CHAPTER 15

Measurements and Instrumentation

INTRODUCTION

Measurements are made for a variety of reasons, and these reasons shape the type of measurement techniques and equipment that are available. Examples include measurements of a controlled process like building heating or the manufacture of soft drinks, performance measurements such as the ultimate strength of a bolt or the efficiency of an aircraft engine, hypothesis testing for comparison to theory, such as the behavior of a chaotic forced pendulum, or the simple need to know "does it work now that I've plugged it in and turned it on?" In this introductory engineering projects course, measurements will be needed to make sure the design process goes according to plan and to test the performance of the finished product.

Prior to making any kind of measurement, there are a number of considerations that must be made before deciding on a technique.

Measurement Considerations

Static vs. Dynamic

The first measurement consideration, is the quantity being measured changing with time? For example, if the strain in a snowboard with a rider standing still is needed, it does not matter when the measurement is made; one moment is as good as the next, as long as the conditions have not changed. This is called a *static* measurement. On the other hand, if a measurement of the maximum strain in a snowboard during landing after a jump is required, a series of measurements should be made very quickly as the board makes contact with the snow. How many measurements to make, how fast to make them and how to trigger the start of the measurement sequence will have to be decided in advance. In engineering jargon, the measurement of a time-varying quantity is called a *dynamic* measurement. The number of measurements is sometimes called record length or number of scans, and the rate of measurement (sample rate) is expressed in samples or cycles per second, with units of Hertz.

Another factor that must be considered in advance is whether or not the measurement device can respond to the quickly changing strain level. How fast a device can respond is expressed by its *frequency response*. Specifically, frequency response indicates how a device responds to a signal of sine wave shape. A device described as flat up to 1 kHz can track sine wave signals of frequencies ranging from 0 to 1 kHz, but it cannot keep up with higher frequency signals. So if a snowboard is vibrating at 2 kHz, and the strain gage is only good to 1 kHz, the output from the gage will be lower than it should be.

On a practical level, static measurements are often one-of-a-kind, and the results are as easily written in a notebook as entered into a spreadsheet. Dynamic measurements may be made so fast (MHz!) or in such large quantities (1 sample every 5 minutes for three weeks) that a computer is required to control the sample rate and record the data. Computer-based data acquisition systems generally read electrical voltages, so the measured quantity will have to be changed (transduced) into a voltage signal. Knowing ahead of time whether a static or a dynamic measurement is needed dictates what kind of measurement equipment can be used.

This chapter focuses on simple, static measurements that can be made using a self-contained measurement device. If a dynamic measurement is needed, check with the course instructor on the availability of an appropriate, existing system.

Resolution

Another question to consider before choosing a measurement technique is "how good does the measurement have to be?" For example, if a measurement of the thickness of a piece of aluminum foil is needed, will an ordinary ruler do the job? Only if a very crude measurement is acceptable: the smallest quantity that a ruler can resolve is 1/16th of an in. The thickness of aluminum foil is smaller than that. A measurement device with much higher resolution is needed, such as a micrometer.

The term *resolution* has at least three meanings with respect to a measurement device. First, the most common meaning is the resolution in the quantity of interest, like the smallest division on the ruler. A device with high resolution is often called *high precision*. Second, a measurement also has a resolution in time; i.e., if it takes several seconds to make a measurement, and the measured quantity changes during that time, then the measurement is poorly resolved in time. Similarly, if the measurement is of a quantity that varies in space, i.e., the quantity is different from one side of the measurement device to the other, then better spatial resolution is needed. For example, if the speed of water at different locations across the diameter of a pipe is needed, then a device that only measures the average water speed will not be useful.

Uncertainty

Another aspect of "how good does the measurement have to be?" has to do with the fact that no measurement is 100% perfect; there is always the possibility of error—a difference between the measurement and the true value. Error might be due to inaccurate calibration, such as a speedometer that consistently reads high. This type of error is known as *bias* or *systematic* error. A device with a low bias error is often termed *highly accurate*, although not necessarily *precise*, which relates to the resolution of the device or the repeatability of the measurement. Another type of error might be due to uncontrollable variables, such that every time the same measurement is made, it is a little different. This second type is called *random* error. In any case, when a measurement is made, the exact size of the errors is never known, so the true value of what is measured is uncertain. However, the likely range of possible errors can always be estimated to some degree. This is called *uncertainty analysis* [1, 2]. This topic is covered in first-year chemistry and physics courses, but for now keep in mind that it is a good idea to check the calibration of measurement tools (measure known values now and then) and make several repeated measurements, just to see if there is a range of values.

MEASUREMENT TOOLS

Dimensional (Size) Measurements

Ordinary rulers measure flat objects a maximum of one foot in length, with a resolution of 1/16th in. or 1 mm. To measure larger dimensions, a yardstick could work, but its resolution may be only 1/8th in. A tape measure can be up to 50 ft in length, with a resolution of 1/16th in. at best. Measurement of larger objects requires surveying tools. Going in the other direction, a machinist's rule represents the next step up in accuracy. Usually these are made of flexible steel, are 4 to 6 in. in length and have a maximum resolution of .01 in.

Even more accurate are measuring calipers, which measure things up to 8 in. with a resolution of ± 0.001 in. (± 0.03 mm). Calipers are excellent for measuring the inner and outer diameters of round objects and the depths of small holes. They may have a dial readout, a digital readout or a vernier scale [3]. The highest accuracy common device, a micrometer, has a range limited to an inch or two, but an accuracy of ± 0.0005 in. (± 10 µm). Measurements of such high precision (a human hair is approximately 0.002 in.) are sensitive to applied pressure, temperature and surface cleanliness — factors that must be controlled for precision measurements. Micrometers have a ratchet tightening screw to provide a standard pressure between the tool and the part. Note that all of these dimensional measurement techniques are good for static measurements only. Time-varying dimensional measurements require much more sophisticated techniques.

Force

Force can be defined as a directed push or pull. The most common force experienced is weight due to gravity. Thus, a scale used to measure the weight of fish in pounds can also be used to measure force in pounds. In fact, fish scales are common, available at hardware and sporting goods stores. They often have hooks on either end, and can measure tensile forces up to 50 lbf, with an accuracy of 2 oz. For measurement of compressive forces up to 5 lbf, a postal scale might be appropriate. A bathroom scale can go up to a few hundred pounds, but with low accuracy and repeatability. High quality laboratory scales for weight measurement are common, but are usually designed to measure small quantities of chemicals with great accuracy, so they are generally not appropriate for force measurement. Higher quality force measurement techniques require electronic transducers and signal processing [4]. If the application of a known force is needed (for example, to pull on something with a force of 2 lbf), it may be possible to hang calibrated weights to exert the correct force.

Temperature

Liquid-in-glass thermometers are commonly used to measure body temperature (fevers) and for cooking purposes. Mercury, often used as the encapsulated fluid, presents a toxic waste cleanup problem if the thermometer breaks. Alcohol is also common, but is limited at the high temperature end of the scale. A typical high-quality thermometer provides a range from -4 to 300°F with a resolution of 0.1°F. Thermometers are designed to be either fully or partially immersed in a fluid (either gas or liquid); thus, they are less appropriate than thermocouples or thermistors [5] for the measurement of temperature in a solid.

Digital thermometers are increasingly common for laboratory purposes. These devices measure temperature electronically and are packaged with a digital readout. Generally, only the sensor element need be immersed. Accuracies of 2°F are typical, so they are easier to use than liquid-in-glass thermometers, but less accurate.

Flow

A measurement of the flow rate of liquid moving in a pipe can be made using a bucket and a stopwatch. The time it takes to fill the bucket is recorded, and then divided into the mass of fluid measured on a weight scale to yield mass per unit time. As the accuracy of this technique is dependent on a person using a stopwatch and the accuracy of the weight-measuring device, it is better to record over a long period of time, if possible. This method may seem crude, but automated versions of this technique are used by the National Institute of Standards and Technology to calibrate the highest accuracy flow instruments.

If the velocity of a stable air stream is needed, a simple device called a *pitot* (pronounced pea-toe) *static tube* can be used [6]. The pitot-static tube is a double-walled probe that is inserted into the air stream as shown in Figure 15.1. This use of the term "static" has a different meaning than discussed earlier with respect to time-constant quantities. The difference in pressure between the central tube and the side holes is related to the velocity:

$$V = \sqrt{\frac{2(P_{stag} - P_{static})}{\rho}}$$

where V = velocity, p_{stag} is the stagnation pressure (measured in the central tube), p_{static} is the static pressure (measured at the side holes), and ρ is the air density. When applying this equation, be sure to use the appropriate conversion factor to make the units cancel.

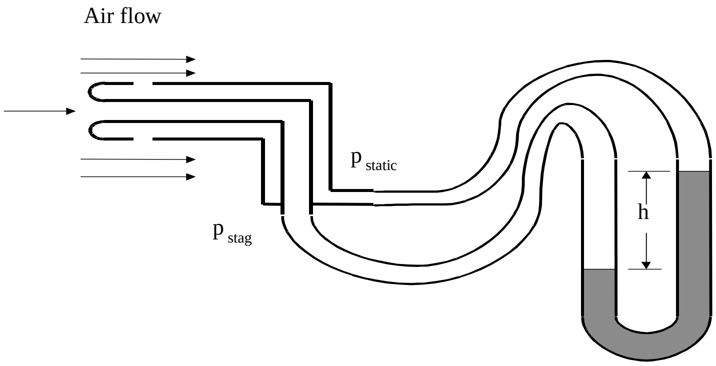

Figure 15.1. Pitot-static tube with manometer.

The pressure difference, $p_{stag} - p_{static}$, can be measured using a manometer. This is simply a U-tube partly filled with a liquid of known density (usually a special oil) as shown in Figure 15.1. The different pressures acting on the two surfaces of the liquid in the tube causes one surface to rise, and the other to fall. The difference in height, h, can be related to the pressure difference Δp:

$$\Delta p = \rho_{liquid} gh$$

where g is the acceleration of gravity. Again, use units conversion factors as needed. Pitot-static tube/manometer combinations are best used when the air velocity is constant with time, or if an average velocity is desired. Depending on the quality of the manometer, accuracies in pressure measurement of one percent can be expected.

Hand-held electronic velocity meters are commonly used in industry. However, they are often expensive ($500 or more), may require calibration and are no more accurate than a pitot-static tube/manometer measurement.

Voltage

Measurement of voltages up to 20V is easy and safe with a hand-held or tabletop digital multimeter (DMM or DVM) [7]. If the voltage is not varying with time, set the meter on DC (direct current). This is appropriate for measuring battery voltages, for example. You may have to choose an expected voltage range, but many meters are auto ranging. If the voltage is varying in a periodic fashion, set the meter on AC (alternating current).

For example, if household AC is measured, it will read 110VAC. Be very cautious when measuring any voltage higher than 20V, AC or DC. The body can easily become a conducting path, and the outcome could be fatal. One safety technique is to first turn off power to the device being studied. Then connect the DMM using clips, stand back and turn the power back on. In any case, the maximum voltage of most DMMs is 200V.

Oscilloscopes are common laboratory tools for measuring a time-varying voltage when an AC measurement provides insufficient information [8]. A screen displays the input voltage as a function of time, as shown in Figure 15.2. The trace is triggered to start the next time the voltage reaches a particular level, at some point during the next cycle of a periodic waveform. Modern scopes provide an auto-scaling feature, but they are not foolproof. If the expected result does not show on the screen, adjust the rate at which the signal is displayed. This control may be labeled *timebase* or *time/division* where division refers to the squares into which the scope screen is divided. If that does not work, adjust the trigger level.

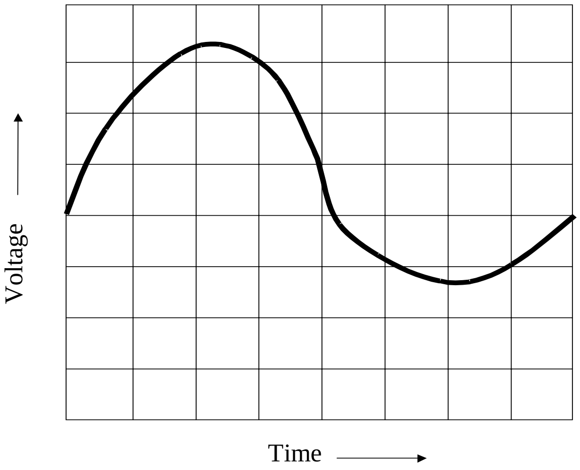

Figure 15.2. Oscilloscope screen.

Tension / Compression Testing of Materials and Structures

Testing machines that stretch or crush samples are often used to determine the strength of materials and/or structures. As shown in Figure 15.3, a sample is held in the machine by grips. The crossbeam is then programmed to move up or down at a specific speed, and the resulting tensile or compressive loads on the sample are measured by the load cell. The deformation of the sample is called *strain* and is measured in units of inches shortened per inch length of original sample.

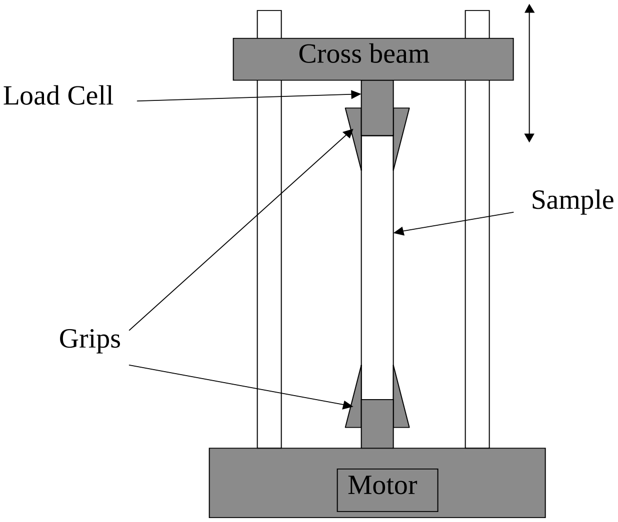

Figure 15.3. Stress-strain testing machine.

The strain is determined by the motion of the crossbeam and can be considered an independent parameter, set by the user. The load cell measures the resulting force, which is thus a dependent parameter. When the force is divided by the area that the force acts over, the result is *stress*. A typical stress-strain curve for a metal that has been pulled to failure is shown in Figure 15.4.

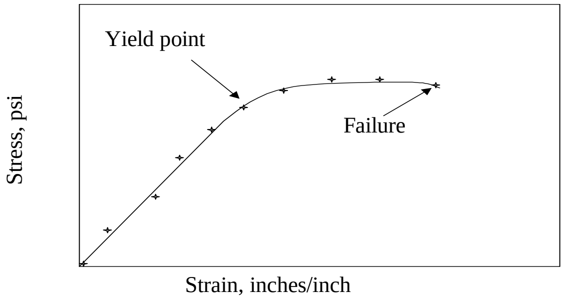

Figure 15.4. Typical stress-strain curve for a metal sample pulled to failure. Data points: +

As the crossbeam begins to move, stress builds up linearly and elastically. Once the strain passes the yield point, the sample will be permanently deformed. It takes little additional stress to continue the deformation. Eventually, the part breaks.

When using such a machine, a number of decisions must be made in advance. The range of expected load (force) must be set. If the load exceeds this range, data could be lost. The rate of strain (how fast the cross bar moves) must be specified too. The time to failure at that strain rate must be estimated, and the number (record length) and rate of load cell samples (data rate) must be programmed in advance as well. Having the strain rate too high and the load cell sample rate too slow could result in having only one or two samples on the chart.

REFERENCES

1. J.P. Holman, *Experimental Methods for Engineers,* Section 3.4, Uncertainty Analysis, 1994, McGraw-Hill.
2. Ronald H. Dieck, *Measurement Uncertainty Methods and Applications,* 1992, Instrument Society of America.
3. http://me.mit.edu/lectures/machine/measure/intro.html This website has a nice description of the use of calipers and micrometers, as well as instructions on basic machine shop techniques.
4. J.P. Holman, *Experimental Methods for Engineers,* Chapter 10, Force Torque and Strain Measurements, 1994, McGraw-Hill.
5. J.P. Holman, *Experimental Methods for Engineers,* Chapter 8, Measurement of Temperature, 1994, McGraw-Hill.
6. R.W. Fox and A.T. McDonald, *Introduction to Fluid Mechanics*, Fourth Edition, pp 241-242, 1992, Wiley and Sons.
7. J.P. Holman, *Experimental Methods for Engineers,* Section 4.5, Basic Digital Meters, 1994, McGraw-Hill.
8. J.P. Holman, *Experimental Methods for Engineers,* Section 4.15, The Oscilloscope, 1994, McGraw-Hill.