

Aerospace Sensor Systems and Applications

SHMUEL MERHAV



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Introduction and historical background

The purpose of aerospace sensors is to provide all the necessary information on the *variables and parameters* of the flight system for the execution of the mission at hand. A *mission* is generally defined in three dimensional space. Sometimes, on adding the fourth 'dimension', namely, time, a four-dimensional space is defined. In contrast to the three spatial coordinates which can increase or decrease, time always grows. The recent concept of 4-D guidance has special significance in coordinating flight paths such as in air traffic control or in space rendezvous operations, where the notions of 'here-now' or 'there-then' assume paramount importance.

As compared to the first generation aircraft at the turn of the century, which were equipped with a compass, a barometric altimeter, and a relative air speed sensor, a modern military aircraft or airliner is equipped with hundreds of sensors at all levels of the flight system. As such, they have become an integral part of it, not only in regular operation but also in preflight procedures for maintenance and safety. It is paradoxical that by introducing components and subsystems with more sophisticated technologies and a myriad of sensors for monitoring their performance and safety, a situation of diminishing returns may be created. This may be so, because in view of their large numbers, a failure in any of them easily causes a mission abort even if an imminent catastrophe is not necessarily indicated. It is therefore not surprising that along with the ever-increasing demands for accuracy and precision, research and development efforts continue to seek improved technologies for better reliability and maintainability. Currently, one already occasionally encounters the term 'unlimited' for the item MTBF (mean time between failures) in the data sheet of an aerospace sensor.

Modern aerospace sensors are direct descendants of the discoveries of physical laws in theoretical and experimental physics in the seventeenth and eighteenth centuries followed by the avalanche of revolutionary inventions in the nineteenth and early twentieth centuries.

At this point, it is enough to recall only a few of the most salient milestones in order to appreciate the direct link between the late twentieth century technology of aerospace sensors and systems and the discoveries in physics and the inventions that followed. Thus, for example, Torricelli's discovery of atmospheric pressure in 1643 was quickly followed by Pascal's invention of the barometric altimeter in 1647 and consequently by his discovery during 1647–1654 of the properties of our gaseous atmosphere. Newton's discovery of the law of gravitation in 1687, his first law on the conservation of momentum, and his second law, that force equals the rate of change of momentum, laid the foundation for the much later development of the accelerometer at the turn of this century following the invention of the seismometer by Milner in 1883. Other principal examples are the early invention of a steam-powered vertical

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Thus, a simple bubble level in the hands of a mason is an instrument just as a signal analyzer is an instrument in the hands of a researcher in the laboratory. Scale of complexity and sophistication also determine proper use of terminology. For example, a Radar, although just a range measurement device, is referred to as a *system* or *subsystem* in a broader context but not as an instrument or sensor. It is probably appropriate to view a system on the scale of a radar, as an organized system of numerous sensors and devices that in their own right and in a different context of application might be just instruments, such as a radar receiver, power amplifier, or oscillator.

Basic sensor elements

A sensor consists of three principal elements, which constitute its core. These are:

1. the sensitive element,
2. the source of the balancing force, and
3. the output device or display.

The sensitive element is chosen so that it responds to the physical medium to be measured. It translates the response into a measurable or displayable quantity and it generally manifests itself as a force, torque, current or voltage. In the thermometer, this force is the thermal expansion force. The balancing force is provided by capillary tension, and the display is the scaled thin glass tube. In the case of very simple sensors, some of these elements coalesce into one element that performs more than one of the three basic functions above. Thus, in the simple example of the thermometer, the sensitive element is the mercury, the source of the balancing force is the thin capillary tube, and the output device, or display, is the very same tube with its temperature scale marked on it. In general, many elements in addition to the three fundamental ones are required in a measurement device.

Auxiliary functions and elements

Often, the sensitive element does not provide sufficient output for the display, so that appropriate amplification is required. In order to accomplish this, it is often required to attach a *detector* to the sensitive element. The role of the detector is to convert the small response of the sensitive element into an electrically amplifiable signal. Thus, two common additional elements are a *detector* and an *amplifier*. The amplification, however, is not necessarily electrical. Turning once more to the mercury thermometer, the minute expansion of the mercury is made displayable by the very small inner diameter of the glass tube. In order to accomplish the display function, or, in other cases, the *balancing* function, it is required to convert the amplified signal into a force or torque. This function is typically performed by an electromechanical *transducer*. The output of the measurement device may be a *display* designed

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critical factor, because the measurement can almost always tolerate the necessary time lag to reach equilibrium. In modern technology, measurements are often required to determine time varying quantities rapidly. Accordingly, the inertia of sensors must be sufficiently small to prevent the measurement from lagging behind the physical variable. Devices can now be summarized by the following definitions, which provide the meanings of the terminology used in this text.

Definitions of sensor functions

1—The SENSITIVE ELEMENT has the primary role of translating a change in the measured physical variable or environmental parameters into another readily measurable quantity, such as a linear or rotational displacement, a voltage, or a current (deformation of a membrane under pressure, displacement of the proof mass in an accelerometer, change in the output voltage of a bolometer under changes of temperature).

2—The DETECTOR is a sensitive element with the secondary role of translating changes in the response of the primary sensitive element into electrical signals. It is characteristically associated with small changes provided by the primary sensitive element (a capacitive element attached to the proof mass in a force-balanced accelerometer, a piezoelectric element in a load cell, a strain gauge in a wind tunnel balance).

3—The AMPLIFIER is commonly electronic and is required for amplification of voltage or current. Its role is primarily to bring detected faint signals to a sufficient level of power or voltage to drive displays, or to be further conditioned for digitization and coding. If the output of the sensitive element is a mechanical displacement or a fluid flow, amplification is often achieved by mechanical levers or suitable tubing.

4—The TRANSDUCER is a device actuated by power from one system or energy source, supplying power in the same form or any other form to a second system, such as a loudspeaker actuated by electric power and supplying acoustic power, or a quartz crystal that produces electric power from mechanical input, such as pressure. In the specific context of sensors, the transducer primarily has the role of converting electrical power into mechanical power (for example, an electrical motor or, in the role of torquers, or forcers to be applied for angular or linear displacement or to exert force or torque).

5—The PICKOFF is an output device mostly referring to a linear and precise translation of substantially large mechanical linear or rotational displacements into electrical signals or code (potentiometers, synchros, resolvers, magnetic or optical shaft encoders in orientation gyroscopes, stabilized platforms, linear or rotational variable differential transformers (LVDT or RVDT)).

6—The DISPLAY is the output device required in conjunction with the tasks of a human operator in monitoring and control. In technical jargon, the display device is often called the *monitor*. It represents the measured variables or parameters in the most meaningful form in the context of the objective of the control or supervision task. Therefore, displays take on a large variety of formats: analog scales, alphanumeric, monochrome, or color.

In order to provide a measurable signal which represents the deflection y , a pickoff is required. In the simplest realizations the pickoff is a potentiometer; otherwise it is synchro or a variable differential transformer. The pickoff introduces the measurement uncertainty v , including noise. Thus, the output is

$$z = \frac{m}{k}a + y_h + \frac{f}{k} + v \quad (1.9.3)$$

A sketch of this deflection-type accelerometer is shown in Figure 1.19.

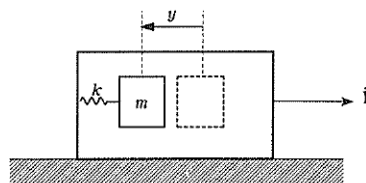


Figure 1.19. Elementary spring-loaded accelerometer.

This simple deflection instrument will be ideally linear if the spring constant k is a precise constant that is independent of the deflection y . Imperfection of k introduces nonlinearity. Imperfect knowledge of m or k causes *scale-factor* uncertainty. It should be noted that since the sensitive element in this example is excited by force, the nature of the restoring element determines what the deflection y represents. In this example, this is k^{-1} , which has the dimension (cm/gram). Thus, the spring scales the force ma into the deflection y which represents the force in cm. The example also demonstrates that even if the sensitive element ideally responds to the input, as is the case for mass and acceleration, it is the transducer or the restoring element that determines precision, linearity, and repeatability. Another critical element is the precision of the pickoff. Some important typical tradeoffs can be brought to light with the aid of the deflection accelerometer described. These will be presented in detail in Section 1.10 with the dynamics of the sensor.

Basic tradeoffs

At this point, however, some important tradeoff factors can be identified by inspection of (1.9.3). In order to reduce the friction error f/k for a given level of friction, k , the spring stiffness should be increased. But doing so would reduce the sensitivity m/k to the input a . Such a reduction decreases the deflection y . This, in turn, would result in poorer precision of the pickoff because its uncertainties would be larger in comparison with the maximum deflection $y_{\max}$. Therefore, to preserve a desired sensitivity, m must be increased, that is, the weight of the sensor will be higher, if the required precision is higher. Conversely, a small weight implies small y so that a low-friction f is required in a high-grade pickoff.

The role of the restoring force

To reiterate; It is the *restoring force* that decides the nature of the measurement. Consider the device shown in Figure 1.20. Here, the mass m is placed in a casing c that is filled with a fluid having a viscous friction coefficient D . The device is rigidly placed in a vehicle that accelerates by $\dot{V}$. The relative velocity between the casing and the mass is v . The total acceleration with respect to inertial space is $\dot{V}-\dot{v}$, and the equation relating the forces involved is

$$m(\dot{V} - \dot{v}) = Dv \quad (1.9.4)$$

where Dv is the viscous resistance restoring force of the fluid. As long as the vehicle accelerates, that is, $\dot{V} \neq 0$, m keeps moving relative to the casing. It is easily seen that in the steady state, $\dot{v} \rightarrow 0$, and (1.9.4) reduces to

$$v = \frac{m}{D} \dot{V} \quad (1.9.5)$$

The distance y that the mass has traveled in the casing is the displayed quantity given by

$$y = \int_0^t v d\tau = \frac{m}{D} \int_0^t \dot{V} d\tau = \frac{m}{D} V \quad (1.9.6)$$

which is proportional to the velocity V . Thus, with a viscous restoring force which is proportional to velocity, we have, in essence, devised a *velocimeter*.

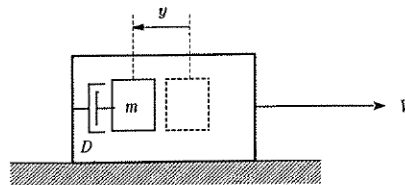


Figure 1.20. Velocimeter based on viscous balancing force

In the preceding examples the sensitive element, namely, the mass m , responded to acceleration, producing a force that had to be balanced by force. It is this *balancing by force, or torque*, that is common to all deflection instruments. However, the sensitive element can be excited by other physical variables or parameters, such as temperature, pressure or magnetic or electrostatic fields. If they manifest themselves as forces or torques, they have the effect of additive errors.

A typical example is the conventional angle-of-attack sensor; a sketch of this instrument is shown in Figure 1.21. A unit of four small winglet-shaped

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2. the source of the balancing force, and
3. the output device or display.

The sensitive element is chosen so that it responds to the physical medium to be measured. It translates the response into a measurable or displayable quantity and it generally manifests itself as a force, torque, current or voltage. In the thermometer, this force is the thermal expansion force. The balancing force is provided by capillary tension, and the display is the scaled thin glass tube. In the case of very simple sensors, some of these elements coalesce into one element that performs more than one of the three basic functions above. Thus, in the simple example of the thermometer, the sensitive element is the mercury, the source of the balancing force is the thin capillary tube, and the output device, or display, is the very same tube with its temperature scale marked on it. In general, many elements in addition to the three fundamental ones are required in a measurement device.

Auxiliary functions and elements

Often, the sensitive element does not provide sufficient output for the display, so that appropriate amplification is required. In order to accomplish this, it is often required to attach a *detector* to the sensitive element. The role of the detector is to convert the small response of the sensitive element into an electrically amplifiable signal. Thus, two common additional elements are a *detector* and an *amplifier*. The amplification, however, is not necessarily electrical. Turning once more to the mercury thermometer, the minute expansion of the mercury is made displayable by the very small inner diameter of the glass tube. In order to accomplish the display function, or, in other cases, the *balancing* function, it is required to convert the amplified signal into a force or torque. This function is typically performed by an electromechanical *transducer*. The output of the measurement device may be a *display* designed

8 AEROSPACE SENSOR SYSTEMS AND APPLICATIONS

critical factor, because the measurement can almost always tolerate the necessary time lag to reach equilibrium. In modern technology, measurements are often required to determine time varying quantities rapidly. Accordingly, the inertia of sensors must be sufficiently small to prevent the measurement from lagging behind the physical variable. Devices can now be summarized by the following definitions, which provide the meanings of the terminology used in this text.

Definitions of sensor functions

1—The SENSITIVE ELEMENT has the primary role of translating a change in the measured physical variable or environmental parameters into another readily measurable quantity, such as a linear or rotational displacement, a voltage, or a current (deformation of a membrane under pressure, displacement of the proof mass in an accelerometer, change in the output voltage of a bolometer under changes of temperature).

2—The DETECTOR is a sensitive element with the secondary role of translating changes in the response of the primary sensitive element into electrical signals. It is characteristically associated with small changes provided by the primary sensitive element (a capacitive element attached to the proof mass in a force-balanced accelerometer, a piezoelectric element in a load cell, a strain gauge in a wind tunnel balance).

3—The AMPLIFIER is commonly electronic and is required for amplification of voltage or current. Its role is primarily to bring detected faint signals to a sufficient level of power or voltage to drive displays, or to be further conditioned for digitization and coding. If the output of the sensitive element is a mechanical displacement or a fluid flow, amplification is often achieved by mechanical levers or suitable tubing.

4—The TRANSDUCER is a device actuated by power from one system or energy source, supplying power in the same form or any other form to a second system, such as a loudspeaker actuated by electric power and supplying acoustic power, or a quartz crystal that produces electric power from mechanical input, such as pressure. In the specific context of sensors, the transducer primarily has the role of converting electrical power into mechanical power (for example, an electrical motor or, in the role of torquers, or forcers to be applied for angular or linear displacement or to exert force or torque).

5—The PICKOFF is an output device mostly referring to a linear and precise translation of substantially large mechanical linear or rotational displacements into electrical signals or code (potentiometers, synchros, resolvers, magnetic or optical shaft encoders in orientation gyroscopes, stabilized platforms, linear or rotational variable differential transformers (LVDT or RVDT)).

6—The DISPLAY is the output device required in conjunction with the tasks of a human operator in monitoring and control. In technical jargon, the display device is often called the *monitor*. It represents the measured variables or parameters in the most meaningful form in the context of the objective of the control or supervision task. Therefore, displays take on a large variety of formats: analog scales, alphanumeric, monochrome, or color.

In order to provide a measurable signal which represents the deflection y , a pickoff is required. In the simplest realizations the pickoff is a potentiometer; otherwise it is synchro or a variable differential transformer. The pickoff introduces the measurement uncertainty v , including noise. Thus, the output is

$$z = \frac{m}{k}a + y_h + \frac{f}{k} + v \quad (1.9.3)$$

A sketch of this deflection-type accelerometer is shown in Figure 1.19.

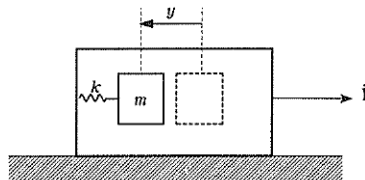


Figure 1.19. Elementary spring-loaded accelerometer.

This simple deflection instrument will be ideally linear if the spring constant k is a precise constant that is independent of the deflection y . Imperfection of k introduces nonlinearity. Imperfect knowledge of m or k causes *scale-factor* uncertainty. It should be noted that since the sensitive element in this example is excited by force, the nature of the restoring element determines what the deflection y represents. In this example, this is k^{-1} , which has the dimension (cm/gram). Thus, the spring scales the force ma into the deflection y which represents the force in cm. The example also demonstrates that even if the sensitive element ideally responds to the input, as is the case for mass and acceleration, it is the transducer or the restoring element that determines precision, linearity, and repeatability. Another critical element is the precision of the pickoff. Some important typical tradeoffs can be brought to light with the aid of the deflection accelerometer described. These will be presented in detail in Section 1.10 with the dynamics of the sensor.

Basic tradeoffs

At this point, however, some important tradeoff factors can be identified by inspection of (1.9.3). In order to reduce the friction error f/k for a given level of friction, k , the spring stiffness should be increased. But doing so would reduce the sensitivity m/k to the input a . Such a reduction decreases the deflection y . This, in turn, would result in poorer precision of the pickoff because its uncertainties would be larger in comparison with the maximum deflection $y_{\max}$. Therefore, to preserve a desired sensitivity, m must be increased, that is, the weight of the sensor will be higher, if the required precision is higher. Conversely, a small weight implies small y so that a low-friction f is required in a high-grade pickoff.

The role of the restoring force

To reiterate; It is the *restoring force* that decides the nature of the measurement. Consider the device shown in Figure 1.20. Here, the mass m is placed in a casing c that is filled with a fluid having a viscous friction coefficient D . The device is rigidly placed in a vehicle that accelerates by $\dot{V}$. The relative velocity between the casing and the mass is v . The total acceleration with respect to inertial space is $\dot{V} - \dot{v}$, and the equation relating the forces involved is

$$m(\dot{V} - \dot{v}) = Dv \quad (1.9.4)$$

where Dv is the viscous resistance restoring force of the fluid. As long as the vehicle accelerates, that is, $\dot{V} \neq 0$, m keeps moving relative to the casing. It is easily seen that in the steady state, $\dot{v} \rightarrow 0$, and (1.9.4) reduces to

$$v = \frac{m}{D} \dot{V} \quad (1.9.5)$$

The distance y that the mass has traveled in the casing is the displayed quantity given by

$$y = \int_0^t v d\tau = \frac{m}{D} \int_0^t \dot{V} d\tau = \frac{m}{D} V \quad (1.9.6)$$

which is proportional to the velocity V . Thus, with a viscous restoring force which is proportional to velocity, we have, in essence, devised a *velocimeter*.

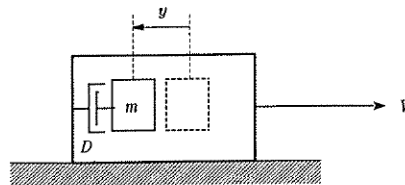


Figure 1.20. Velocimeter based on viscous balancing force

In the preceding examples the sensitive element, namely, the mass m , responded to acceleration, producing a force that had to be balanced by force. It is this *balancing by force, or torque*, that is common to all deflection instruments. However, the sensitive element can be excited by other physical variables or parameters, such as temperature, pressure or magnetic or electrostatic fields. If they manifest themselves as forces or torques, they have the effect of additive errors.

A typical example is the conventional angle-of-attack sensor; a sketch of this instrument is shown in Figure 1.21. A unit of four small winglet-shaped