THE STANDARD HANDBOOK FOR AERONAUTICAL AND ASTRONAUTICAL ENGINEERS

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PART 5

INSTRUMENTATION

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6.18 INTRODUCTION

Many aspects of aerospace engineering depend essentially on the ability to make measurements of relevant quantities. This is as true of measurements taken in flight as it is of research and development and manufacturing quality control. In some areas, such as nondestructive testing or experimental stress analysis, the techniques for making the measurements are linked so closely to the rest of the subject that they are better dealt with in their particular context. Here we consider the more general measurements encountered throughout the whole field and the instrumentation that makes them possible.

In later sections techniques are described under the headings of the quantities to be measured—sometimes referred to as measurands. First, it is useful to discuss topics that are of importance in many instrumentation systems.

Sometimes the process of measurement is a simple one, with the human operator playing a direct part: putting a rule alongside a component to determine a length, or measuring time using a stopwatch. More often a more complex system is used, which can be understood by thinking of the elements that make it up. Such a system is shown in Figure 6.32. Many variations are possible.

The measurand acts on a transducer and produces a signal corresponding to its value. This output signal is commonly electrical, but may be pneumatic or optical. The signal can then be transmitted as needed. We show the transmission or telemetry as a distinct part of the system in Figure 6.32 to indicate its importance. Some processing of the signal is often needed before it is displayed or recorded. Often a computer is used to control the whole operation, probably covering many transducers, partly in the light of the information given by the measurements.

For instance, temperatures might need to be determined at many points on a plant. Thermocouples could be used as transducers, other equipment being some

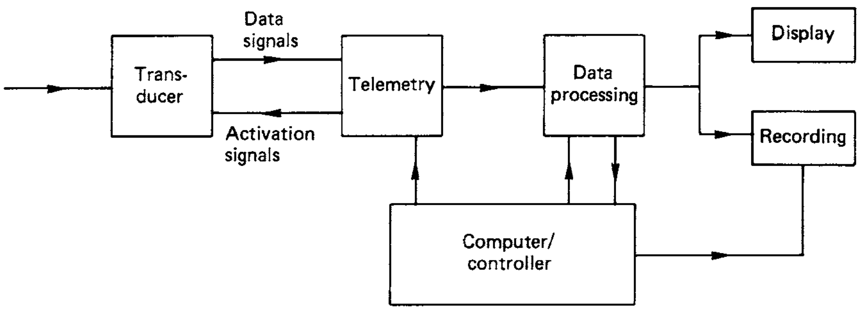

FIGURE 6.32 Typical instrumentation system.

distance away, more accessible, and in a less severe environment. Temperatures should be recorded at regular intervals, maxima, minima, and averages being extracted and an alarm given if any temperature exceeds a prechosen limit. Such a system might be part of the control of operational plant, signals being available as inputs for actuators. Alternatively, it might be logging the results of an experiment.

Most data processing and computing use digital signals, as does complex telemetry; simple, short-range telemetry can be analog. Most transducers have analog outputs, so an analog-to-digital converter (ADC) is needed at the input to data processors. If the transducer gives an output in the form of frequency, the ADC can operate simply by counting the number of cycles in a given time.

Communicating to operators the results of measurement is a distinct phase of the whole. It may amount to recording permanently for study later, possibly simply on paper, more probably in some form suitable for computer input. Alternatively, an indication (called Display) may be needed to show immediately the output of the instrumentation system. This is all part of the human/machine interface.

Accuracy

The accuracy of any instrumentation system is, of course, of great importance. When making a measurement it is possible to distinguish systematic and random errors. When a measurement of what should be the same thing is repeated it will be found that the readings are not identical; the spread of readings corresponds to random errors between individuals. The final error can be reduced by repetition and averaging (provided time allows). However, even the average is not necesssarily correct, because it contains the systematic error. Systematic errors can be greatly reduced by careful calibration under conditions resembling the operating ones as closely as possible. Calibration is in fact an important feature of all systems where it is required to relate the readings taken back to absolute values of the quantities concerned. The word "traceability" is used to describe building up links in this chain. Absolute values of measurands, are not always important. Sometimes it is "repeatability"—the capability of giving the same reading (even if it is the wrong one!) under the same conditions—that matters. The precision of a reading relates to the smallest difference in value that can be detected.

When considering how faithfully an instrument represents what it is supposed to be measuring, the idea of "influence quantities" should be taken into account. The resistance of a strain gauge, for instance, varies with strain and so is used to measure it; but it also varies with temperature, so a one-to-one correspondence with strain will only hold provided temperature is constant. Temperature is an influence quantity. Reducing the errors introduced by influence quantities is facilitated by making bridge measurements. This idea is most familiar in electrical circuits, when two components are connected so that changes in them affect the output in opposite directions. It can then be arranged that influence quantities affect them equally and so cancel, while the measurand either only affects one component or affects them oppositely.

Another concept that is helpful in understanding transducer performance is that of gauge factor. This is the ratio of the fractional change in output to the fractional change in measurand. Again it is easily understood in the frequently quoted example of the resistance strain gauge, where it is given by the formula

$$\delta R/R = \delta l/l$$

However, the concept is more generally applicable, with the expectation that a transducer with a higher gauge factor will be more immune to influence factors.

Hysteresis is observed in many instruments. This is the name given to the defect of indicating a different output according to whether the quantity measured is increasing or decreasing (see Figure 6.33). Nonlinearity is also shown in Figure 6.33. This is the situation when the relation between input and output cannot be exactly represented by a straight line.

Reliability

The reliability of any equipment is often of the utmost importance, and instrumentation systems are no exception. Attempts have been made to develop the concept of reliability, putting it on a semiquantitative—though necessarily probabilistic—basis, so allowing the chances of failure to be calculated. While carrying out such an exercise, lessons can be learned of features that have been identified as significant. With large systems, the configuration in which different items are connected can make an unexpected difference. The schedule of servicing plays a large part in the down time that is to be expected. The consequences of any particular failure, which may be very diverse, should be analyzed. The idea of independence may be developed; this implies that it is safer for two measurements, if they are intended to corroborate one another, to be made with essentially different components—or even techniques—because they are then less likely to suffer from a common fault. In all considerations of instruments and their installations due weight must be placed on reliability. High accuracy has little value if it cannot be counted on, or perhaps it may be put that the possibility of a very large error can be more damaging than the probability of a small one.

Environmental Conditions

In a broad way, it is always recognized that there are limits to the conditions under which instruments can be used. The working temperature range may well be specified. Users should be aware of other significant conditions. The atmosphere can be harmful, from moisture or other corrosive effects; dust in the atmosphere is an

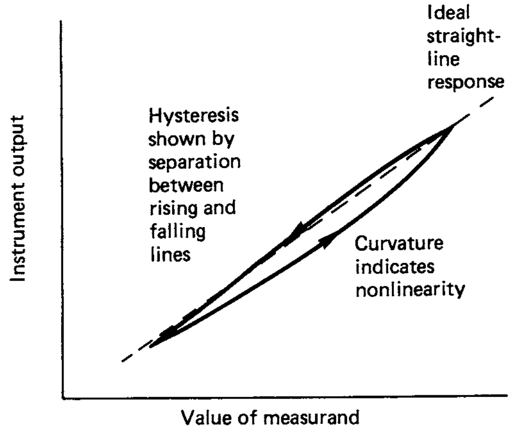

FIGURE 6.33 Hysteresis and nonlinearity errors.

enemy to many instruments. Subjection to mechanical abuse (notably excessive vibration) must also be guarded against. More sophisticated hazards include electrical interference and nuclear radiation. The capabilities of particular items to withstand all these are often not spelled out. Common sense is often called for to judge what is reasonable to expect. Sometimes precise limits are quoted by suppliers, but it should be noted that approaching these limits closely may reduce accuracy and especially reliability.

Frequency Coverage

A simple description of what an instrument does may imply that there is an indefinite amount of time in which to make a measurement—the steady-state or d.c. behavior. Sometimes this is not the whole relevant story. There are certain devices that cannot be used for steady-state measurements, but only for varying ones. There is always an upper limit to the frequency at which an instrument will operate faithfully. This may restrict the number of readings that can be taken in a limited time and is very often of concern when the measurement process is part of a closed control loop (see Part 7). It is therefore of great importance to take account of this feature of an instrument's performance.

6.19 DIMENSIONAL/GEOMETRICAL MEASUREMENTS

The lengths that people have been interested in and hence wanted to measure range from perhaps 10^{-15} to 10^{18} meters. At the extremes the interest is mainly from nuclear physicists and astronomers, and we shall here concentrate more on the middle distances.

Of course, there are simple, manual instruments that will continue to be used: rules, micrometers, calipers. A dial gauge incorporates gears to provide magnification so that a movement of even a fraction of a millimeter gives an observable rotation of a pointer. Gauge blocks should be mentioned—elements with accurately parallel faces a precise distance apart; they can be thought of as coming into a calibration exercise, or as forming references allowing the dimensions of other parts to be compared with them.

However, a large part of modern dimensional instrumentation involves converting lengths into electrical (or, occasionally, optical or pneumatic) signals. The three electrical quantities—resistance, inductance, and capacitance—are all used in transducers for this purpose.

Resistance Transducers

In one form of transducer a slider moves over an extended resistance element, which may be either wire-wound or made of some nonmetal. The resistance between the contact of the slider and either end of the element varies with the position of the former. Such devices are simple and only need simple electrical equipment. They can be made to obey some nonlinear law if that should be wanted. However, they are not of the highest accuracy, and, because rubbing and friction occur, cannot be expected to have indefinitely long lives.

A different form of resistance transducer is the strain gauge. In essence, a small element is bonded to a structural unit and changes its resistance with the dimensional changes brought about by the latter being strained. The length changes are small (typically a fraction of a percent) and the resistance changes are generally only a little larger. However, because it is possible to measure electrical resistance very precisely, strain gauges can still be used in accurate work. When directly measuring strain, they are, of course, measuring very small movements and need a large force to act on them. The range can be increased and the force reduced by having the movement to be measured applied to a flexible strip on which the gauge is mounted, as shown in Figure 6.34.

Inductance Transducers

The inductance of a coil is given approximately by

$$L = N^2 \frac{A}{l} \mu$$

where N is the number of turns, A the cross-sectional area, μ the effective permeability, and l the length of the magnetic path. For an iron-cored coil with an air gap as shown in Figure 3.35 two very different values of μ arise, and the formula becomes

$$L = \frac{N^2 A}{(l_{\text{iron}}/\mu_{\text{iron}}) + (l_{\text{air}}/\mu_{\text{air}})}$$

Even for small values of the air gap, $(l_{\text{iron}}/\mu_{\text{iron}} << (l_{\text{air}}/\mu_{\text{air}})$ and L is very sensitive to changes in l_{air}. Many inductance transducers make use of this principle.

FIGURE 6.34 Strain gauge on flexible strip.

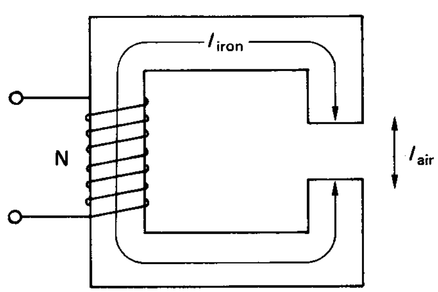

FIGURE 6.35 Coil with air gap.

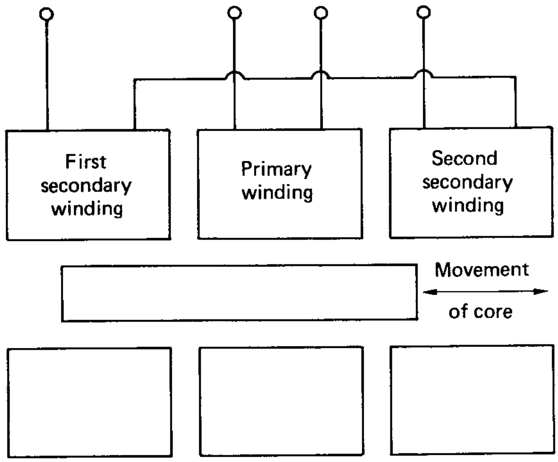

FIGURE 6.36 Linear variable differential transformer (LVDT).

If extreme sensitivity is not required, the iron circuit need not be so nearly closed. An example of an instrument of this type is the linear variable differential transformer (LVDT), where there are two further refinements shown in Figure 3.36:

1. A differential system is used so that the inductance of one winding increases at the same time as that of another decreases; and
2. By having a further winding, a mutual inductance or transformer replaces the self-inductance.

These additions increase the magnitude and linearity of the output and give an inbuilt bridge system, so increasing the effective gauge factor.

While most practical devices employ ferromagnetic (iron) cores, it is, in principle, possible to have an air-cored inductor serving as a transducer.

Capacitance Transducers

The electrical capacitance in farads between a pair of parallel plates (as shown in Figure 6.37) is

$$C = \varepsilon_0 \varepsilon \frac{A}{d}$$

where ε_0 = the permittivity of free space (= 8.9×10^{-12} F/m)
ε = the relative permittivity of the material between the plates
A = the area of either plate, or of their overlap if they are not exactly equal and opposite
d = the separation between the plates

C can therefore be changed by changing either A or d. Since d can be a millimeter