Module – 1

INTRODUCTION TO FLIGHT TESTING AND FLIGHT TEST INSTRUMENTATION

Syllabus:

Introduction: Sequence, Planning and governing regulations of flight testing. Aircraft weight and center of gravity, flight testing tolerances. Method of reducing data uncertainty in flight test data - sources and magnitudes of error, avoiding and minimizing errors.

Flight test instrumentation: Planning flight test instrumentation, Measurement of flight parameters. Onboard and ground based data acquisition system. Radio telemetry.

1.1 The Purpose and Scope of Flight Testing

Modern aircraft are complex integrated systems with the propulsion, avionics, and aerodynamics blended together to achieve optimum performance, stability, and control.

The flight testing of such aircraft is an endeavor that involves a number of engineering disciplines in addition to the study of the man-machine interface that we know as human factors. Engineering disciplines such as aeronautical, mechanical, electrical and structural all come together at this phase of an aircraft's development. In addition, it is at this time that the human crew, which has both tremendous capabilities and finite limitations, must begin to interact with the aircraft and its systems. That interaction must be examined from the standpoint of human workload, which has a component of human psychology and industrial engineering. In addition, the management of a flight test program for a modern aircraft requires management skills that are not often included in most engineering curriculums. As a result of this mix of disciplines, flight testing can not be claimed by any one and is therefore a discipline unto itself.

The flight test comes at the end of the aircraft design process and is a unique part of it, as one of the purposes of the flight test is to validate and refine the design. This means that changes to the design will continue to be made to the aircraft during the flight testing, as a result of the testing. Such changes to the design may affect the results of testing previously done, requiring it to be reaccomplished. We can see then that unless our flight test is properly planned it could result in a never-ending series of tasks. Additionally, because the flight test comes at the end of the aircraft's development, it will face the pressures of schedule brought on by the economics of any product development. Since flight testing is also a hazardous endeavor with important requirements for the safety of the aircraft and its crew, we must have a well-managed program to avoid accidents while accomplishing the program in a timely manner. Therefore, the flight test team has a very difficult and exciting task.

The principal purpose of today's flight testing is to determine if this complex aircraft and its crew can safely accomplish its intended mission. Other purposes may include collection of aerodynamic, power plant or systems data, and research into these or other related fields.

1.1.1 Types of Flight Testing

There are a number of reasons to flight test. One reason has been the desire of man to push the frontiers of knowledge. This desire results in the research flight test. Examples are the Wright Brothers' research flights at Kitty Hawk and the tests of the X-series of aircraft during the 1940s, 1950s, and 1960s. Such flight tests continue today as man tries to expand his knowledge of aeronautics and space.

Another type of flight test is that for product development. Aircraft companies in their attempts to make profits for their stockholders must develop new products. These tests, unlike research flight tests, may not be to push the state of the art. Their purpose is to determine the characteristics of the new product and to determine and solve problems with the product.

A third and important reason is to determine if the new vehicle will accomplish its intended mission. A 10-place aircraft that can only carry 2 passengers is an example of an aircraft that does not meet its mission requirements. If the aircraft does not meet its mission, additional development may be required.

The final reason for flight testing is to comply with established requirements and regulations for safety of flight. These flight tests are the purview of government organizations such as the Federal Aviation Administration (FAA), which conducts or directs such flight tests in the United States. Other countries have similar organizations, and in most of the world it is not possible to sell an aircraft—other than a home-built kit—to the public without it having successfully completed these tests.

1.2 Sequence, Planning And Governing Regulations of Flight Testing (FT)

1.2.1 Sequence of FT

In general, the development of a new aircraft should follow a set sequence to have a safe and efficient flight test. First, the aircraft should receive a number of preliminary ground tests leading up to its first flight. If there is more than one aircraft in the flight test program, some testing may be conducted in parallel.

Certification testing usually comes at the end of the development program. The sequence of certification testing is somewhat different than developmental testing.

1.2.2 Planning the Test Program

The success or failure of the flight test program will hinge on how well it is planned. The planning process will allow the flight test team to think through the safest and most efficient way to administer the program. In conducting this planning the test team should first answer the following questions:

1) What are the purpose and objectives of this test program?
2) What specifications or regulations must be met?

All too often testing is started without a defined purpose and specific objectives. Such an approach always results in a larger expenditure of effort than does one in which the purpose and objectives are well defined.

Once the test objectives have been defined (and agreed upon by all concerned parties) one can set about to determine what regulations and/or requirements apply. In most cases these requirements may need to be negotiated with the aircraft certification agency (Federal Aviation Administration in the United States) who has responsibility for aircraft certification.

1.2.2.1 Test Program Plan

Once the purpose and objectives have been firmly established and the certification regulations that apply to the test defined, one is ready to start designing the tests.

First, we should decide what types of tests and test methods best satisfy our purpose and objectives. Next, we need to group the tests so as to reduce the total number of flights required. If the test program has more than one test aircraft, the planning needs to include what testing will be accomplished on each aircraft. Once this has been accomplished the instrumentation requirements for each aircraft can be established.

At this stage in the planning process the instrumentation engineer, if one exists, should be included to assist in planning the instrumentation requirements. This position can be of great assistance in the planning of the instrumentation required to meet the test objectives along with pointing out excessive requirements for instrumentation and system accuracy, which have a great impact upon costs. However, the instrumentation engineer should not be allowed to dominate this part of the planning process.

Although it may appear obvious, the project test pilot and other test crew members should be involved in every phase of the planning. They can be of particular assistance in planning the testing sequence and in establishing the safety limitations. Their understanding of the purpose of each test, and where it fits into the overall test program, will be invaluable as the testing proceeds.

If the test program requires off-site testing, such as high-altitude takeoff and landing tests, the planning should include any logistic, instrumentation, and data collection/reduction support required at the off-site.

If one has conducted previous test programs, one should review the lessons learned from those programs. In addition, one should ensure in the planning process that provisions are made for collecting and documenting, for future use, the lessons learned from the current test program. Smart testing does not "reinvent the wheel."

During the planning process, brainstorming sessions are well worth the time spent. During these sessions, attempt to cover all of the possibilities. If we have designed a good test plan, problems that arise during the testing will be less likely to have an adverse impact upon our test schedule. The shorter the test schedule the lower the costs.

1.2.2.2 Planning Individual Flight

Using the sequence developed in the test plan, individual flights should be planned so that they include more items than can be accomplished during a single flight. These items should be organized so that the most important items are accomplished first. In this manner, a flight will not be wasted if the instrumentation for the primary items fail because the back-up items can be accomplished. All test items should be thoroughly planned with test altitude ranges, power settings, trim airspeeds, airspeed limits, and other test-critical items considered. Airspeeds should be in the values that the pilot will observe on the instrument. Once the flight has been planned the flight data card should be prepared.

1.2.2.3 Flight Data Record

Flight data cards can be of the 5 × 7-card variety if data must be taken on a kneeboard or of the 8.5 × 11-notebook type if data are taken on a clipboard. It is not a good idea to plan these cards out in detail more than a day in advance of the flight since the requirements of an individual flight may change as the flight test progresses. These data cards may be personalized, but they should all contain the following information.

General Data

1) date of the test
2) type of aircraft
3) aircraft N number or serial number
4) purpose of the test
5) aircraft takeoff gross weight and center of gravity or a loading number
6) time of day of takeoff and landing
7) total flight time
8) configuration or a configuration number
9) test technique

The data card may be so arranged as to have the above data as the heading of the card, and the cards may be standardized to your liking with a large number of blank boxes for test specific data.

For test-specific data the cards should be arranged for ease of data taking and should contain the following information.

Test Specific Data

1) trim conditions (airspeed, altitude, ambient temperature, power setting, and so forth) if required by the type of test
2) test limitations (airspeed, altitude, control force, and so on)
3) all required data arranged in the order in which it will be collected with the most likely to change data shown first
4) comments on test conditions (such as air turbulence), specific data points, or other relevant comments

1.2.3 Governing Regulations and Requirements

The federal regulations for the certification of fixed-wing, propeller-driven aircraft date back to the Air Commerce Act of 1926 and were codified in the U.S. Department of Commerce Bureau of Air Commerce Aeronautics Bulletin No. 7, "Airworthiness Requirements for Aircraft." This bulletin was amended to Aeronautics Bulletin No. 7-A (Ref. 1) on 1 October 1934. Bulletin No. 7-A is 58 pages long, including figures, and applies to aircraft built during this time period. It still applies to certain antique aircraft. Special requirements for transport aircraft were covered by Aeronautics Bulletin No. 7-J.

In the late 1930s the Civil Aeronautics Authority was established and issued replacements for Bulletin No. 7. This regulation was Civil Air Regulation (CAR) Part 4. It recognized the need for separate regulations for small aircraft and larger transport aircraft with Part 4 being for small aircraft and Part 4T covering transport aircraft. Later when helicopters appeared on the scene certification regulations were added for these aircraft. The Civil Aeronautics Act of

1938 resulted in the issuance of new regulations: Civil Air Regulations 4A for small aircraft and 4B for transport aircraft. Later these were changed to Civil Air Regulation Part 3 for small aircraft (defined as aircraft not exceeding 12,500 lb takeoff gross weight [TOGW]) and CAR Part 4b for transport aircraft (defined as those aircraft with TOGW in excess of 12,500 lb). Corresponding Civil Aeronautics Manuals (CAM 3 (Ref. 2) and CAM 4b (Ref. 3)) gave the regulation along with accepted interpretations of certain regulations including acceptable methods of conducting the flight test. Aircraft in the restricted category, such as agricultural aircraft, were certified under CAR Part 8 and its corresponding CAM 8 (Ref. 4).

Since Civil and Federal Air Regulations set the Type Certification Regulatory Basis for an aircraft as the regulations that applied when the manufacturer applied for the *original* type of certificate, many of today's light aircraft and some transport aircraft still use the CARs as their certification regulations.

1.2.3.1 FAA Regulations

In 1958 the Civil Aeronautics Agency became the Federal Aviation Administration and new aircraft certification regulations were issued in 1965. They were FAR Part 23 (Ref. 5) for small airplanes and FAR Part 25 (Ref. 6) for transport airplanes. Originally they were nearly the same as the older corresponding CARs; however, politics, changes in technology, and aircraft accidents have caused them to be revised and changed considerably from the original CARs. Fig. 1.1 shows the development of the federal aviation certification regulations.

1.2.3.2 FAA Flight Testing Advisory Circulars

Since the technical details of how to perform a given flight test are not provided in the FARs as they were in the CAM material, the FAA, in the 1970s, issued "how-to" documents under FAA orders. These documents were FAA Order 8110.7 "Engineering Flight Test Guide for Normal, Utility and Aerobatic Category Aircraft"[7] and FAA Order 8110.8 "Engineering Flight Test Guide for Transport Category Aircraft."[8] However, FAA orders are only available to individuals with FAA responsibilities and are not available to the general public. As a result, the FAA rewrote these documents and issued them

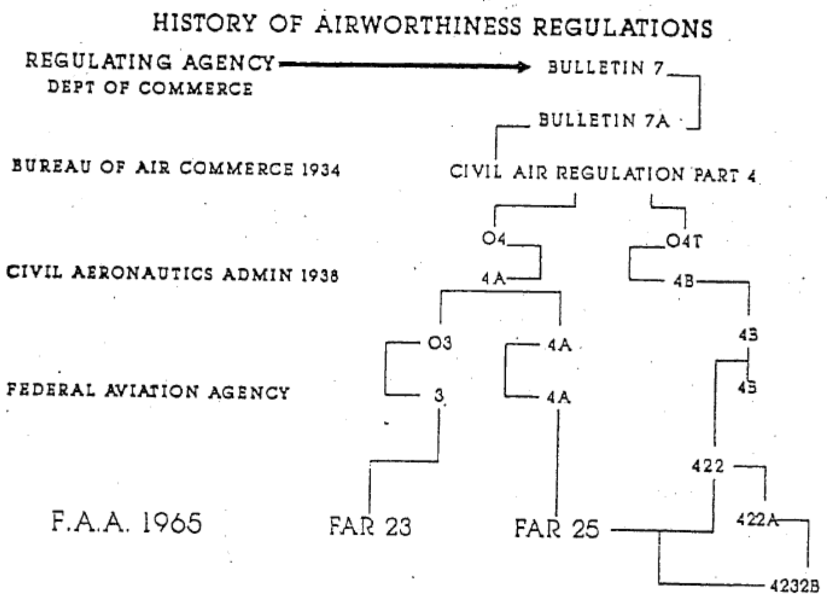


Fig. 1.1 History of U.S. airworthiness regulations.

as advisory circulars. Advisory Circular No. 23-8A is entitled "Flight Test Guide for Certification of Part 23 Airplanes."[9] This advisory circular is complete and replaces the FAA Order 8110.7. The replacement advisory circular applying to transport aircraft is AC No. 25-7 "Flight Test Guide for Certification of Transport Category Airplanes."[10]

One should understand that advisory circulars and FAA orders do not have the force of law as do FAA regulations, and the flight test methods and data reduction techniques given in these documents are not the only acceptable methods of performing the flight test. However, if an individual chooses to use a method other than one given in the advisory circular, that person is responsible for convincing the FAA pilots and engineers that it is a valid method.

1.2.3.3 Other Requirements

To sell airplanes or aeronautical equipment anywhere other than the United States, one must ensure that the requirements of the foreign nation are met. Although many countries accept the FARs, others, such as European nations and Australia, do not. Many of these countries certify their aircraft under the Joint Airworthiness Regulations (JAR). Although considerable effort has been made by all parties to ensure that the current FARs and JARs are equivalent, if the aircraft was approved under an earlier regulation, such as CAR 3, the JARs should be consulted to ensure that all requirements are tested and comply.

1.3 Aircraft Weight and Center of Gravity

The aircraft loading, or weight and balance as it is sometimes called, is one of the most important items in the flight test as both the aircraft's performance and its stability and control are functions of the loading. The most accurate way to determine the aircraft's loading is an actual weighing of the aircraft, with crew, ballasted to the test loading. However, this is not always possible since it is time consuming and costly. If an accurate empty weight and center of gravity (c.g.) have been determined through weighing then the loading can be calculated for noncritical tests. If the tests are considered critical to either flight safety or certification then the loading should be determined by weighing in the flight-ready configuration.

The weight and c.g. requirements are covered in CAR 3.71 through 3.76 (Ref. 2) and in FAR 23.21 through 23.31 (Ref. 5) and are discussed in AC 23-8A in paragraphs 6 through 10 (Ref. 9).

1.3.1 Weighing and Ballasting Techniques

In weighing an aircraft, the aircraft should be in a level attitude. Different designs use different methods for achieving a level attitude, but common methods are the use of leveling points on which a spirit level is placed or a point from which a plumb bob is suspended with a corresponding mark to show level.

The scales used in weighing the aircraft can be the platform type or the electronic type. One advantage to the electronic type, or load cell type, is that they are mounted on top of aircraft jacks and the aircraft is lifted from the surface with the jacks. If individual jack extension is adjusted the aircraft can also be leveled without compressing landing gear struts or flattening tires as is usually required to level the aircraft when platform scales are used. In most flight test programs of prototype aircraft a set of jack-mounted electronic scales will pay for themselves in time saved in aircraft weighing.

FAA Advisory Circular EA-AC 65-9A "Airframe and Powerplant Mechanics General Handbook"[14] Chapter 3, contains considerable detail on how to weigh an aircraft and additional weight and balance information may be found in AC 91-23A "Pilot's Weight and Balance Handbook."[15]

In ballasting the aircraft for flight tests several techniques and types of ballast may be used. The types of ballast include both solid and liquid.

Solid ballast can be bags of sand or cement, however, more compact solid ballast consist of lead shot as used in shotgun shells. This shot is available in 25-lb bags of various sizes from most gun shops, and the bags are small enough to be placed in nearly any location in the aircraft. Although lead bars can also be used, the lead shot is much safer in the advent of an accident as it is not as likely to become a missile as is a lead bar. Lead shot may also be placed in shot tanks that have dump valves allowing the shot to be dumped overboard in an emergency.

Liquid ballast in the form of water may also be used by securing water tanks in the fuselage of the aircraft. This form of ballast may also be dumped in an emergency.

Both solid and liquid ballast have their advantages and disadvantages which may be a function of the test to be performed. Whatever type of ballast is used, the FAA advises in AC 23-8A that attention be paid to both the longitudinal and vertical c.g. of the aircraft in ballasting. So if a solid ballast like lead shot is used, it should not be placed on the cockpit floor but in a location above the floor that would represent the vertical c.g. of the crew, passengers, and cargo.

1.3.2 Weight and CG Requirements for Testing

Both CAR 3 and FAR 23 require that the aircraft be loaded to certain weights and c.g. for certain tests. In general, the FAA requires that the aircraft be tested at the most forward c.g. at maximum TOGW for performance. For stability and control the aircraft is tested at both forward and aft centers of gravity at maximum TOGW and at the most forward c.g. regardless of weight for control. [illegible]

1.3.3 Determination and Use of the Mean Aerodynamic Chord

In flight testing it has been found that plotting the c.g. in percent of the mean aerodynamic chord (MAC) has more use than plotting it in inches aft of an arbitrary datum.

The aircraft's datum, from which all locations on the airplane are measured, is determined by the airplane's designer. As a result, the location of the datum is likely to be different for different airplane designs. An example of this difference is shown in Fig. 1.2 (Ref. 14). As a result it is nearly impossible to compare one design to another using the center of gravity stated in terms of inches aft of datum.

On the other hand, if the c.g. is referenced in terms of percent of the MAC it is easy to compare one aircraft to another. For instance, most tail aft aircraft have c.g. ranges of 10–30% when expressed in terms of MAC, while tail first aircraft will have c.g. ranges from −10 to +5% MAC. Therefore, if you were testing a tail aft aircraft that would still meet stability requirements at 35% MAC and control requirements at 5% MAC you would know that your aircraft had a wider c.g. range than most of that configuration (tail aft).

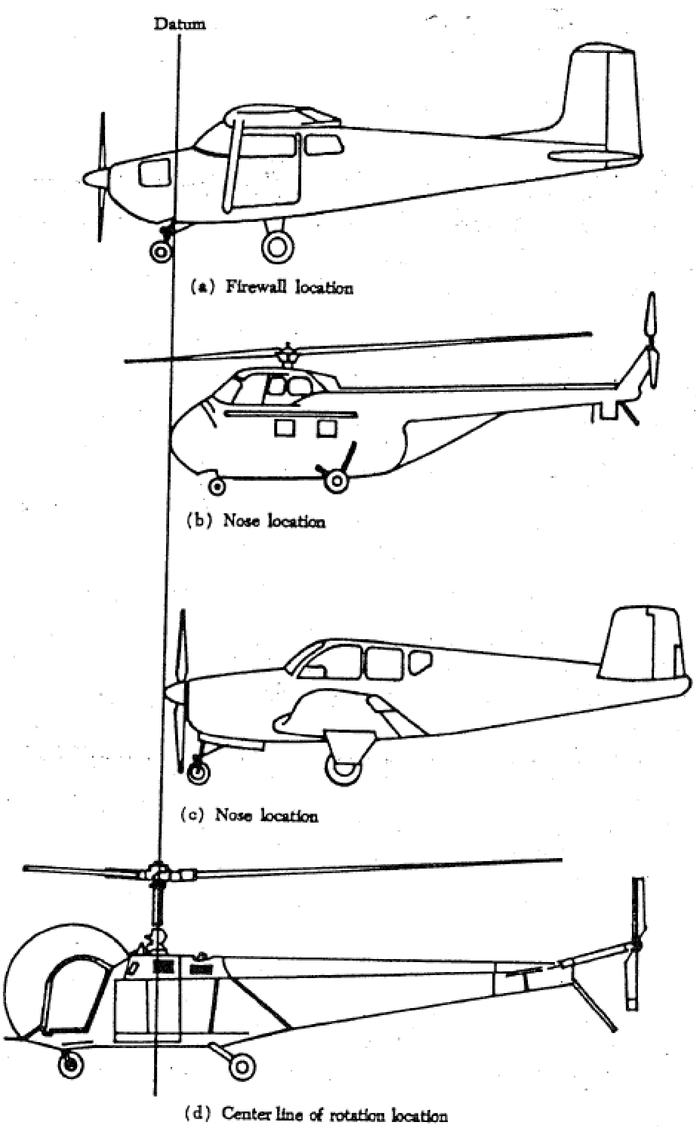


Fig. 1.2 Various locations for aircraft datum.[14]

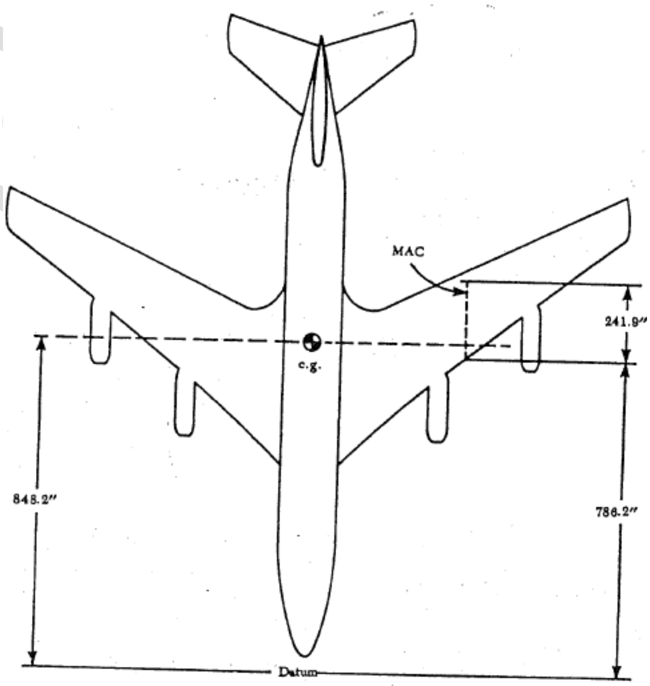


Fig. 1.3 The c.g. in relation to mean aerodynamic chord.[14]

There are several methods of determining the MAC. Mathematically, the MAC can be defined as:[16]

$$MAC = 2\int_{-s}^{s} c^2 \mathrm{d}y/S \tag{1.13}$$

where
s = the semi-span, $b/2$
c = the local chord length
y = the span wise location
S = the wing planform area

For straight tapered wings, the MAC can be written as:[16]

$$\mathrm{MAC} = C_R(2/3)(1+\lambda+\lambda^2)/(1+\lambda) \tag{1.14}$$

where
C_R = the root chord length
λ = the taper ratio, C_T/C_R

If the wing has several sections each with a different taper ratio, then the MAC of each section can be calculated and an equivalent straight-tapered wing determined.

In addition to the length of the MAC, the location of its leading edge with respect to the datum must be determined. The distance of the leading edge of MAC from the apex of a swept or tapered wing is expressed as:[16]

$$X_{LE} = C_R[(1+2\lambda)/12]A \tan \Lambda_0 \tag{1.15}$$

where
X_{LE} = the distance from the wing apex to the leading edge of the MAC
C_R = the root chord of the wing
λ = the wing taper ratio
A = the wing aspect ratio, b^2/S
Λ_0 = the sweep angle of the wing leading edge

The distance from the aircraft datum is then added to the value of X_{LE} obtained in Eq. (1.15) to determine the location of the leading edge of MAC in inches aft of datum as is shown in Fig. 1.3 (Ref. 14).

To determine the c.g. location in percent of MAC, the leading edge of MAC in inches aft of datum is subtracted from the c.g. in inches aft of datum and divided by the MAC in inches and multiplied by 100.

1.4 flight testing tolerances

AC 23-8A (Ref. 9) states in paragraph 6(a)(4): "The purpose of the tolerances specified in FAR 23.21(b) is to allow for variations in flight test values from which data are acceptable for reduction to the value desired."

In AC 23-8A, the Federal Aviation Administration accepts the following tolerances for flight testing:

1) Airspeed: 3 kn or ±3%, whichever is greater
2) Power: ±5%
3) Wind (takeoff and landing tests): not to exceed 12% V_{S1} or 10 kn, whichever is lower
4) Weight: +5% to −1% for weight critical items such as performance and +5% to −10% for nonweight critical items such as stability
5) Center of gravity: ±7% of total c.g. travel

1.5 Method of Reducing Data Uncertainty in Flight Test Data

In most scientific endeavors, we must deal with errors or uncertainty in the data we collect. Flight testing is no exception. In fact, many of our error sources are unique to our field and require special attention. The purpose of this chapter is to examine the sources of error related to flight testing, to discuss some methods of eliminating or minimizing these errors, and to determine how to deal with the remaining uncertainty when we present our data. Flight testing is a complicated experimental technique. As a result, it combines most of the types of errors found in experimental methods. For instance, fixed, or systematic, errors are found in the instruments from which we collect our data. Random errors come from the atmosphere, from pilot technique, and from errors in taking readings. Gross blunder errors can come from poor test planning, pilot technique, and several other sources.

Although most flight tests can be performed as multisample experiments with considerable improvement in accuracy, the cost of performing the test normally limits us to a single sample experiment. This being the case, we must understand where the sources of our uncertainty lie, take steps to avoid or minimize that uncertainty, and then present the data in a manner that recognizes the remaining uncertainty.

1.5.1 Sources and Magnitudes of Error

Before we can find the sources and magnitudes of errors we must first define errors. An error can be defined as the difference between the true value and the measured value. Although this definition seems simple enough, determining its magnitude from flight test data is difficult due to the number of potential error sources. Let us now examine some of these sources.

1.5.1.1 Instrument Error

Instrument error is one of the easiest errors to determine since it is determined in the laboratory. It consists of two types of error: hysteresis error and bias error.

Instrument hysteresis is the difference in instrument readings between increasing and decreasing values. Nearly all instruments have hysteresis (see Fig. 2.1). However, mechanical instruments are more prone to it than are other types. Instruments with large hysteresis should be discarded or repaired prior to use in flight tests.

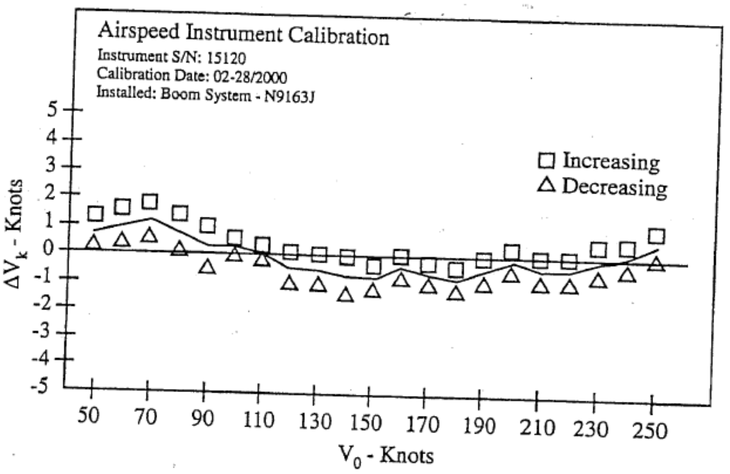


Fig. 2.1 Airspeed instrument calibration.

Bias error can be described as the difference between the correct reading and the average of the hysteresis band. For good instruments this error should not change significantly with time.

Flight test instruments should be calibrated for both bias and hysteresis on a regular basis. For normal testing, instruments should be calibrated every three to six months with the shorter interval being desirable. For critical testing, where flight safety is involved, or high accuracy is desired, instruments should be calibrated on monthly intervals or less.

The magnitude of instrument bias errors is not significant as long as it is a repeatable error and the instrument is not used as a pilot's flight instrument. The magnitude of hysteresis errors is significant and should not exceed ±1% of the scale reading.

Fig. 2.1 shows the method for plotting the instrument error for a mechanical instrument. Mechanical instrument error should be plotted with straight line variation between calibration steps since the mechanical friction in the instrument and friction bumps are more likely to make the instrument behave in this manner. Today, however, there is a tendency for new engineers to want to plot these data as a curve since curve fitting routines are available in most spread sheet programs. Curve fittings are acceptable for electrical transducers since their behavior follows a curve. However, mechanical instrument error should be plotted linearly as shown in Fig. 2.1.

One other item related to any data plotting: an old rule is that if one finds a data plot that has been dropped on the floor there should be enough information on the plot for the person who found the plot to find the owner and to have a good idea as to what the plot is about. Fig. 2.1 gives an example to follow.

1.5.1.2 Airspeed and Altitude Position Error

The error in airspeed and altitude readings caused by the location of the static pressure source on fixed-wing aircraft, and the static and total pressure source on helicopters, is determined by flight test. It is worth noting, however, that since the error is determined by flight test it is also subject to uncertainty. Since an accurate determination of airspeed and altitude is basic to all flight testing, having a high confidence level in the position correction is essential. Since the only way to obtain this confidence is through repeated sampling, this test is a definite candidate for a multisample experiment. In addition to multisampling, it is worthwhile to use several different flight test methods to obtain this data. If the data are repeatable using several methods, then the confidence in the position correction is greatly increased.

Since position correction data are subject to many of the causes of uncertainty to be discussed in the following sections, the use of curve fitting and statistical analysis techniques is necessary.

1.5.1.3 Reading or Discrimination Error

Reading error can occur in both hand- and automatic-data recording. For hand recording, errors can occur due to an indirect view of the instrument being read. This is sometimes called parallax error. Normally, these errors are small when compared to other hand-recording reading errors. Misreading errors are caused by powers of ten. If the instrument has not been consistently misread these errors are usually easy to identify.

Reading errors for automatic recording equipment are more correctly described as discrimination errors. In automatic equipment these errors are most pronounced in analog oscillograph and brush recorders where the width of the trace may provide the error magnitude.

1.5.1.4 Uncertainty Due to Atmospheric Conditions

The atmosphere can be the source of large random errors. Atmospheric temperature inversions and nonstandard temperature lapse rates can create data scatter that is difficult to explain or correct. Changes in wind velocity with altitude may also introduce error in data that are collected at several altitudes. Climb and descent data are particularly subject to temperature and wind effects.

Humidity or water vapor in the air can also create problems for the flight test engineer. Most water vapor in the atmosphere is found in the first 3000–4000 ft above sea level. This phenomena tends to make data collected in this region disagree with data collected at higher altitudes.

Atmospheric turbulence will always introduce errors in flight test data and should be avoided for all flying qualities and performance testing. The magnitude of atmospheric errors can be large and may not be correctable. Therefore, in flight testing, one should attempt to avoid atmospheric conditions that tend to introduce these errors.

1.5.1.5 Errors Due to Pilot Techniques

Since most aircraft are flown by human pilots, we must be alert for errors caused by pilot technique. Errors due to pilot technique result from failures on the part of the pilot to properly trim the aircraft, to allow sufficient stabilization time on a data point, to properly configure the aircraft or engine, or to account for friction in a control system to name a few. The pilot can also be guilty of gross blunder errors by violating known principles of testing.

1.5.1.6 Errors Due to Inaccurate Thrust or Power Determination

For performance flight testing, knowing the correct value of thrust or power is essential. However, most aircraft engines have tolerances on the thrust or power that they develop for a given power setting. If it is not possible to calibrate the engine prior to the test, which is often the case, these tolerances become data uncertainty.

Typical values for the magnitude of these tolerances are +5 to −2% of the desired thrust or power value.

1.5.1.7 Errors Due to Control System Friction or Hysteresis

Both reversible and irreversible control systems suffer from problems of friction or hysteresis. These problems can introduce significant data scatter and error to control force data. In addition to error in flight test data, the friction—and breakout forces associated with it—have an adverse effect on the pilot's opinion of the airplane if they are large.

The magnitude of these errors is a function of control system design and maintenance. In general, the simpler the control system the smaller the friction or hysteresis.

1.5.2 Avoiding or Minimizing Errors

Since many of these errors just discussed are of unknown magnitude, they do not readily lend themselves to the error analysis technique used in other engineering disciplines. However, there have been techniques developed by the flight test community to minimize these errors.

1.5.2.1 Instrument Calibrations

To minimize instrument errors, some steps can be taken while applying the instrument correction. First, on tests such as climbs and accelerations the increasing side of the instrument hysteresis should be used. On descents and decelerations the decreasing side of the instrument hysteresis should be used. For level flight data the average of the increasing and decreasing hysteresis values should be used. A similar approach should be used for other types of tests.

1.5.2.2 Sample Size

As discussed previously the airspeed and altitude position error confidence level can be increased by increasing the sample size and applying the curve fitting techniques of statistical analysis. Nearly all flying qualities and performance flight test data can benefit from an increased sample size. However, increasing the sample size to increase confidence level in the data is a tradeoff with the increased cost of conducting the flight test. Before one can make the cost vs sample size decision, one should decide if the increased data confidence is worth the cost. In many cases it is not.

1.5.2.3 Methods to Avoid Reading Errors

There are several tricks to avoid reading errors on hand-recorded data.

Parallax errors may be avoided by the observer being positioned directly in front of the instrument to be read.

Misreading errors may be reduced by writing down the first one or two numbers prior to final stabilization on the data point. For example, the thousands and hundreds of feet in altitude may be recorded before reaching the data point, and upon reaching the data point the tens of feet are read. Similar approaches may be used on other parameters.

Additional data scatter may be avoided on hand-recorded data by determining which are the most important parameters and then reading those parameters first. Increased accuracy will also be obtained by reading parameters in the same sequence at each data point.

For automatic recording equipment, reading errors will be reduced by selecting larger rather than smaller scales for data traces and by reducing the amount of data to be collected on any one device. Digital rather than analog data recording may also offer advantages for certain types of data, however, this is not always true. For certain dynamic data analog recording is superior to digital.

1.5.2.4 Minimizing Atmospheric Errors

Errors caused by temperature inversions, nonstandard lapse rates, and wind shear may be avoided or reduced by using several techniques.

First, it has been found that collecting data through a temperature inversion will introduce uncorrectable errors in the data. Climb and descent data are particularly subject to these kinds of errors. One way of avoiding them is to have another aircraft climb through the altitude band where testing is to take place and record outside air temperature vs altitude. The test aircraft can then use this data to avoid temperature inversions and areas of turbulence.

The effects of wind shear may be reduced on climb and descents by performing these maneuvers at right angles to the prevailing wind and by repeating all climbs and descents on opposite headings. Opposite heading data is then averaged to come up with the corrected value of climb or descent for the given airspeed.

It is best to avoid high humidity days for flight testing. However, this is not always possible. In such cases, we may correct for humidity by taking wet and

dry bulb temperature readings at each test altitude. With this data a psychometric chart may be used to determine the partial pressure e of the water vapor in the air at the time of test. Once this value is obtained the density ratio σ may be corrected using Eq. (2.1) (Ref. 1).

$$\sigma = 9.625(P - .375e)/(273 + t) \tag{2.1}$$

where
P = the atmospheric pressure in inches of mercury
t = observed air temperature in Celsius

Engine power will also be affected by humidity. There are two methods of correcting for humidity on reciprocating aircraft engines. The first method is to subtract the partial pressure of water vapor in the air from the instrument corrected manifold pressure prior to entering the engine power charts to determine horsepower. A second method that will work for a variety of engines is to use the following equation:[1]

$$HP(\text{dry air}) = HP(\text{moist air})\{P/(P - e)\} \tag{2.2}$$

1.5.2.5 Minimizing Errors Due to Pilot Technique

A good test pilot can trim and stabilize an aircraft in a minimum amount of time. However, all test pilots will not perform these acts in the same amount of time. Therefore, pilots should be given the amount of time they feel necessary to trim and stabilize on data points since most data errors due to pilot technique result from the pilot trying to rush through the procedure. It has been found that stabilization occurs faster if data points are approached from a higher airspeed rather than a lower airspeed.

Many gross blunder errors made by the pilot and crew can be avoided if test checklist are prepared and followed for each test and if the configurations and power settings are checked and rechecked prior to each data run.

1.5.2.6 Minimizing Errors Dueto Inaccurate Thrust and Power Measurement

If possible prior to testing, the power plant should be calibrated while installed in the test aircraft. For jet aircraft this should be accomplished on a thrust stand and for propeller-driven aircraft using a torque meter. Although it is only possible to do the thrust calibration on the ground, these data may be used to adjust the engine manufacturers altitude data, thereby reducing some of the known error.

Other items for reducing installed thrust or power errors are accurate measurement of the engine inlet temperature and other engine parameters.

1.5.2.7 Minimizing Friction Errors

Prior to commencing flying qualities testing the control system friction and breakout forces should be measured and recorded. If these values are found to be excessive the control system should be inspected, cleaned, and lubricated, and any source of friction not inherent in the basic design corrected.

During data acquisition the pilot should attempt to work out the friction prior to taking readings or to obtain a friction hysteresis by obtaining increasing and decreasing readings. In addition, free return speeds should be obtained on longitudinal force data for aircraft with reversible control systems and breakout forces should be obtained for irreversible control systems.

1.6 Planning Flight Test Instrumentation (System Planning in Flight Test Instrumentation)

The development of an aircraft type i.e, the phase before the aircraft is accepted for production by military or civil authorities-can be divided into two stages: a design stage (including the production of one or more prototype aircraft) and a test phase.

During the design phase, estimates of the aircraft characteristics must be based on previous experience with similar aircraft, on wind tunnel tests of reduced-scale models, and on theoretical calculations. These design aids are quite sophisticated and are becoming very realistic. In wind tunnels the range of achievable Reynolds and Mach numbers increases, the effects of all kinds of errors become better known so that corrections can be applied.

The increased capacity and speed of digital computers has tremendously stimulated the development of powerful calculation methods in the fields of stress analysis and aerodynamics. These improved design aids significantly reduce the probability of large design errors. Nevertheless, the test phase is still essential to prove that the aircraft meets its design goals and to verify its performance.

Test programmes are not only essential for the development of new aircraft, they also satisfy a variety of objectives of military services, other government agencies, manufacturers of engines and aircraft equipment, and commercial airlines. The test results provide information:

- To provide product designers with feedback they need to evaluate the design's validity or to provide the basis for design alterations.
- To evaluate whether or not the product is being built in accordance with the design specification. This is of importance for the organization acquiring the equipment.
- To provide insight into how well the system will work once fielded. Tests of military aircraft must determine whether or not the system will be operationally effective and suitable for use in combat by typical military forces.

The planning of the test phase is slightly different for civil and military aircraft. The testing of civil aircraft was originally regulated in detail in each country separately, whereby the FAR gradually became the main example for other countries. During the last decades the European countries have developed their own joint regulations which have been set up along lines very similar to FAR, though there are several important differences. A civil aircraft that has been shown to meet these requirements receives a Type Certification. For military aircraft the requirements, and therefore the test programme, are more specifically determined by the use that is to be made of the aircraft.

1.6.1 Test Planning

Test planning documentation falls within the broad categories of a master test plan and detailed test plans.

The master test plan contains test management concepts and discusses the objectives of the tests that are to be executed, test locations and resources, and overall support requirements. Master test plans should contain enough information on specific test particulars to allow test engineers to develop detailed test plans and instrumentation measurement list.

1.6.1.1 The Master Test Plan

There should be an overall test and evaluation plan for any development test program. This plan should identify:

- The critical technical and operational characteristics to be evaluated during the tests and quantitative values.
- The division between ground tests and flight tests, and the specification of the flight tests required to verify the results of ground tests.
- Whether real-time data analysis will be used and, if so, whether this will be done on the ground using a telemetry link between the aircraft and the ground processing station or using onboard computers.
- The analysis techniques that will be used in processing the test data. Modern computer based design techniques make extensive use of computer models. An important part of the flight testing will consist of verification of those computer models. The modern analysis techniques available for this verification (parameter identification techniques) often require very specific flight tests to provide optimal results.
- The number of aircraft to be used and the definition of the parts of the test program each of these aircraft is to execute.

- All key test resources that are to be used during the course of the test program and basic specifications for those that must still be purchased.
- General requirements for the instrumentation systems and for the installation of the flight test instrumentation in the prototype aircraft. These latter are c'oncerned with the integration of the normal operational wiring with the wiring required for the special flight test instrumentation and with safety aspects in case the test instrumentation system must be connected to operational systems in the aircraft.

This Master Plan must be finalized at a very early stage in the design of the aircraft. It will be the basis for purchasing the components for the ground simulators and the onboard measuring equipment, and for defining the wiring and other provisions for the instrumentation system that must be incorporated in the prototype aircraft. It should be kept in mind that the same ground simulation computers can, in many cases, be used for simulations during both the design stage and the test stage.

1.6.1.2 Detailed Test Plans

On the basis of the Master Plan all those who require information from the test programme should provide test management with descriptions of the tests they want to have executed. Such descriptions will be supplied, for instance, by the authorities who must certify the aircraft, by future users who want verification of the performance claims of the manufacturer and information that may be essential for the future operation of the aircraft, or by design engineers who want to verify theoretical or wind-tunnel results. The descriptions must indicate the principles of the test procedures, the number of tests, and the limitations and constraints which are essential to obtain usable results.

The test management must then integrate the requirements from different users, decide which tests must be done by flight tests and which by ground tests, and establish a time sequence for the complete test programme. This information is then handed to groups of more specialised engineers for further development:

- Flight test engineers must work out the details of the flight procedures and write step-by-step instructions for the flight crews. They also specify what measurement parameters will be required for each specific test and what are the requirements regarding measuring range, accuracy, sampling rate, etc. They will also set up the sequence in which the tests are to be executed.

- Instrumentation engineers must work out the details of the instrumentation system that will be required to execute these measurements and must select the individual parts that must be purchased and define the software that must be developed.
- Computer engineers must work out the details of the computer systems that will be required. This applies in the first place to planning for the hardware and software of the main ground processing system, but can also include onboard computers and microprocessors, and computer systems for auxiliary ground equipment.

The brief review of the planning process given above may seem to indicate that the several stages of the master plan and the detailed plans follow each other in a continuous sequence. In reality this is never the case. During the whole design process there is continuous consultation between the test managers and all participating specialists, so that new requirements that come up can be accommodated and the effect of new ideas in one specialty can be considered in the light of the total project. Even while the flight tests are actually being executed, problems may come up which require new parameters, new software, new sampling rates, etc. A good relationship between the test managers and the many groups of specialists involved in the design and maintenance of a flight test system is one of the critical aspects which determine the success of the programme.

1.7 Measurement of Flight Parameters

1.7.1 Displacement Measurement

Displacement may be considered as the primary measurement, firstly, because it may be either a discrete measurement, or it may be part of a transducer. Secondly, it is the most frequent method of transducing from mechanical to electrical data. Because of these and the mathematical relationships it is logical to consider displacement firstly, and in some detail, and then to follow with he other parameters.

1.7.1.1 Direct and inertial measurements

There is a fundamental difference between the direct methods used for small distances and the inertial methods used for the larger distances, in particular in the areas of navigation.

A direct measurement is one where an attachment may be made to both the fixed and moving parts. This is satisfactory for relatively small displacements, possibly up to about 1 metre, such as may be required about the aircraft structure. However, when it is necessary to measure the much larger distances found in navigation, it is impossible to make a direct attachment and inertial methods are necessary.

For linear inertial measurement it is normal to use an accelerometer producing acceleration data which may be integrated twice to produce displacement data. For rotary movement, gyros are usually used, either the free gyro for angular displacement or the rate gyro for angular velocity.

Vibration and shock is frequently measured by inertial means using accelerometers, because, although displacements may be small, it is invariably impossible to establish a known fixed reference. By the nature of vibration, the structure around the vibrating object usually absorbs some of the vibration energy and sets up vibration modes of its own. Similarly, with shock measurement, a reference is usually difficult to establish.

1.7.1.2 Potentiometers

The potentiometer (Fig. 5.5) is probably the most basic of displacement transducers, where a voltage is placed across a resistive element and a moving wiper contact picks off a part of this voltage in proportion to displacement.

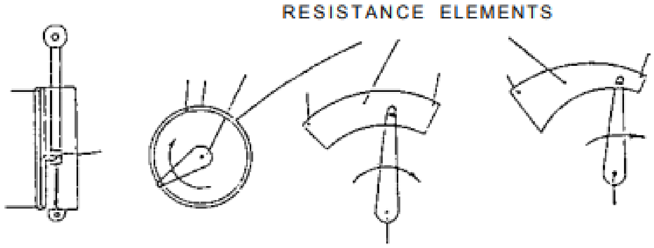


Figure 5.5. Some basic potentiometer layouts.

This a simple and economic method which is widely used, but has a number of disadvantages, particularly for long term use. Because of the rubbing contact, there is friction, stiction, and always the possibility of poor contact because of dirt and vibration; all these degrade the accuracy and can produce noise (unwanted signals). Additionally, in a permanent installation, wear becomes a problem, which would mean replacement and recalibration. Because of these disadvantages, altemative methods are often sought, in particular, inductive transducers.

Potentiometers have been progressively developed, and various conductive plastic film and film/wire techniques are available which provide greater resolution than the original wire-wound elements, whilst still retaining the good linearity. Some, however, do show some nonlinearity error near to the connections. All types may be shaped to provide a nonlinear law, for example, a transducer square-law may be inverted to provide a linear parameter to data relationship.

Potentiometers find extensive use in instrumentation, both as an integral part of a transducer and as a discrete displacement measuring instrument, particularly for the larger measurements. In angular measurement they allow virtually a full 360° of movement.

1.7.1.3 Inductive Displacement Transducers

These work on electromagnetic principles in a similar manner to the electrical transformer. Mechanically and magnetically there are many configurations including the E and 1 pick-off, the rotary (angular) pick-off, and the linear LVDTs (Figs. 5.6, 5.7, and 5.8).

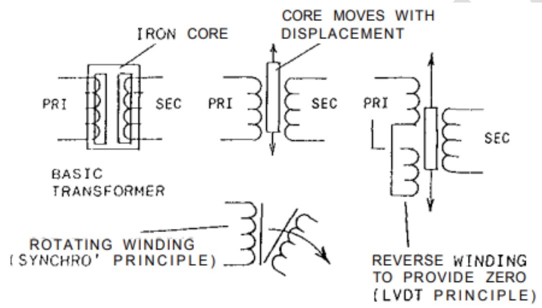


Figure 5.6. How the basic transformer may be modified to measure displacement.

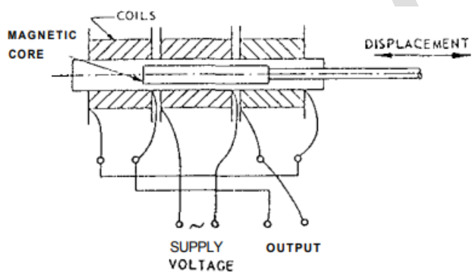


Figure 5.7. Linear variable differential transformer (LVDT).

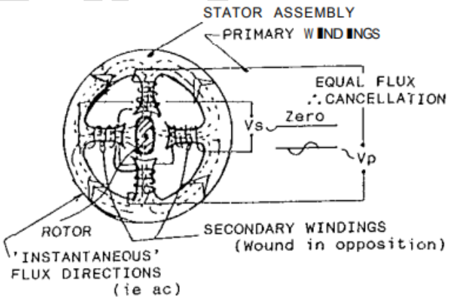


Figure 5.8. The rotory (angular) pick-off.

The windings are frequently arranged so that there is zem secondary output at balance, and the output increases linearly with displacement of a magnetic (not magnetised) slug; the direction being indicated by the electrical, input to output phase relationships.

Inductive transducers frequently take the physical form of a potentiometer, although the electrical aspects are obviously very different. One of the major factors which may make this type of tranducer so rugged and relable is the fact that often the only moving parts are simple magnetic components with no electrical connections.

The measurement range might typically be from a few micro-metres or a few min's of arc for the most sensitive instruments, to 1 metre or so. However, rotary movement is usually limited to $\pm 45^0$.

1.7.1.4 Synchros

The traditional designs of synchro were for transmitting angular data, i.e., that two shafts may be synchronised in angular position; this was one of the original positional force balance developments.

The basic synchro has similarities to the angular pick-off except that it has windings on bth the rotor and stator assemblies; this allows a full 360° of measurement, which is not possible with the pick-off. Also, the data is produced in ratio form which, because of this, the absolute amplitude of the data is of secondary importance and thus polarisation amplitude changes or transmission losses are less significant; all of which considerably enhances the over-all accuracy.

The synchro is a much more precise, expensive, and delicate a device, is more applicable to the requirements of control systems or avionics, and has been developed into many variations, including linear versions. However, most are for rotary movement, where accuracies to seck of arc are possible.

1.7.1.5 Capacitive Displacement Transducers

A capacitance is formed when two conductive plates are placed together and they have the ability to store to store electrical charge. The amount of stored charge depends upon the area, the spacing, and the material between the plates (the dielectric); thus any one of these may be changed to give an electrical change with respect to displacement. This principle is vely simple to use mechanically, although it is not so easy to contend with electrically; however it has the particular advantage of minimal loading upon the measurement (Le., good finesse). For example, a capsule instrument such as an altimeter or a barometer is relatively fragile, and any load applied would reduce the accuracy, but a capacitive pick-off (PO) may be simply applied in the form of a single plate, using the metallic surface of the capsule as the second plate. A number of precision altitude and airspeed transducers of this class are available, but the use of capacitance as a means of direct displacement measurement is generally limited to situations requiring high precision and given clean conditions (Fig. 5.12).

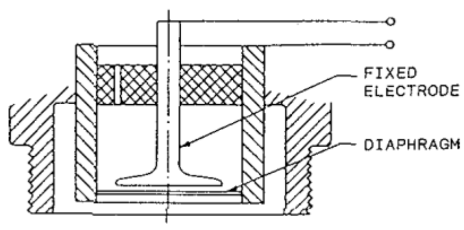


Figure **5.12.** Capacitive pressure transducer,

1.7.1.6 The Piezo-Electric Principle

Certain materials have the property of generating a voltage across their surfaces when they are physically distorted. Thus if a conductive coating (often a silver plating process) is placed upon two opposite surfaces, conductors may be connected to sense these voltages. The materials may be natural (i.e., quartz) or man-made, and they are produced in many shapes and size:s and for a variety of distortions, i.e., twist, bend, or compress.

Although the principle is fundamentally a displacement in the sense of the material distortion, it is unusual to use the method for the direct measurement of displacement. It is, however, frequently used as a means of measuring force, and in particular as part of a transducer. Because the principle is basically that of measuring a charge across a capacitor, the signal conditioning should theoretically have infinite impedance in order to measure down to steady-state (dc). In practice this is not possible, and the minimum frequency is typically about 2 Hz, or down to about 0.1 Hz with special precautions. This is one .area where the integrated package type of construction excells.

It is generally not possible to damp piezo-electric transducers, and the damping ratio is frequently in he region of 0.1. However, because the high-frequency performance is usually good, many transducers having a natural frequcncy, fn. in the region of 10 to 250 kHz, there is usually no problem in working well below fn. Often below 0.1 to 0.2 fn.

Hence, these. principles are essentially suited to dynamic measurement 2nd are not always applicable to aircraft performance measurement. Particulair areas of application are for the measurement of vibration under harsh environment such as engine monitoririg, high frequency measurement of pressure and force, and also domcstically, for such applications as record player cartridges.

It may be noted here that the process is reversible such that an applied voltage will create a physical distortion. This has found many uses in micro-positioning, for example, in optical equipment or within transducers such as the RLG for creating dither.

1.7.1.7 Strain Gauges (Metallic)

As the name imulies, this device is for measuring - strain, but by usinz - mechanical cantilevers, diaphragms, etc., it may be considered as a displacement transducer. Fundamentally the strain gauge is a piece of metallic wire held between two points. This wire will have a resistance (R) and a length (e), but if the wire is stretched slightly (well within the elastic limits) the length will increase and the area will decrease. This physical change creates a resistance increase and because there are the two physical changes, the resistance change (ΔR) is approximately twice the length change (Δl). This is known as the gauge factor (GF), and GF = 2 (approximately) for metallic materials.

The device described so far would be known as an unbonded strain gauge, and because of its fragility it would normally be confined to uses within transducer assemblies. For structural stressing applications the bonded strain gauge is normally used, where the strain-gauge wire is formed into a grid and adhered to an insulating backing material which in turn is cemented to the structure.

Many current bonded strain-gauges are constructed from foil rather than wire, (Fig. 5.14) rather like a small printed circuit. This generally provides a superior performance, in particular, to the cross-axis sensitivity, this is because of the ability to make the return curves much thicker than the main strain-gauge conductors.

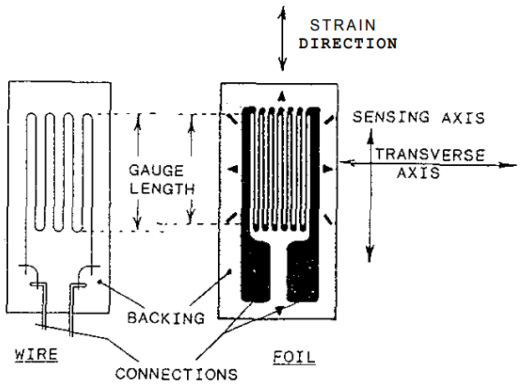


Figure 5.14. Wire and foil strain gauges.

1.7.1.8 Encoders

The term encoder rcfcrs broadly to a range of transducers which rely upon I3 mechanical scale or grating as a reference and a means of translating displacement or velocity into electrical data. The scale is frequently in the form of an optical grating, either circular, or in some linear form.

Techniques using the basic grating may be used for high-accuracy displacement or velocity measurement; or by employing gratings with more complex patterns, true digital encoders (mechanical A-D converters) may be constructed.

1.7.2 Velocity and Flow Measurement

A primary measurement for aircraft is airspeed, normally measured by the pitot and static systems, thus giving a pressure difference. More broadly, velocity encompasses the measurement of linear and rotary machinery components, typically involving a whole range of tachometers, ground speed, and all the related vehicle speed measurements. To these may be added the general of fluid subject flow.

1.7.2.1 Pitot-static systems

These will not be discussed in detail here because there are many specialised publications on the subject The basic concept is to measure the ram-head pressure from a tube facing into the airstream and to compare this as a difference with a static pressure. Ideally, the static pressure is the ambient pressure distant from any disturbance of the aircraft, but standard installations normally take an average of a number of static vents mounted at various quiet positions on the aircraft surface. For research, it is common to have booms extending beyond the aircraft aerodynamic disturbance, or sometimes a trailing static is towed many metres behind the aircraft.

1.7.2.2 Tachometers

Standard tachometers are fundamentallv electro-mametic generaton which provide a linear relationship between speed and electrical output. It may be noted here that, in principle, the only difference between a displacement transducer and a tachometer is the fact that for displacement the rotor is simply a piece of magnetic material, and thus the transducer requires to be polarised, but for the tachometer, the rotor is magnetised, and thus the transducer becomes self-generating.

Typical aircraft engine tachos are ruggedly constructed and give a three-phase voltage which may be transmitted to the indicator on a ratio basis. Other types produce either ac or dc, the latter being more applicable to servo requirements. Funher types give purely a frequency or pulse rate; these are more applicable to the more accurate requirements and to digital systems.

1.7.2.3 Measurement of Flow

Basically, this may be considered as an extension to velocity measurement, and in practice many of the techniques are common.

The techniques generally group into liquid flow (fuel, coolant, etc.) and gas flow (air, etc.), although it is often possible to use the same principle for both, is., pitots for aidgas flow and orifice plates/pressure drop for liquid and similarly for turbine methods and anemometry principles.

Fuel and Liquid Flow

For engine performance measurement, the true requirement is to measure the mass flow passing into the engines, for example, the mass of fuel (i.e., Kg) being bumed for a given performance. In practice the majority of flowmeters measure rate of flow (and hence volume) which is another form of velocity measurement. Hence, mass flow must be derived.

Turbine Flowmeters

Many aircraft use the turbine flowmeter principle to measure fuel flow, one transducer for each engine. This type of transducer is fitted directly into the pipeline to the engine and contains a small turbine, which spinsround at a speed which is in proportion to the flow rate. Because fuel density changes are not usually significant in normal service, it is satisfactory to calibrate the transducer output in terms of mass flow. Compensations for temperature or fuel changes may be built into this type of flowmeter (Fig. 5.15).

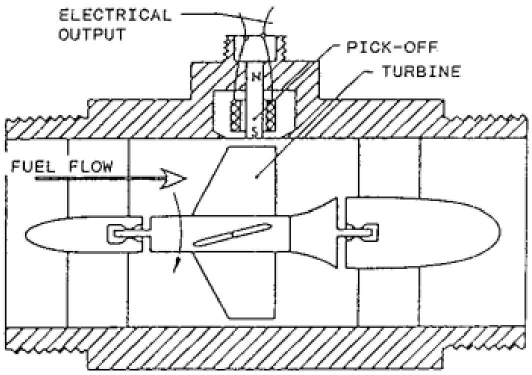


Figure 5.15. Pulse generating turbine flowmeter.

A small pick-off is placed near to the turbine vanes which produces electrical pulses in proportion to the flow rate. The normal method is to pass these pulses into an electronic circuit which provides a meter indication in the pilot’s cabin. The relatively simple analogue approaches to processing these pulses only yield accuracies of a percent or so and more accurate electronic logic methods are used for test instrumentation to provide either a numeric read-out or digital data for such parameters as fuel consumed.

Mass Flowmeters

These tend to more complex and expensive and therefore limited to installation where there is a strict requirement for mass flow measurement. The basic principle is to impart an annular velocity into the fuel as it passes through the transducer, and the torque requijred to achieve this annular motion is directly proportional to mass flow.

Positive Displacement Flowmeters

These generally apply to the fuel dispensing and consumer industries, wher': the transducer measures volumes of the fuel dispensed.

Areddisolacement Flowmeters

This is where the flow forces against a spring loaded vane or cone (rotameter) and are generally known as variable area or variable volume flowmeters, Le., they essentially produce velocity/volume data.

Other Flowmeter Types

The electro-magnetic types are popular for measuring water flow, including sea water. They work on the principle of using the flowing liquid as an electrical conductor passing between the poles of a magnet. Thus as the liquid conductor cuts the magnetic flux, a voltage generation is created which is proportional to flow velocity.

Vortex types have been used extensively for wind tunnel and atmospheric measurement and also water flow measurement. The principle is that a vortex flow pattem is created over specifically shaped bodies and changes in the pattem or frequency vary with rate of flow.

Ultra-sonic methods are used for both anemometry (gas/air) and liquids. For liquid measurement, they have the particular advantage that a system may be attached to a pipeline without any mechanical intrusion.

Laser methods are similarly used for nonintrusive flow measurement and have been developed into a very sophisticated and powerful measurement tool. They are mainly applicable to the laboratory situation and provide an effective method of studying of fluid flow and flow patterns.

1.7.2.4 Anemometers

Anemometers were originally developed for the measurement of wind velocity, and many devices may come under this category. These may include, cup-anemometers, pitothtatic systems, vortex and ultra-sonic instruments, but one of the major instruments is the hot-wire anemometer.

The basic principle is to measure the cooling effect of a heated wire when placed into the flow. The very fine filament wire is held on supports and heated by an electrical current and thus the cooling effect of the wire may be measured by resistance change. However, this open-loop system has a number of disadvantages, including the secondary effect of heat flow in and out of the support wires, and therefore, the majority of anemomenten are force balanced. This is where the temperature is kept constant and the current is varied with flow rate by a servo feedback system. These instruments are particularly used for the various aerodynamic measurements and will respond up to 100 kHz or more.

1.7.2.5 Flowmeter Performance

As a very general statement, there are no upper limits to the measurement of flow; it is simply a matter of providing areas, pipes, etc., large enough to accommodate the flow without choking and so on. Low flow rates may produce difficulties and are often limited by the dynamic range of the instrument, often to about 10 percent or 15 percent of full scale. Generally the hot-wire anemometers, ultra-sonic, and laser methods show good performance at low rates.

High-frequency performance is usually very limited for the mechanical instruments, but again the hot-wire and laser methods show the best performance.

1.7.3 Acceleration Measurement

This parameter is usually sensed by a springbass system, where the spring is distorted under the influence of acceleration. The movement of the mass with respect to the case of the transducer is then measured by a displacement transducer; this in turn provides a signal in proportion to the accelcration.

1.7.3.1 Practical Accelerometers

There are three basic types of accelerometer, namely:

- The conventional spring-mass accelerometer (Fig. 5.16). When used as a general purpose instrument, only nominal accuracies of 1% or so are obtained; also, there may be a high cross-sensitivity of 3% or so. There are a few instruments of greater precision, but the cost of these generally makes them less competitive with the force balance class of transducer. In all cases, the frequency range is generally from steady-state to about 250 Hz. The spring and mass configuration is constructed in a rigid manner so that ostensively only one axis is sensitive to acceleration, frequently utilising leaf-springs, diaphragms, or cantilevers. The mass is usually made of a stable material and may form part of the magnetic circuit of a displacemcnt pick-off, whilst other designs use potentiometers, strain gauges, either wire or semi-conductor (piezoresistive), or of fluid capacitive pick-offs.

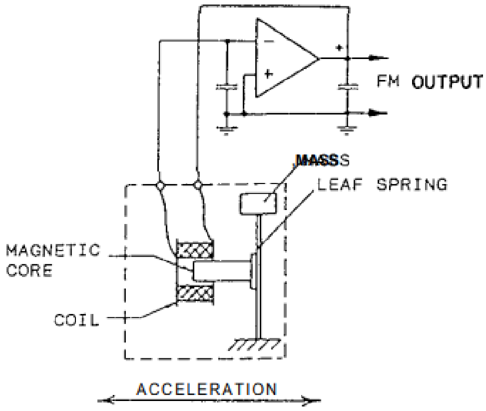


Figure 5.16. Variable self-inductance accelerometer in an oscillator circuit.

- Piezo-electric accelerometers (Fig. 5.17). These are essentially for dynamic measurement, such as vibration and shock. There is no steady-state response, but the top measurement frequencies may be in kilohertz to hundreds of kilohertz region. In essence, the mass is directly attached to a piece of piezo material which provides both the spring and signal output function, and this very stiff construction usually provides the very high natural frequency fn. However, it is essential to isolate the piezo/mass system from the case of the instrument in order to provide immunity from temperature and case distortion effects, and therefore, only the very cheapest of instruments have this basic construction.

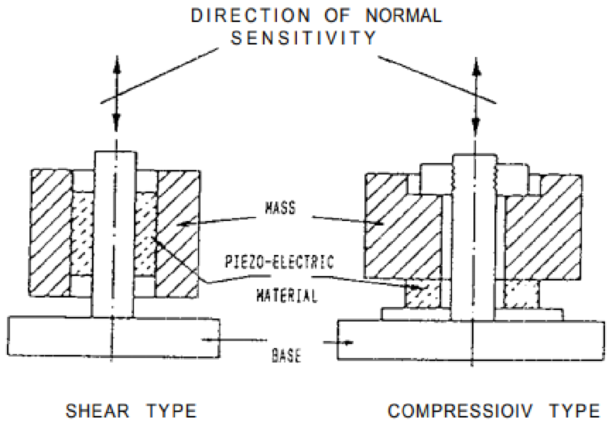


Figure 5.17. Two types of piezo-electric acceleration transducer.

- Force balance accelerometers. These generally replace the spring-mass instrument when good performance is required. They may be very expensive but may provide very good accuracy and frequency performance, ranging from steady-state to as high as 1 kHz or so. Generally this is the choice for such applications as inertial navigation systems.

1.7.3.2 Force Balance Techniques (Servo Feedback Transducers)

It is basically a principle of forcing all the moving parts of the measurement transducer to remain at balance position by opposing changes due to the parameter with some form of servo controlled force system (Fig. 5.18). For an accelerometer, the mass is controlled in a servo loop such that, immediately a movement of the mass is sensed, a force is applied which resists any further movement. Provided that the gain of the servo loop is high, it may be assumed that there is no movement of the mass, and the only change which takes place is an electrical change of current into the forcing coils. This current may then be used as the data representing acceleration.

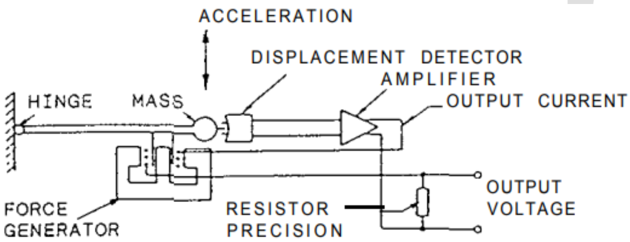


Figure 5.18. Force balance acceleration transducer.

1.7.3.3 Frequency Response verses Range and Damping

As a general rule, the more stiff the. construction of the instrument, the higher the acceleration range and the higher the frequency response. The relationship is basically a square law, i.e., 4 times acceleration range, will approximate to a 2 times frequency response.

As a general statement, the spring/mass type will range from about 1 g to a few hundred g, the piezo types have a much higher range, up to 10,000 g in extreme cases, whilst the force balance types may be extremely sensitive and range up to 1000 g.

1.7.3.4 Vibration Measurement

The basic definition of vibration is displacement peak to peak at a given frequency, although peak values are often used. In most cases the measurement will be made inertially using an accelerometer, and thus the data must be integrated twice to deduce the displacement.

Direct measurement of vibration may be achieved by using a springhass instrument with a very low fn and making all measurements at frequencies well above fn . Thus the transducer is constructed in a similar manner to an accelerometer, but with a very low fn and no damping. Thus the mass remains seismically balanced in space, and the transducer body moves with respect to the mass. Obviously, any large movements of the transducer would create a limit stop situation, and therefore these instruments are generally limited to stationary measurements, i.e., stationary generators, engines, etc.

Various inductive or capacitive probe methods may be used to measure the vibration displacement provided a stable reference may be found. Optical and particularly laser methods may be very effective, but are often limited to the laboratory situation.

1.7.4 Gyros

The two basic types are the free gyro and the rate gyro. Both types rely upon the spinning mass (similar to a flywheel and often known as the "wheel") which has the properties of rigidity (or stiffness) and precession.

1.7.4.1 Free Gyros

Rigidity is a resistance to any force which attempts to change the spin axis and is the main property utilised for the free gyro (Fig. 5.19).

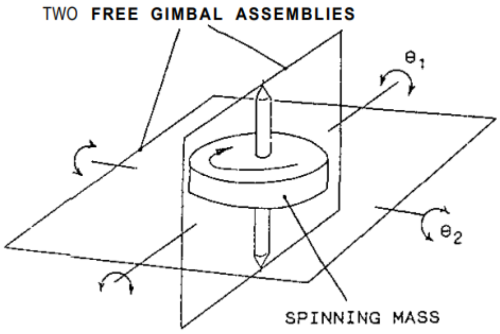


Figure 5.19. Free gym assembly (vertical).

The wheel is mounted within a gimbal assembly which allows angular movement of the instrument case with respect to the wheel, thus the free gym measures angular displacement and typically, in two planes. If the spin axis is vertical, the two angular planes are pitch and roll, and this would be known as a vertical gyro. If the axis were horizontal, it would be known as an horizontal gyro, directional gyro or azimuth gyro because it would measure displacements in the horizontal plane, commonly known as azimuth.

It is not possible to make a very general statement about range and accuracy; one reason is that so many instruments are related to compensation techniques, i.e., vertical pendulous gyms designed to track towards the Earth's gravity, compass and flux-gate correction systems and so on. But, the range is potentially up to 360^0. although many vertical gyms are limited to less than fl quadrant of arc; and the fundamental accuracy is normally related to a few deg/min. or less for precision instruments. Damping does not apply to these instruments.

1.7.4.2 Rate Gyros

A rate gyro is similar in principle except that it is designed to measure angular velocity and uses the property of precession to detect the rotational rate. The gimbal assembly has only one degree of freedom and even this is restrained by a spring. When an angular input is applied in the axis which forces the wheel spin axis to rotate, the precessional forces react at right angles and against the spring. "Thus the sum of precessional force and spring stiffness provides a calibrated means of measuring angular velocity.

In gcneral, instruments are available to cover measurement from about 20^0/sec up to 1000^0/sec. Most rate gyros are damped, and because most show considerable self heating, there is often an in-built temperature/damping coefficient compensation process. Accuracies are typically approaching the 0.1 percent range for good instruments. These instruments are normally optimally damped although phase requirements or dynamic requirements sometimes demand less or more damping respectively.

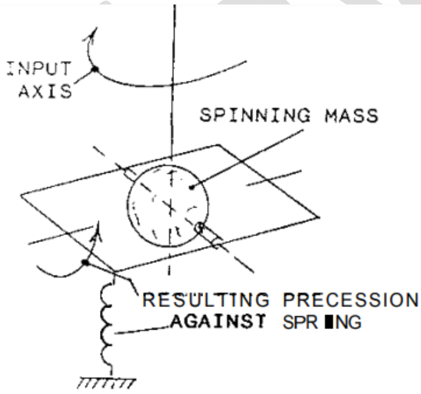


Figure 5.20. Rate gym assembly.

1.7.5 Pressure Measurement

This parameter may be fluid or gas (including air), and the three basic ways in which it may be sensed are discussed below. Each method produces a displacement, and therefore there is always the dual choice, firstly of how to sense the pressure and then of how to sense the displacement to provide electrical data. Most of the displacement transducing principles have been employed throughout the range of pressure transducers available. Clearly such instruments as the traditional pilot's altimeter, ASI, and other pressure instruments do not require electrical output, and therefore the displacement is directly coupled to a pointer through mechanical linkages.

All pressure measurements are fundamentally made as a difference of two pressures, (Fig. 5.21) and therefore there are three concepts, i.e.,

- Gauge pressure - Unknown pressure with respect to atmosphere (i.e., industrial measurement)
- Absolute pressure - Unknown pressure with respect to a vacuum (or as near as possible) (i.e., altimeters, barometers, etc.)
- Diffcrential pressure - The difference of two unknown pressures (i.e., ASI, flow, etc.)

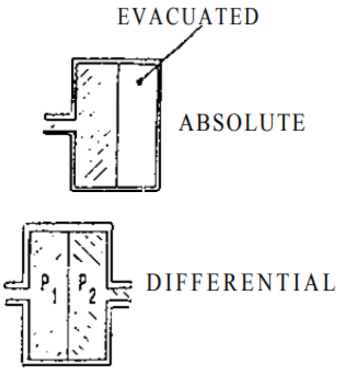


Figure 5.21. Pressure concepts.

1.7.5.1 Capsules and Bellows (Altimeters and ASIs)

This is probably the most sensitive method and is typically used for altimeters, ASIs, and barometers. The sensing element basically comprises an evacuated chamber, usually cylindrical and with either corrugated sides (bellows) or a single flat capsule, or sometimes a number of capsules connected in series (Fig. 5.22).

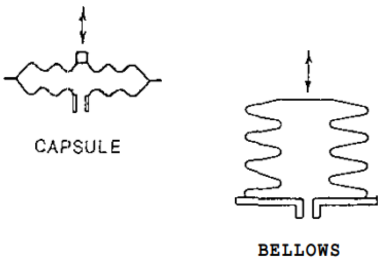


Figure 5.22. Capsule and bellows.

A typical air speed indicator (ASI) would Ix similarly constructed and would measure the difference of the two pressures from the pitot and static system. Additionally, since pressure difference is proportional to the square of the speed, special linearising linkages are often used to give a near linear reading of air speed.

The above discussion has related mainly to the visual, cockpit type of ins,t”ent, but similar principles are used to provide electrical data, and it is one area where the capacitive type of displacement pick-off is of value because of the minimal loading effects upon the sensor elements.

1.7.5.2 Diaphragms

This is probably the most widely used principle in general instrumentation. The diaphragm may be metallic, plastic, or a semi-conductor material (usually silicon) and is usually formed as a thin circular membrane mounted into a solid casing which is suitably fitted with pipe connections (or any other requirement).

As pressure is applied, the diaphragm begins to distort and the displacement of the diaphragm is measured by some form of displace ment pick-off (PO). Many transducers are constructed with a diaphragm and inductive PO combination, but many other types are available, including capacitance, piezo, and strain gauge. In the latter case silicon diaphragms and integrally diffused strain gauges arc bccoming increasingly available. See Figurcs 5.23 and 5.24.

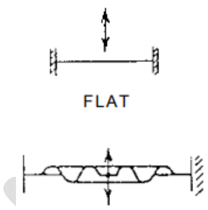


Figure 5.23.

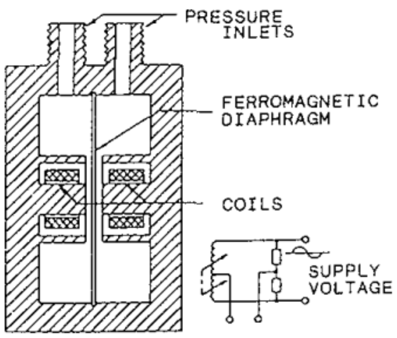


Figure **5.24.** Variable self-inductive pressure transducer in a bridge circuit.

1.7.5.3 Bourdon Tube

This type of instrument uses a length of curved tube to sense the pressure. Traditionally the tube is bent into a C shape and the curve progressively unwinds as pressure is increased inside the tube; the displacement may then be used as required. This instrument has established itself in industry to measure the medium to high pressures, many being the traditional brass bound pointer and dial gauge. For aircraft it is similarly found in the pilot's cabin to indicate engine and hydraulic pressures (Fig. 5.25).

Capsule and Bourdon tube instruments may attain similar performance, although the sensitivity to acceleration must he recognised. The instrumentation industry has developed the principle, sometimes with tubes of other shapes, and although the general use is for the medium to higher pressures, there are exceptions used for lower pressures, even to calibration equipment standards.

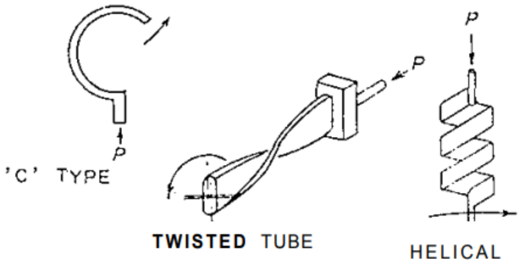


Figure ***5.25.*** Some types of Bourdon tube.

1.7.5.4 Performance and Damping

The most general purpose instruments are based won the diaphragm and may range from a few millibar for the very sensitive, up to 350 bar and much higher in extreme cases, particularly for the piezo-electric types. Basic accuracies usually approach 0.1%, although there is usually a notable degradation with temperature change.

The sensor system usually has a natural frequency of around a few kilohertz up to a few hundred kilohertz for the higher range instruments. Damping is rarely built into the transducer, but it may be achieved by extemal flow/plenum control. Sensitive instruments are often very acceleration/vibration sensitive.

1.7.6 Temperature Measurement

The three main electrical methods of sensing lemperature are metallic resistance, semi-conductor resistance, and the thermocouple, these being in addition to the various optical methods and the many traditional methods such as bimetal strips which bend with temperamire, capsules lilled with fluid and coupled to pressure transducers, and so on. However, the electrical methods are generally the most applicable to aircraft instrumentation.

1.7.6.1 Resistance Bulbs and RTDs

Most metallic materials increase electrical resistance, with temperature and some show a very linear relationship, notably nickel and platinum. In many aircraft systems it is satisfactory to use the cheaper, although less accurate, nickel element. Transducers based upon these elements are often hiown as the resistance temperature detector (RTD). See Figure 5.26. Construclion typically takes the form ol‘ a grid of the nickel or platinum resistance wire sealed inside a protective metal bulb, often termed a “resistance bulb.” These are generally used for the near ambient temperatures such as atmosphere, engine oil, and cooling systems, although some types of RTD will work to above 1000^0C. An alternative construction is to form the resistance element into a film, often similar in construction and application to the strain gauge.

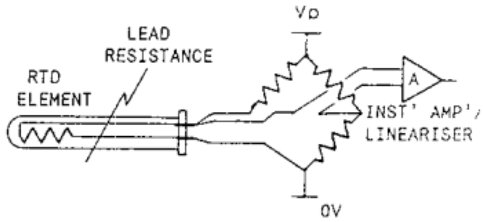


Figure 5.26. **A** typical resistance (RTD) bulb and a 3-wire bridge circuit.

Platinum is used extensively in general instrumentation as well as aircraft systems, both in wire and film form and provides a very good accuracy over the atmospheric temperature ranges and higher. Nickel does not provide the same order of accuracy. The resistance bulb construction gives a slow response, usually many seconds, whereas the film types may respond into the msec region; however, self heating from the polarising currents must be allowed for.

These transducers essentially become the one active arm of a Wheatstone bridge, and because of the relatively large deviations, the nonlinear law must be accounted for, and there are many signal conditioning modules available to cater for this. Additionally, steps must be taken against error due to lead resistance and the associated temperature coefficent; it is usual to connect the transducer with a three-wire, or even four-wire bridge system, or alternatively, a constant current circuit may be employed.

1.7.6.2 Thermistors

These are semi-conductor resistances and may be made to either increase resistance with temperature, or decrease. In both cases the increment of resistance change with temperature is generally greater than for wire, although fundamentally the linearity and accuracy is not so good. In many aircraft, thermistors are used as the sensors for the cabin temperature control, engine sensors, and a wide range of specialised applications. The construction may take many forms, ranging from small beads to larger or specifically designed packages. There are a variety of characteristics available, affecting both time and resistance response, and these methods are finding increasing use.

1.7.6.3 Thermocouples

These may probably be classed as the simplest form of transducer and are generally used for the higher temperature ranges in aircraft systems. Basically, if any two metallic conductors of differing alloy are joined together, a smallvoltage will be generated across the junction with increased temperature, and thus an electrical output is obtained in direct response to the parameter (temperature).

A complete thermocouple consists of both a hot and a cold junction, this is because the generated voltage is the result of the difference in temperature between the hot (the measurement) and the cold (the reference) junctions; however, this is not a serious problem in practice, and there are many signal conditioning and integrated circuits (IC) techniques available (Fig. 5.27).

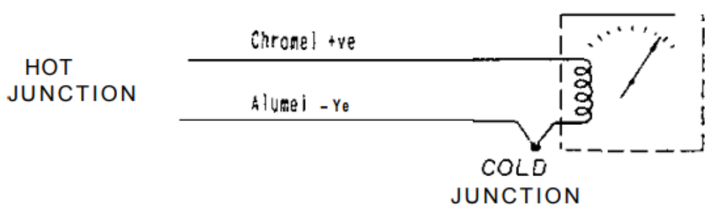


Figure 5.27. The basic thermocouple circuit.

Thermocouple Alloys and Performance

Because of its simplicity and ruggedness, the thermocouple has a wide range of application and is particularly useful for rugged, high-temperature measurement, and specialised research functions. However, the data voltages are small and the accuracy is not good, particularly at the lower temperature. Comprehensive data are published for the various thermocouple alloys, but it is generally not possible to make a measurement to better than 3/4 ^{O}C, often worse.

The main alloys in use are as follows:

- Chrome/Alumel (Type K), approx. 40 microvolts/°C.
- Generally the most accurate and widely used - up to about 1000^{O}C.
- Iron/Constantan (Type J), approx. 46 microvolts/°C. More frequent in industrial applications - up to about 700^{O}C
- Platinuflhodium-Platinum (Types R & S), approx. 9 microvolt/^{0}C. Specifically for higher temperatures - up to about 1700^{O}C.

Additionally, copper/constantan is frequently used for inter-connection, this being less expensive than the thermocouple alloys, but having a similar characteristic. The time response of the common wire thermocouple is normally in the order of many seconds; however, film techniques are possible which vastly increase this response.

Jet Pipe Temperature (ET)

A typical jet-pipe temperature measuring system would consist of an array of thermocouples around the inside of the jet-pipe, all connected in parallel. This provides a good average measurement of gas temperature, plus integrity, in that a number of thermocouples could fail, but still leave others to give the data. This is a valuable feature for such a vital engine measurement and in such a harsh an environment. Typically the signals from the thermocouples are taken to a pilot's meter and also to the top temperature unit; both of these equipments are usually fitted with synthesised cold junctions.

1.7.6.4 Optical Methods

When a body is heated, both heat and light energy is radiated and methods of sensing this as a means of temperature measurement are briefly as follows;

- Total radiation - This is where the heat energy is focussed onto a thermocouple or similar, and thus a data voltage may be produced in response to energy radiation. This is generally more useful for the higher temperatures.
- Photon or continuous optical pyrometery - In these methods the measured radiation is totally from light energy, and thus die detector must be some form of photoelectric device. These methods are increasing in use and may include the various infrared (IR) image forming techniques, all of which may be used with a fair amount of accuracy down to ambient temperatures.

Optical techniques are of particular value where noncontacting measurement is required; however, there are a number of serious error sources, in particular with regard to the radiation qualities (emissivity) of the radiating surface. A perfect black body radiator is said to have an emissivity of 1.0 but in practice emissivities of as low as 0.2 may be encountered, and the concct figure for a particular subject may not always be evident.

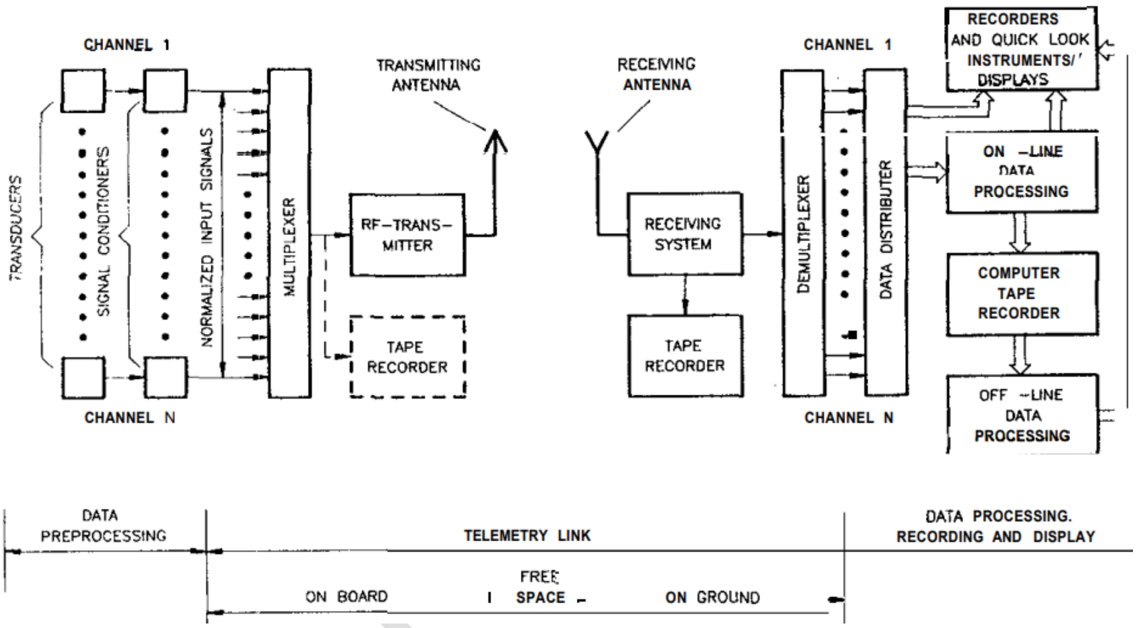
1.8 Onboard and ground based data acquisition system: Radio telemetry

A telemetry measuring system in general makes use of the following components and functional blocks (see Fig. 12.1)

On board the aircraft:

- Transducers for conversion of physical data into electric signals.

- Signal conditioners for matching the transducer output signal to the normalized inputs of the multiplexer.
- A multiplexer for combining the N normalized data signals to a single output signal in a reversible process.
- An onboard magnetic tape recorder for recording the multiplexed data signal (optional).
- A radio frequency transmitter for transmitting the multiplexer output signal by means of a modulated RF carrier.
- A transmitting antenna for radiating the modulated RF carrier.



On the ground:

- A receiving antenna for converting the electromagnetic field at the ground station into an electrical receiver input signal.
- A receiving system for selecting and amplifying the weak wanted inpiit signal out of the background of unwanted signals and noise.
- A tape recorder for storing the multiplexed data signals on magnetic tape.
- A demultiplexer for converting the multiplexer output signal back into the original N data signals.
- A data distributor for providing the subsequent data processing and display units with the required data signals,
- An on-line data processing facility for]processing a selected set of data which are important for a quick analysis of flight test results in order to respond by corrective commands while the test aircraft is still in the air.

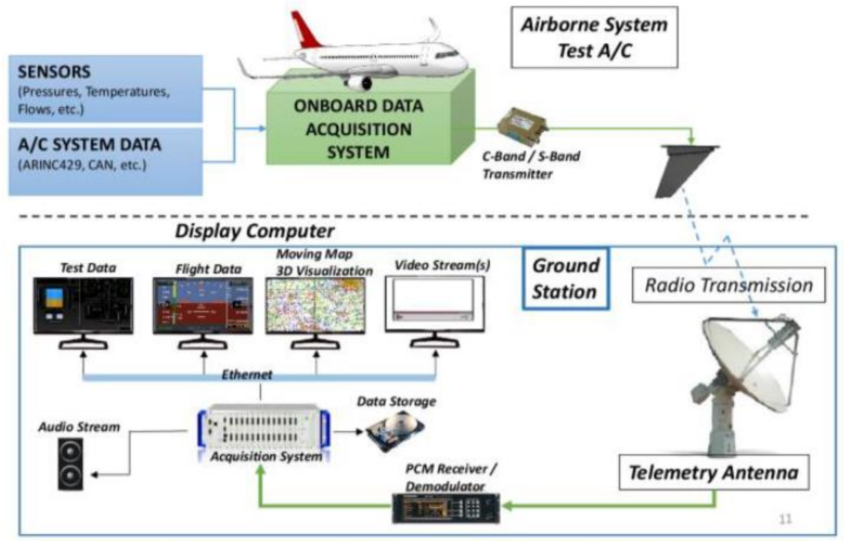
- Recorders and quick-look facilities for on-line display of original data ,and processed data.
- An off-line data processing facility for detailed processing of the test data in order to get the final test results.

In comparison to on-board recording telemetry of flight test data is advantageous in many applications. The main advantages are:

- Less weight and volume of the onboard equipment.
- Less sensitive to extreme.environmenta1 conditions like shock and temperature.
- Better quick-look and on-line data processing capabilities; access of experts on the ground to the on-line test.
- Further improvement of flight-test efficiency possible by use of an additional up-link telemetry system for transmission of relevant ground data to the test aircraft (e.g., precise ground radar position data and commands).

On the other hand there are a few drawbacks which may prevent the use of telemetry or make the use of onboard recording recommendable in some applications:

- The range is limited by the physical characteristics of wave propagation to line of sight conditions.
- The positioning of onboard antennas may be difficult.
- Dropouts of data reception due to fading in the radio frequency channel w:hich can be caused by shadowing of the onboard antenna by the aircraft structure a certain flight attitudes or by multipath wave propagation. A powerful means against these perturbances is available by the use of diversity.



Overview of Telemetry system in Aircraft Testing (Don't draw this in exam)

Previous exam questions:

1. (10AE831 – June/July 2018)

a. Briefly discuss the purpose and scope of flight testing, and types o flight testing. (10M)

b. Explain the sources of errors in flight testing and the techniques for minimizing the errors. (10M)

c. Describe a sensing/transducing technique for measuring: i)Linear acceleration ii)Angular acceleration iii)Vibration iv)Force v)Temperature. (12M)

d. Describe the functioning of on board and ground based data acquisition systems for flight testing. (8M)

2. (10AE831 – June/July 2017)

a. Explain techniques for minimizing errors related to flight testing. (12M)

b. Explain the weighing and ballasting techniques. (8M)

c. Explain on board and ground system radio telemetry functions for data acquisition.(10M)

d. What are temperature sensing devices used in flight testing? (10M)

3. (06AE831 – June/July 2011)

a. What are FAA regulations? (6M)

b. Explain techniques for minimizing errors related to flight testing. (14M)

c. Explain system planning in flight test instrumentation. (10M)

d. What are temperature sensing devices used in flight testing? (10M)

3. (06AE831 – June/July 2010)

a. Explain the weighing and ballasting techniques. (8M)

b. Briefly describe the sources and magnitude of errors in flight test data. (12M)

c. Describe the following instruments:

   a. Instruments for measuring acceleration. (10M)

   b. Measurement of static and total pressure. (10M)