chord (including flap)	3.00
Flap Chord	0.82
Maximum Thickness	0.54

Table 1. Dimension of the rectangular planform wing at zero flap angle.

[1] The camber line of a wing's cross-section connects the midway points between the upper and lower surfaces.

[2] See for example, Anderson's Fundamentals of Aerodynamics.

Aerodynamics Coefficients

Aerodynamics forces on a wing are typically normalized and expressed as aerodynamic force coefficients. For example, the lift coefficient (CL), drag coefficient (CD) and pitching moment coefficient (CM) are defined as:

$$C_L = \frac{L}{q_\infty S}$$

(1)

$$C_D = \frac{D}{q_\infty S}$$

(2)

$$C_M = \frac{M}{q_\infty Sc}$$

(3)

where L is the lift force, D is the drag force, M is the pitching moment, S is the plan form area of the wing, c is the chord length (see Figure 1), and q_∞ is the dynamic pressure. For our rectangular wing, $S = c \times b$, where b is the span (tip-to-tip length) of the wing.

Thin airfoil theory predicts that CL for a symmetric airfoil, i.e., where the chord and camber lines are the same (also known as a zero camber airfoil) that also has infinite span is given by

$$C_L = 2\pi\alpha$$

(4)

This expression is valid only for small and moderate angles of attack. At sufficiently large angles of attack, the flow over the wing no longer follows the surface, and the wing's lift coefficient begins to drop, i.e., the wing stalls.

The dynamic pressure q_∞ is given by

$$q_\infty = \frac{1}{2} p_\infty v_\infty^2$$

(5)

where p_∞ is the density of the approaching flow and v_∞ is its speed (relative to the body/wing). This is called the dynamic pressure because according to Bernoulli's equation (which is valid for a low speed, constant density flow) it represents the difference between the stagnation (or total) pressure and static pressure of a flow, i.e.,

$$p_o - p = \frac{1}{2} p_\infty v_\infty^2$$

(6)

The static pressure is the pressure one would measure if moving with the flow (or without requiring a change in the flow velocity), while stagnation pressure is the static pressure that the flow would achieve if it was slowed (in an ideal manner) to zero velocity. For an ideal gas, the density is given by

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

(7)

Here p is the (absolute) pressure, T is the (absolute) temperature, and R is the gas constant for the specific gas.

Sensors and Transducers

Sting Balance

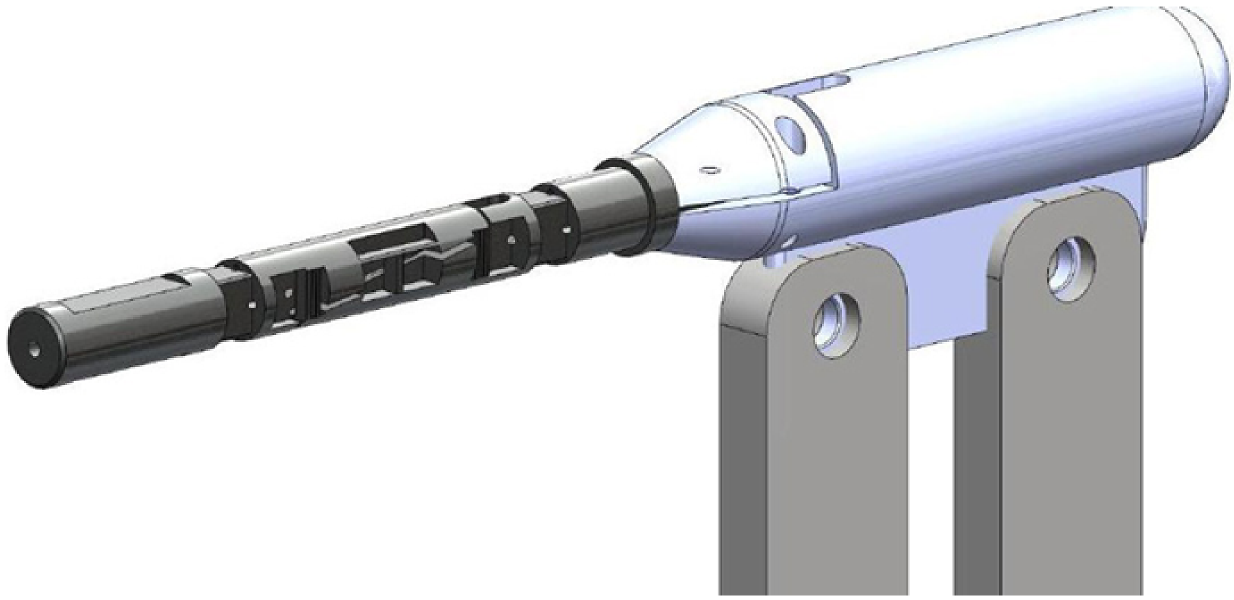


Figure 2. Schematic of Aerolab internal strain gauge sting balance (shown without protective sheath) mounted on model positioning system (MPS).

The force-measuring device to be used in these experiments is a sting balance mounted on a model positioning system (MPS) that controls both pitch and yaw angles. Wind tunnel force balances can be categorized into two basic types: external and internal. The force transducers for external balances are located outside the wind tunnel test section, and the aerodynamic forces must be mechanically transmitted from the test body in the wind tunnel to the balance outside. Internal balances have their force measuring unit within the wind tunnel, and thus provide a more direct measurement of the aerodynamic forces. The AerolabsTM internal balance (Figure 2) employed in our wind tunnel uses strain gauges mounted within a rod cut from a single piece of precipitation-hardened stainless steel with a protective sheath to protect the fragile foil strain gauges. The strain gauges are connected to electronics (including wheatstone bridges), which are in turn connected to a computer data acquisition system located in the wind tunnel control room. The Aerolab system will acquire 5000 samples every 100 ms and report the average. By setting the dwell time of the MPS, you can set the number of measurements that will be recorded at each angle of attack (e.g., a dwell time of 1 second would result in 10 measurements).

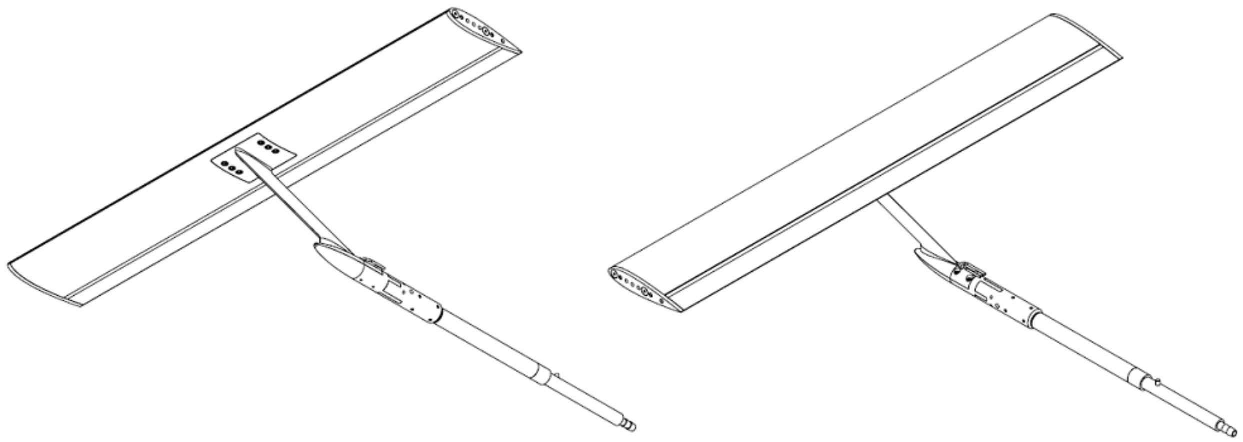


Figure 3. Schematic of wing and support structure connected to sting balance (left – bottom view; right – top view).

Two procedures are required to convert the voltage outputs from the strain gauge system into accurate measurements of the aerodynamics forces (and moments). First, the strain gauges must be calibrated. This is accomplished using an attachment of known mass that can be connected to the balance. Second, any forces transmitted to the balance that are not produced by the wing must be removed. In this experiment, there is a support structure that connects the balance to the wing (see Figure 3). This support structure can produce its own aerodynamics forces. In addition, even with the wind tunnel off, the weight of the structure and wing will load the balance. Removing these wind-off (or tare) loads is known as taring the system.

If the data are to be meaningful, each test run must be carried out at a (nearly) constant value of wind tunnel dynamic pressure. Ideally, the magnitude of the aerodynamics force coefficients would be independent of the magnitude of the dynamic pressure. In reality, this assumption might not be completely accurate, so the dynamic pressure should be held constant during a particular data-taking run so that the coefficients will not be influenced by changes in freestream conditions. The speed of the fan that drives the wind tunnel is nominally held constant by the fan's motor control system. This should produce a nearly constant wind tunnel dynamic pressure. (If necessary, the dynamic pressure can be manually adjusted with the tunnel speed control.)

Pitot-Static Probe

In addition, a second data acquisition system will simultaneously acquire and store the dynamic pressure during the experiment. The dynamic pressure is measured directly by means of a Pitot-static probe mounted in the freestream. The probe has one hole facing directly into the wind tunnel flow and another located so the air flows along the surface of the hole (see Figure 4). The pressure in the first hole is the stagnation pressure (p_o) and the second experiences the static pressure (p). The two holes are connected via long lengths of tubing to the two sides of a capacitance-type differential pressure transducer (Baratron). This transducer interprets the displacement of a diaphragm due to a change in pressure difference across the diaphragm as a change in capacitance in an electronic circuit, which is output as a DC voltage change. This DC voltage is displayed on a digital voltmeter, which can be monitored by the wind tunnel operator (as noted above, it is also connected to the data acquisition system). The output voltage of the Baratron can be converted to a pressure using the sensitivity of the transducer (e.g., mmHg/Volt).

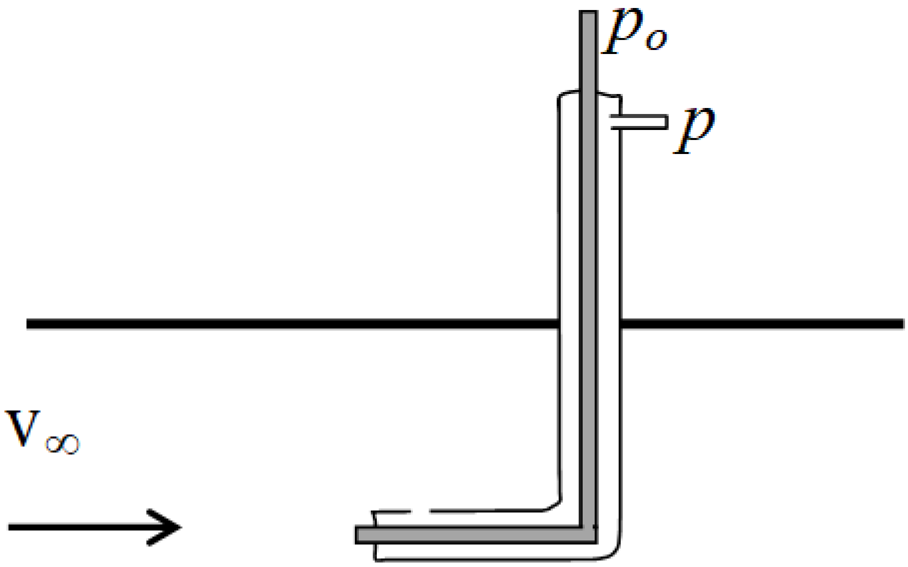


Figure 4. Schematic of Pitot-static probe in a wind tunnel.

The Wind Tunnel

A wind tunnel is a duct or pipe through which air is drawn or blown. The Wright brothers designed and built a wind tunnel in 1901. The basic principle upon which the wind tunnel is based is that the forces on an airplane moving through air at a particular speed are the same as the forces on a fixed airplane with air moving past it at the same speed. Of course, the model in the wind tunnel is usually smaller than (but geometrically similar to) the full size device, so that it is necessary to know and apply the scaling laws in order to interpret the wind tunnel data in terms of a full scale vehicle. The wind tunnel used in these experiments is of the open-return type (Figure 5). Air is drawn from the room into a large settling chamber (1) fitted with a honeycomb and several screens. The honeycomb is there to remove swirl imparted to the air by the fan. The screens break down large eddies in the flow and smooth the flow before it enters the test section. Following the settling chamber, the air accelerates through a contraction cone (2) where the area reduces (continuity requires that the velocity increase). The test (working) section (3) is of constant area (42" ´ 40"). The test section is fitted with one movable side wall so that small adjustments may be made to the area in order to account for boundary layer growth, thus keeping the streamwise velocity and static pressure distributions constant. The air exhausts into the room and recirculates. The maximum velocity of this wind tunnel is ~50 mph, and the turbulent fluctuations in the freestream are typically less than 0.5% of the freestream velocity. Thus, it is termed a “low turbulence wind tunnel.”

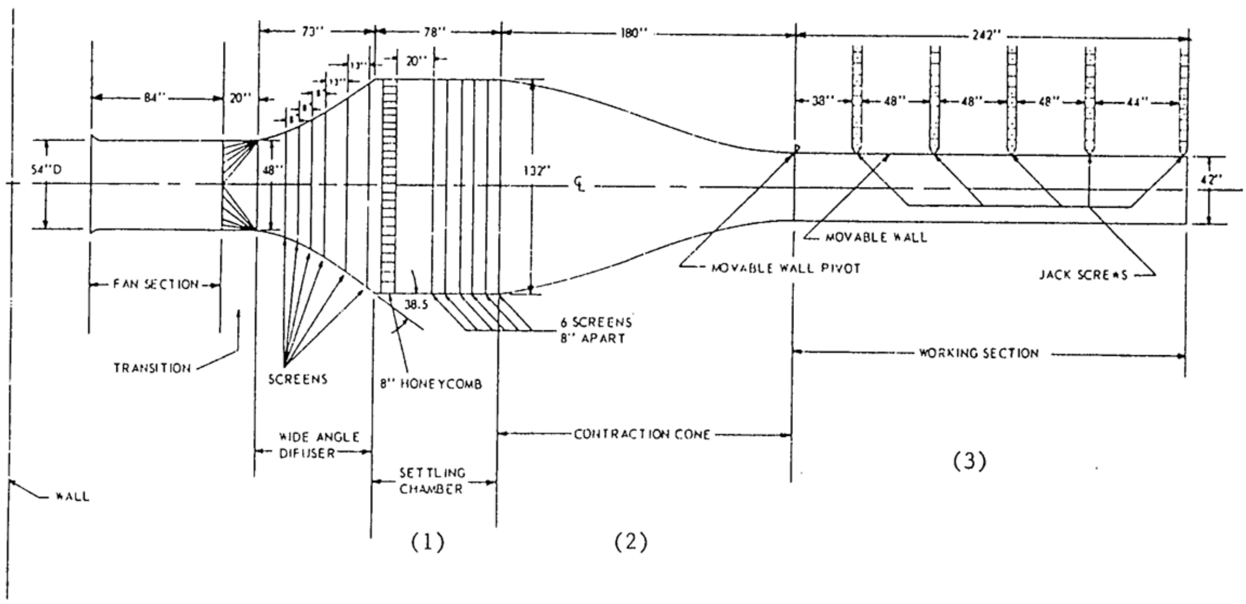


Figure 5. Georgia Tech low turbulence wind tunnel.

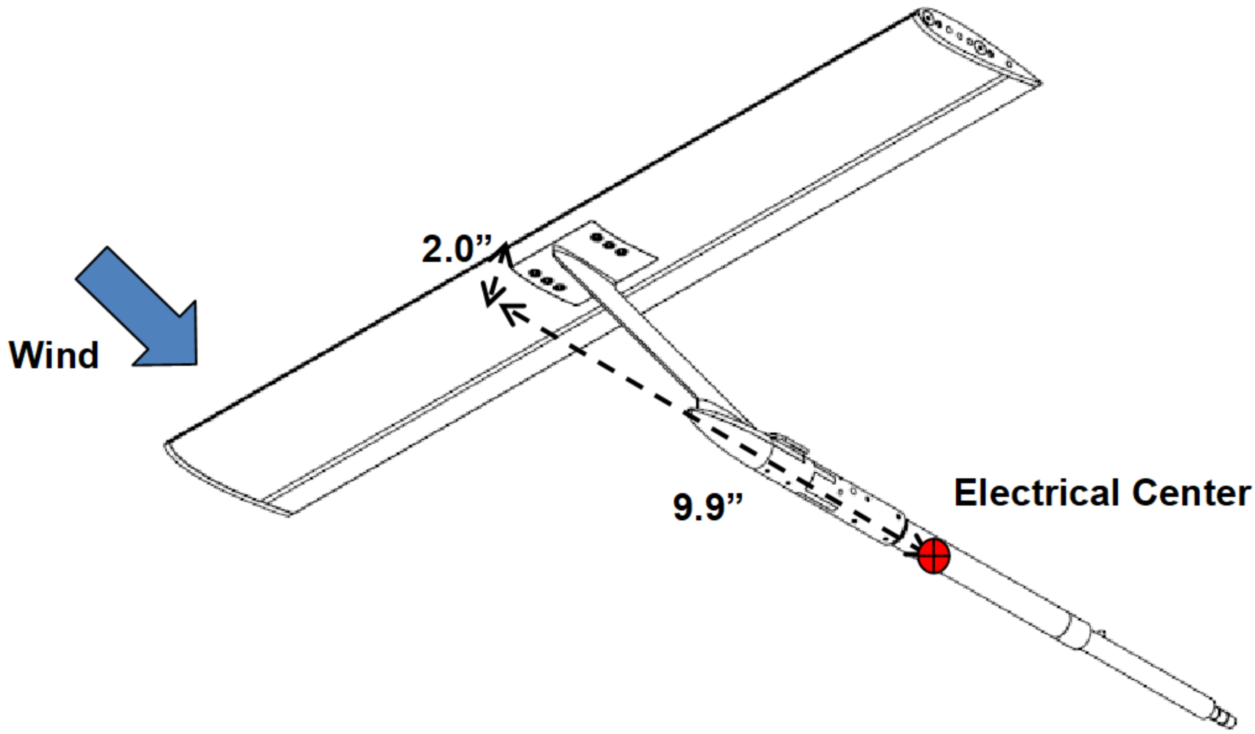


Figure 6. Electronic center of sting balance relative to wing leading edge.

Procedure

Please note: the sting balance rod can be damaged if large loads are applied. For this reason, great care should be taken when handling it and your TA should connect the balance to the MPS.

1. Determine the Baratron output voltage (dynamic pressure) required to produce two wind tunnel speeds: the first somewhere between 33 and 36 mph, the second between 21 and 24 mph, and the angles of attack your group will use.

2. With the help of the TA, attach the wing support and balance rod to the MPS without the wing.

3. Make sure the MPS motor and control switches are powered on (they are found under the wind tunnel). Please make sure that the MPS is free of obstructions and take extreme caution at all times while the servo drives are powered.

4. Run the Aerolab software by choosing the daqX shortcut in the ‘Georgia Tech’ folder (located on the desktop). Then choose the 2nd option in the list provided under the Georgia Tech header.

5. Start the MPS module and wait for the network status to report an operational status. The MPS hardware requires 45-60 seconds to initialize during which the connectivity may be intermittent. If the network does not turn to an operational status, press the ‘Network Reset’ button to reinitialize the servo drive network. **Please do not stop the MPS module without turning off the network at any time during the experiment.**

6. Start the balance module and check the ‘axial’ and ‘normal’ options to visualize how the axial and normal forces change with time during your runs (the software will acquire ALL the forces and moments – but just these two will be displayed on the screen during the experiment).

7. Start the Datalogger module and choose **Timed Run** as the recording method. Set the recording time long enough to include the sum of the dwell times for each angle of attack (see step 8) and an additional 30 seconds to account for the rest of the time required to complete an angle-of-attack (pitch) sweep.

8. In the MPS module, make sure the model is set to a nominal pitch and yaw angle of zero. If not, use can use the **Single Point** control option to return the MPS to zero. Then switch to the **Sweep** control option. Set your group’s 20 pitch angles and set the dwell time to record 50 measurements per pitch angle.

9. On the Balance module, click the **Tare** button (all the readings displayed on the Datalogger plot should go to ~0. If instead they stop being near 0, you have just “untared” the values and need to click the Tare button again.

10. Run a sweep with the wind tunnel off to record the balance wind-off loads. Do this by clicking the **Take Data** button on the Datalogger and the **Move** button under Sweep on the MPS in quick succession. When the sweep has ended, click **Save Data** on the Datalogger to save the results. Choose a suitable file name to help you remember to which experiments the file corresponds. Then return the MPS to a zero pitch position.

11. The next step is to acquire a data sweep for the same model configuration but with the tunnel running. 1) On the 2nd computer, begin the Labview program labeled

‘WindSpeed.vi’ and “turn-on” the Labview VI. Provide a suitable file name to save the dynamic pressures (and in an appropriate folder). 2) Follow the message on the screen and use the wind tunnel controller to set the wind tunnel to the desired speed. DO NOT hit start on the Labview program yet!

12. Now you will record the aerodynamic forces with the tunnel on by following the same procedure outlined in step 10 - HOWEVER this time you will need to synchronize the start and end points of the acquisition on the Aerolab and Labview software by beginning both at the same time (this will require two people – one working each computer).

13. Repeat steps 11 and 12 for the second wind tunnel speed that your group has chosen.

14. Have the TA help with removing the test model from the MPS. Then attach the wing after setting the flap angle to zero. Then, have the TA help reinstall the model to the MPS.

15. Repeat steps 9-13.

16. Have the TA help with removing the test model from the MPS. Then set the flap angle to your chosen angle. Then have the TA help reinstall the model to the MPS.

17. Make sure the MPS is set to zero pitch (and zero yaw), and make sure the system is retared.

18. Repeat steps 12-13 (i.e., sweeps for both wind tunnel speeds at your new flap angle).

19. After the tests are concluded, the appropriate data files will be transferred by the TA’s to the lab website for later data reduction (as noted below).

Data to be Taken

1. You must record the room temperature and barometric pressure in order to set the wind tunnel speed.

2. Tared forces and moments of wing support structure at 20 angles of attack and two wind tunnel speeds.

3. Tared forces and moments of wing and support structure at the same 20 angles of attack and two tunnel speeds.

Data Reduction

1. Remove the support structure loads from the loads acquired with the wing + support structure to find the wing-only normal force, axial force and pitching moment.

2. Convert the measured forces in the balance reference frame to the wind frame (i.e., convert to lift and drag).

3. Convert the recorded pitch moments about the electrical center of the sting balance to the (nominal) aerodynamic center of the wing. The electrical center of the sting balance is located as shown in Figure 6.

4. Express all forces and moments in coefficient form. The chord to be used is the chord of the wing from the wing leading edge to the flap trailing edge.

Results Needed for FORMAL Report (also see instructions on Canvas)

1. Wing geometry - chord of wing (including flap), span, chord of flap, planform, thickness ratio.

2. Plot a figure showing lift coefficient (ordinate) versus angle of attack (CL vs. a) for the wing at the two wind speeds and flap deflection angles.

3. Plot a figure showing drag coefficient (ordinate) versus angle of attack (CD vs. a) for the wing at the two wind speeds and flap deflection angles.

4. Plot a figure with drag coefficient as abscissa and lift coefficient as ordinate (CL vs. CD – also known as a **drag polar**) for the two wind speeds and flap deflections.

5. Plot a figure with moment coefficient (ordinate) versus angle of attack (CM vs. a) for the wing at the two wind speeds and flap deflection angles.

Tensile Testing

Objectives

This experiment is intended to explore the stress-strain behavior of ductile metals subject to tensile loads and to introduce transducers that are used in mechanical testing. The tensile test is the most basic structural test of a material and is used to characterize its response to structural loads. The characterization data obtained from a tensile test is used directly for structural analysis and design. This experiment requires the use of several mechanical transducers that are used to measure the elongation of the specimen and the force applied by the load frame. As part of this lab, you will also be exposed to the physical principles that are used in these devices.

Safety

Wear close-toed shoes in the lab to avoid injuries to your feet if you drop lab equipment, and the eye protection glasses supplied to you. This experiment also involves the use of chemical adhesives and solvents; so make sure to wash your hands after performing the lab.

Background

Stress and Strain

A tensile test is designed to experimentally characterize the relationship between stress and strain. Stress and strain are fundamental concepts in the study of mechanics of materials and we briefly summarize them here.

Stress is a measure of the intensity of a force exerted over an area. In this test, we will measure axial or normal stress. Consider a prismatic bar with a cross-sectional area A_0 , loaded at both its ends with opposing forces with magnitude *P*, the stress in the bar is given by:

$$\sigma = P/A_0$$

(1)

which is the ***normal stress***. Stress has units of force per unit area, which in SI units are pascals [Pa] and in English units are pounds per square inch [psi]. Since the magnitude of stress can be large, it is common to use units of megapascals [MPa] and ksi (i.e., thousands of psi). Note that during the tensile test, the cross-sectional area of the specimen will change; however, we will continue to normalize the force by the initial area. This is usually referred to as ***engineering stress***.

Strain is a measure of the elongation of the structure per unit length. Given a prismatic bar of initial length L_0 and the ***elongation*** of the bar, δ, under load, the ***normal strain*** is given by:

$$\varepsilon = \delta/L_0$$

(2)

Since both δ and L_0 have dimensions of length, strain is a dimensionless quantity. The length of the bar will change during the test, especially at high loads. However, we will always use the initial bar length as a reference.

Tensile Testing Specimens

In this experiment, you will measure the strain in a bar using a strain gauge, and the elongation of the bar under load using an extensometer. These measurement devices are described in a later section.

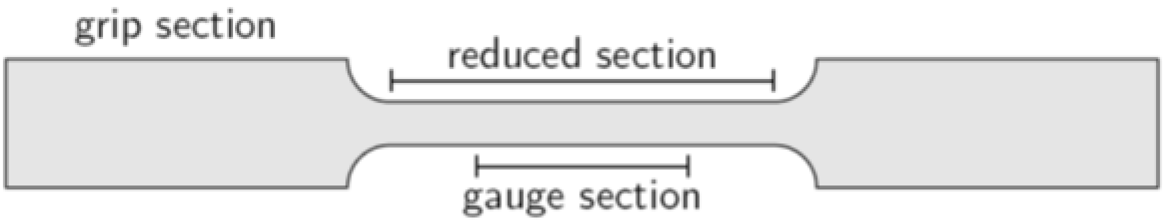


Figure 1. Dog bone test specimen.

You will use aluminum that has been machined into a typical material specimen shape, specifically, a dog bone specimen, as shown in Figure 1. The shape of the specimen is designed to produce a uniform tensile stress and tensile strain in the gauge section. If the specimen were to fail outside this region, in either the grip or shoulder areas, then the results from the test could not be used because stress and strain in these regions are not uniform. The dog bone specimen is designed so that we can fasten the test machine to the grips at either end of the specimen to apply an axial load.

Stress-Strain Diagrams and Material Models

In this experiment, you will generate experimental stress-strain diagrams. A sketch of a stress-strain diagram for a generic ductile metal is shown in Figure 2. As engineers, we use mathematical approximations that are designed to model the measured stress-strain response. Thus, we can explore how closely these mathematical models match the measured stress-strain diagram.

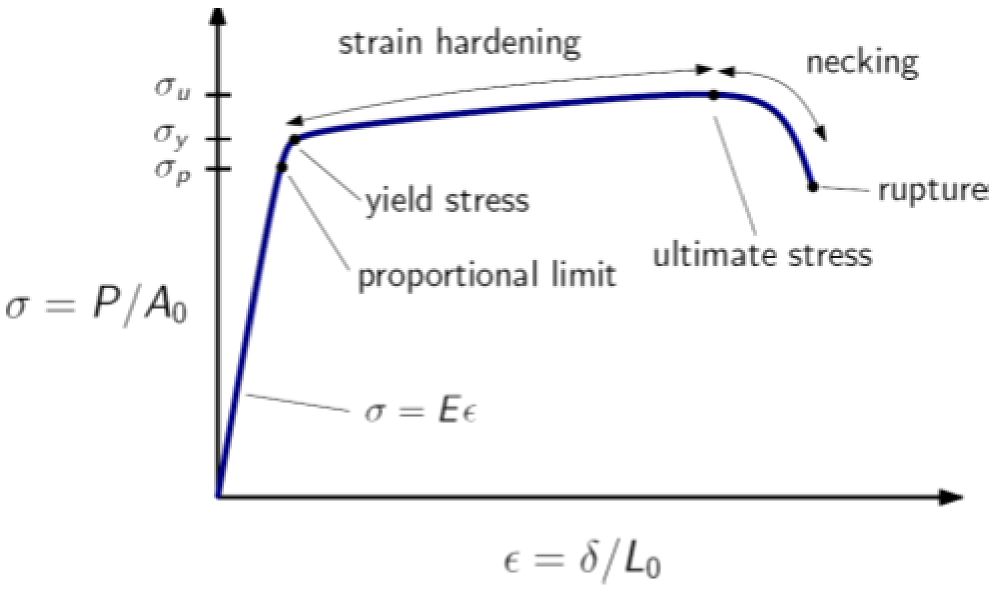


Figure 2. Stress-strain diagram for a ductile metal.

Material models can be classified as either **elastic** or **inelastic**. An elastic response is one in which the loads on the structure are low enough so that no permanent deformation or damage to the specimen occurs. Once the loads are removed, the specimen returns to its original shape, and the experiment could be repeated to produce the same stress-strain response. An inelastic response is one in which permanent deformation occurs, so that when the specimen is unloaded it returns to a different shape than the original specimen.

The simplest mathematical model of an elastic stress-strain response is ***Hooke's Law***. Hooke postulated a linear relationship between stress and strain, written as follows:

$$\sigma = E\varepsilon$$

(3)

Here, the proportionality constant, *E*, is called ***Young's modulus*** or the elastic modulus. Note that since the strain is dimensionless, Young's modulus has the same units as stress. Hooke's Law is often a good model for the stress-strain relationship when the stress is below a threshold called the ***proportional limit***, σ_p . Some ductile metals have a clearly defined proportional limit, others do not. Beyond the proportional limit, the material may still exhibit an elastic response but the relationship between stress and strain is nonlinear. Another important point on the stress-strain diagram is the ***yield stress***, σ_y . Above the yield stress, materials exhibit inelastic behavior where permanent inelastic deformation occurs, even when the load is removed. Again, this is a model of the response of a ductile metal, and some metals have a clearly defined yield point while others do not.

In ductile metals, as the specimen enters the yielding regime it undergoes a large elongation without a large increase in stress. The slope of the stress-strain diagram, called the stiffness, is much smaller than before yielding. As the yielding progresses, metals often exhibit strain hardening (also called work hardening) where the stress increases as the specimen elongates. At some stress, called the ***ultimate stress***, σ_u , a neck begins to form in the specimen. In this necking region, the local stress and strain increase beyond the engineering stress and strain normalized by the initial length and area of the specimen. In this region, the stiffness is negative, and the load must be reduced as the specimen elongates further. Finally, the specimen will rupture or fail.

True Stress and Strain

Thus far, we have examined engineering stress and engineering strain, which are force and elongation normalized by the INITIAL geometric properties. In addition, there are also true stress and true strain; they represent the force normalized by the instantaneous area, and the elongation normalized by the instantaneous length.

The true stress and true strain can be evaluated from the engineering quantities under a constant material volume assumption. Assuming a constant volume, such that $A_0 L_0 = AL$, we can find the ratio

$$\frac{A_0}{A} = \frac{L}{L_0} = \frac{L_0 + \delta}{L_0} = 1 + \epsilon$$

By combining the area ratio above with the expression for engineering stress, Eq. (1), the true stress is given by:

$$\sigma_T = \frac{P}{A} = \frac{P}{A_0}\frac{A_0}{A} = \sigma(1 + \varepsilon)$$

(4)

Similarly the true strain can be related to the engineering strain,

$$\varepsilon_T = \int_{L_0}^{L} \frac{dL}{L} = \ln\left(\frac{L}{L_0}\right) = \ln(1 + \varepsilon)$$

(5)

Note that when the engineering stress and strain are small, then $\sigma_T \approx \sigma$ and $\varepsilon_T \approx \varepsilon$.

Within the strain hardening regime, ductile materials often satisfy the strain hardening law:

$$\sigma_T = K\varepsilon_n^T$$

(6)

where K is called the ***strength coefficient***, and n is called the ***strain hardening exponent***. On a logarithmic scale, this strain hardening law becomes linear:

$$\ln \sigma_T = \ln K + n \ln \varepsilon_T$$

(7)

Plotting the logarithm of the true stress and true strain for the entire loading history produces a piecewise linear curve, where the first curve is from the linear elastic regime, that is,

$$\ln \sigma_T = \ln E + \ln \varepsilon_T$$

(8)

and the second is from the strain hardening regime. An example of a log-log diagram for true stress and true strain is shown in Figure 3. The y-intercept is $\ln K$ and the slope in the strain hardening regime is n.

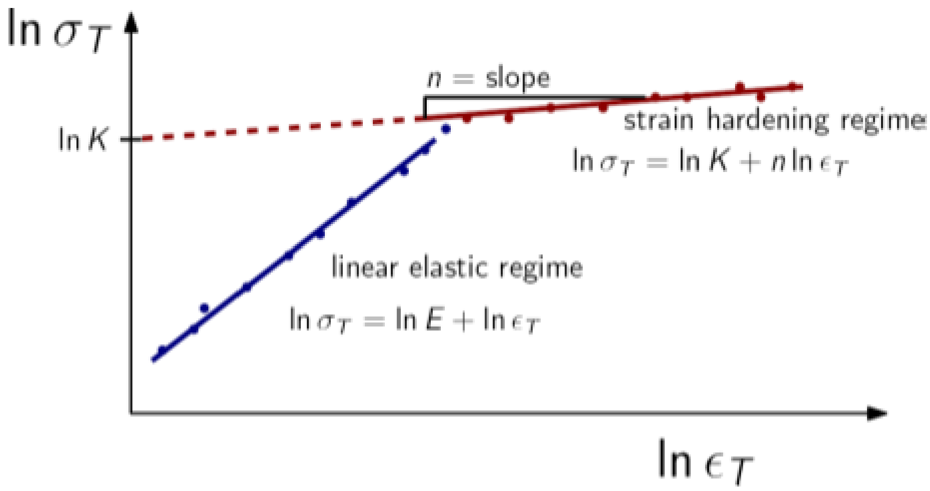


Figure 3. Log-log plot of true stress vs. true strain.

Tensile Testing Equipment

Load Frame

In this lab, we will use a load frame to apply a tensile load to a coupon of an aluminum alloy. The load frame in our lab is an Instron 5982 (see Figure 4) that is capable of delivering 100 kN of axial force to the specimen for testing purposes. It consists of two columns with a crosshead and a base. The crosshead moves up and down the columns driven by lead screws. The crosshead is attached to a load cell, which measures the force applied to the specimen. The test specimen is fastened between two test fixtures attached through pin joints to the base of the frame and the load cell/crosshead. The pin joints ensure that no moments are transmitted to the test specimen.

Figure 4. The Instron 5982 load frame used in the tensile test lab.

The load frame controller can operate in either displacement-control mode or a force control mode. In load control mode, the load frame applies a commanded load and measures the extension. Under displacement control, the controller measures the applied force through the load cell and finds the force required to produce the specified displacement. For this experiment, you will use displacement control to measure the full response of the specimen up to the point of rupture or failure.

Strain Gauge

A strain gauge is a device that is used to measure the strain at the surface of a structure. The gauge consists of a thin conductive metal foil grid pattern that is mounted on a flexible backing (see Figure 5).

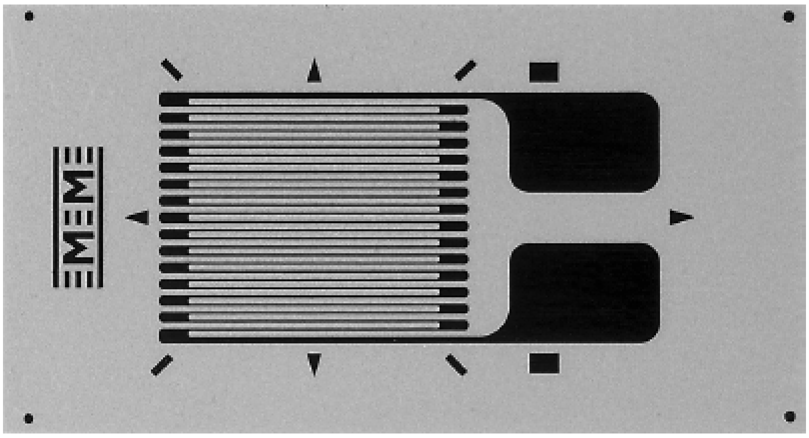


Figure 5. A linear strain gauge.

The backing is then bonded with an adhesive to the test specimen. The strain gauge measurement is determined by the change in resistance of a current passing through the gauge. This change in resistance is proportional to the strain through the gauge factor, S_g, which is provided by the manufacturer. The strain is then measured as:

$$S_g = \frac{1}{\varepsilon}\frac{\Delta R}{R} \Rightarrow \varepsilon = \frac{1}{S_g}\frac{\Delta R}{R}$$

(9)

where ΔR is the change in resistance (and is the strain). The gauge factor for many gauges is about 2, however, each gauge may have a slightly different gauge factor and it is therefore important to note this factor in your notes during the experiment. The ratio of the change in resistance to the initial resistance, $\Delta R/R$, is measured using the Wheatstone bridge circuit. The details of the analysis of this circuit are straightforward but beyond the scope of this lab. In our lab, the resistance of the strain gauge is measured by the Vishay 7000. You will input the gauge factor into the Vishay system which will output the strain directly for later data analysis.

Before beginning the structural test, you will first bond the pre-wired linear strain gauge to the specimen. The quality of the bond between the strain gauge and specimen has a direct impact on the quality of the strain measurements. Achieving a good bond between the strain gauge and the specimen requires careful surface preparation while avoiding contamination. Surfaces that have not been thoroughly cleaned must be treated as if they are contaminated. Touching the strain gauge contaminates it and can lead to poor bond quality. Therefore before bonding the strain gauge to the specimen, the surface of the specimen must be prepared.

Extensometer

The extensometer is a linear variable differential transformer (LVDT) that measures the relative displacement between two points on the specimen. As shown in Figure 6, the LVDT is attached to the specimen using arms that are attached to the body of the extensometer. In the lab, you must measure the initial distance between the attachment points on the specimen.

Figure 6. Extensometer on a test specimen (image courtesy of MTS).

The LVDT is a transducer that measures the displacement using the principle of induction. The LVDT consists of a central primary coil and two secondary coils wired in sequence within an assembly with a movable internal core. An AC current is passed through the primary coil while the induced current is measured in the secondary coils. The secondary coils are wound in opposite directions on either side of the primary coil. The movable core within the assembly is attached to the object whose displacement is being measured. An AC current in the primary coil induces an AC current in the second coil that depends on the relative displacement of the core. The displacement of the core within the LVDT can be estimated by measuring the output AC signal relative to the input signal. An advantage of the LVDT is that it experiences little wear during use and is very robust. In addition, the LVDT can have a high resolution of the displacement.

Load Cell

A load cell is a transducer that is used to measure force. Most load cells are made from an arrangement of strain gauges on a load carrying material with known material properties. The strain gauges are arranged to reduce the sensitivity of the measurement. In subsequent labs, we will see a load cell used to measure forces on an airfoil in a wind tunnel. These instruments and transducers for measuring the stress-strain data are connected as shown in Figure 7.

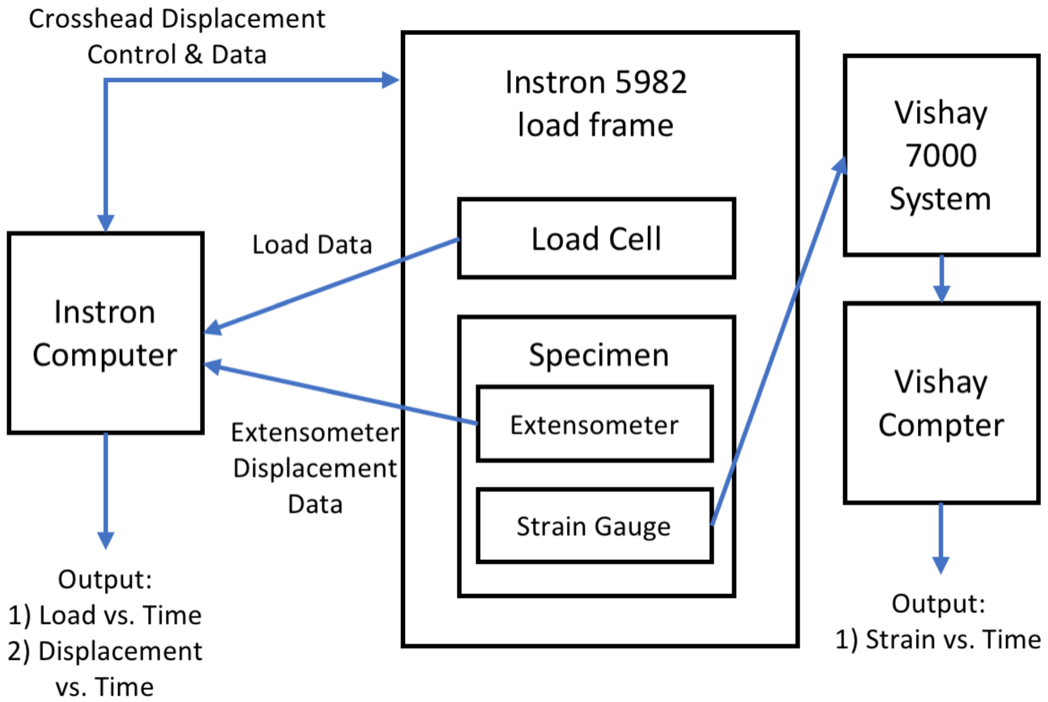


Figure 7. Instrumentation configuration for tensile testing lab.

Pre-Lab Preparation

1. Before coming to lab, read this lab manual and watch the following online Vishay/Micromeasurements videos about surface preparation and strain gauge bonding.

- for surface preparation: https://youtu.be/a5n4wHYThCc
- for strain gauge bonding: https://youtu.be/SjXpF61HRys

Procedure

Bonding linear strain gauge to test specimen

1. Surface preparation requires the following steps:

1. **Degreasing**: This step removes contaminants from the specimen surface that are either chemical residues or organic contaminants. If possible, it is best to degrease the entire specimen so that contaminants are not reintroduced into the bonding area in subsequent steps.

2. **Abrading**: This step is performed to remove any coatings, oxides, or other poorly bonded surface adherents that may result in a poor bond. In addition, this step creates surface texture to which the bond can adhere. In this lab, we use a wet abrading procedure in which the surface is kept wet with M-prep conditioner A.

3. **Application of gauge layout lines**: Positioning the strain gauge on the specimen in the correct orientation is extremely important so that we measure the component of strain aligned with the axial direction. The best practice is to mark the surface with a pair of perpendicular crossed lines to indicate the positioning of the gauge. In this lab, we'll use a drafting pencil so that it does not score the surface.

4. **Conditioning**: Apply conditioner A to and scrub the surface with a cotton tipped applicator until the tip is no longer discolored. The lines indicating the gauge location should still be apparent as a burnished (shinny) line.

5. **Neutralizing**: The last step is to apply a neutralizer to the surface to bring the surface of the specimen back to an optimal pH level.

2. Next, bond the strain gauge to the surface by following these steps:

1. **Attach the strain gauge to the tape**: Clean the glass working surface. Carefully extract the strain gauge from the packaging and place it on the working surface with the bonding side down. Be careful not to touch the gauge itself.

2. **Position the gauge on the specimen**: Attach clear plastic tape to the top surface of the gauge, covering the entire gauge. Lift the tape and the gauge from the glass surface, being careful not to damage the gauge or the wires. Position the gauge on the surface of the specimen using the clear plastic tape. Reposition the gauge if necessary.

3. **Apply catalyst and bond the gauge**: Lift the tape back to expose the gauge. Apply a thin layer of catalyst to the gauge surface. Wait one minute to allow the catalyst to dry. Apply a drop of adhesive epoxy to the specimen. Fold the tape and gauge back onto the specimen and use your thumb to firmly apply pressure on the gauge for one minute. Wait at least two minutes before removing the tape. Inspect the bond to make sure the gauge is well-bonded to the surface.

4. **Fasten the wires to the RJ45 connector**: This part of the procedure depends on the gauge manufacturer. Ask your TA for guidance.

Instrument configuration

3. Determine specimen dimensions and gauge length:

Carefully measure and record the specimen dimensions using a digital caliper in order to determine the gauge cross sectional area. The specimen gauge length (L_0) corresponds to the initial separation of the extensometer (knife edges). Your TA will help you determine the latter quantity.

4. Record strain gauge data:

Note and record the gauge factor (S_g), resistance (R), catalog number, and active gauge length from the documentation provided by the strain gauge manufacturer.

5. Specimen mounting within grips of tensile testing machine:

Select the pre-wired linear strain gauge specimen from your group's batch of prepared test specimens. You will conduct a monotonic tensile test on this specimen. Your TA will guide you as to how the specimens are carefully mounted, aligned and clamped by the grips of the tensile testing machine. Carefully center the specimen with respect to the grips and be very careful to avoid any mechanical interference between the extensometer and the delicate strain gauge lead wires. A brief description of the tensile testing machine will be provided along with an explanation of the input/output test parameters such as the programmed displacement rate, specimen dimensions, and recorded (output) data variables such as force, stress, elongation, and strain.

6. Configuration of the Wheatstone bridge strain gauge data acquisition system:

The lab will also feature the use of a Vishay model 7000 strain gauge data acquisition system, which is controlled through a software interface called StrainSmart. Your TA will guide you through the circuit configuration process. Among the many features that will be highlighted, you will see how the strain gauge type, resistance, the gauge sensitivity factor, and excitation voltage are set within the software. You will also see how the bridge is balanced and then shunted through the software interface in order to compensate for lead-wire resistance. You will then follow the StrainSmart tutorial to configure your linear strain gauge to the Vishay 7000 data acquisition system.

Tensile test procedures

You will be using two specimens: one with both a strain gauge and an extensometer, the other with only the extensometer. The first test measures the full stress-strain response, while the second test examines elastic versus inelastic behavior.

7. Strain gauge and extensometer test:

Mechanically load the tensile test specimen containing the linear strain gauge as specified in Table 1. Continuous load and strain/displacement data will be acquired using the system load cell, strain gauge, and extensometer. Strain vs. time files acquired by the Vishay 7000 and force-displacement records acquired by the tensile testing machine should be saved at the conclusion of test. The test specimen will be monotonically loaded to failure. Observe the specimen carefully and try to note the peak load achieved during the test. Record this value. Try to see if you can visually detect at which point the specimen begins to neck. In this test, leave the extensometer mounted to the specimen all the way up to the point of failure.

Table 1. Parameters for the tensile test.

Parameter	Value
Loading Stage (axial gauge)	Monotonic
Loading Range	0-*Pfail*; *Pfail*~3000lbf
Displacement Rate	0.05 in/min
Strain Gauge	YES
Extensometer	YES

8. Measure the necked region:

Remove the fractured tensile test specimen from the grips. Measure the cross-section dimensions of the necked region of the specimen and the region adjacent to the final fracture that undergoes uniform deformation. Your TA should provide you with digital calipers to make accurate measurements of these dimensions.

9. Extensometer test:

Continuous load and elongation data will be acquired using the system load cell and extensometer. The test software will perform the following test procedure – all while taking data. First it will preload the specimen to 0.18% strain, which is within the *elastic regime*, and then remove the applied load. Note the maximum applied load. The code will then load the sample to 1.5% strain, which moves the sample into the *inelastic regime*, and then remove the applied load. After unloading, the code will then load the sample to 3% strain and then unload the specimen. After unloading at 3%, the code will finally load the sample to failure. Note the peak load and the maximum strain.

Data To Be Taken

1. Cross-sectional dimensions of both specimens.

2. Initial gauge lengths, L_0 , for both specimens corresponding to the initial extensometer separation.

3. Load vs. time, strain gauge strain vs. time and extensometer strain vs. time files for the first test specimen.

4. Load vs. time and extensometer strain vs. time files for the second specimen.

5. Load values from the second specimen test where you began to unload the specimen.

Data Reduction

1. Using the linear elastic region from both tests, isolate and truncate a segment of the data from this region from each data set and estimate the Young's modulus of the aluminum. For the first data set, calculate the relative difference between the Young's modulus estimate using the extensometer and strain gauge results.

2. For the second specimen, isolate and truncate the data for the unloading and reloading curves in the inelastic regime. Determine the tangent stiffness (slope) of the stress-strain diagram in this region.

3. For the first specimen test, compute the true stress and strain using the engineering strain from the extensometer readings.

4. Using the data from the first tensile test, estimate the ultimate tensile strength (UTS in [ksi] and [MPa]), ultimate tensile strain, fracture stress, (in [ksi] and [MPa]), and fracture strain directly from your engineering and true stress-strain curves.

5. Calculate the fracture strain using the dimensions you obtained from the fractured test specimen.

6. From the data obtained in the plastic regime, use the procedure explained in the background section to determine the strain hardening index *n* and strength coefficient *K*.

Results Needed For Data Report

Note: Closely follow the instructions on Canvas for preparation of the Data Report.

1. Cross-sectional dimensions of and initial gauge lengths for both specimens.

2. A single graph of engineering stress vs. strain, with two curves, one based on the strain gauge data and the other using the extensometer data to determine strain. Clearly label the plots in such a way to distinguish between the strain gauge and extensometer data. Plot the stress axis using MPa and the strain axis in microstrain (increments of 10^{-6}).

3. A single graph of engineering stress vs. strain using the extensometer data for the second specimen. Clearly label the points on the stress-strain diagram where you began to unload the specimen.

4. A table that lists your three estimates of the the elastic (Young's) modulus in both ksi and MPa units (i.e., from specimen 1/strain gauge, specimen 1/extensometer, specimen 2/extensometer). The table should also include the relative difference between your extensometer and strain gauge values for *E* from specimen 1, as well as the moduli of the aluminum alloys you found on www.matweb.com.

5. A table of the tangent stiffness results for the unloading and reloading curves in the inelastic regime from specimen 2.

6. A single graph of the axial strain versus time, with result plotted for both the extensometer data and the strain gauge data. Clearly label the axes, color-code the curves, and identify each curve.

7. A single graph showing both the *engineering* and the *true* stress-strain curves for the first specimen test, based on the extensometer readings.

8. A table of your measured estimates of UTS in ([ksi] and [MPa]), ultimate tensile strain, fracture stress (in [ksi] and [MPa]), and fracture strain (for the latter, provide both the results from obtained from your true stress-strain curve and from the the measurement of the fractured test specimen).

9. A table of your measured strain hardening index and strength coefficient.