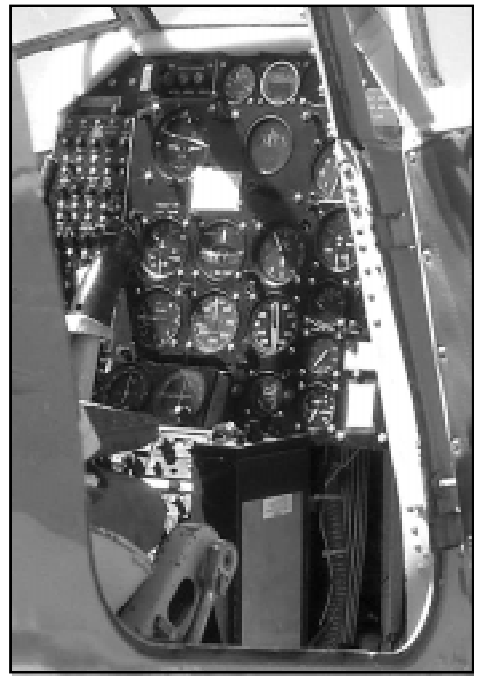
PRECISION PRESSURE TRANSDUCERS FOR AIR DATA MEASUREMENTS

AN–104

Larry Bashaw and Peter Nussbaum



This technical note briefly describes the fundamentals of utilizing pressure measurements for aircraft air data instrumentation, and the factors to be considered when selecting a pressure transducer for these applications.

Modern air data instruments and modules provide primary or backup capability to measure a number of critical parameters for aircraft flight and navigation. These include altitude, airspeed, Mach number, rate of vertical change, ground speed, and air density, the latter important for determining take-off loads. The two fundamental pressure measurements required to provide these parameters are static (barometric) air pressure, and the air pressure induced by the movement of the aircraft through the air, called *pitot pressure*. These measurements are coupled with temperature readings and correction factors in air data computers, which use algorithms of varying complexity and look-up tables to compute the parameters of interest.

Computing power is generally not an issue for air data instruments. Inexpensive but powerful silicon microprocessors and memory chips are readily available and provide key building blocks for high performance designs. Rather, the challenge to the air data designer in the signal processing area may be to achieve systems rugged enough to survive the spectrum of radiated and conducted electromagnetic emissions encountered in service. For instance, a lightning strike to an aircraft's electrical system can induce a spike of many hundreds of kilovolts, which the air data instrument must survive.

The largest challenge in the overall air data instrument design, however, may be the selection of an accurate and reliable pressure transducer. The transducer must be capable of providing stable, highly-accurate measurements, with high resolution, for long periods of time, with a primary part of the device deliberately exposed to an outside environment manifesting large temperature extremes, humidity variations, ice, various aircraft fluids, dirt, and other factors not conducive to high precision operation. The pressure transducer must operate accurately and reliably in these conditions, and yet be reasonably priced to allow the product to be competitive in the marketplace; the transducer is invariably the most expensive single component in the instrument and so is a major factor in determining manufacturing cost. Identifying a pressure transducer which offers the necessary combination of accuracy and reliability at an attractive price is a key task for the designer. Honeywell's Precision Pressure Transducer (PPT) provides a powerful solution for air data applications, offering a high-value combination of accuracy, stability/reliability and digital output at a very competitive price.

Using Pressure Measurements for Air Data Parameters

Altitude

It is commonly known that atmospheric pressure, the force per unit area of the air in the Earth's atmosphere, decreases monotonically with distance above the surface. The relationship of height above (or below) sea level to air pressure is determined by the equation:

$$d(\log_e p) = -(gW_M/RT)\,dZ \quad (1)$$

in which p is free-stream static pressure, g is the acceleration due to gravity, W_M is the molecular weight of air, R is the universal gas constant, T is absolute temperature, and Z is the geometric height above sea level. Tables of US Standard Atmosphere, published in *The Handbook of Physics and Chemistry* and in *U.S. Standard Atmosphere, 1976 (2),* provide full tabulations of pressure versus altitude which the air data designer can load into the memory of the instrument. These take into consideration the variation of the acceleration due to gravity, and tabulate "geopotential altitude", H. This can differ significantly from the geometric altitude. For example, at 16km, the difference between the geometric and geopotential altitude is 40m. An excerpt from an altitude/pressure table is shown in Table 1.

Since barometric pressure varies locally as a function of weather conditions, several altitude measurements are defined from the static pressure reading. *Pressure altitude* is the altitude referenced to a standard sea level pressure of 29.92 inHg. *Pressure altitude baro-corrected*, also called *baro altitude*, is referenced to the local barometric pressure.

Conceptually simple, the conversion of static air pressure to altitude entails some real-world challenges. As the aircraft moves through the air, errors relative to a still-air measurement are induced by the port and the "plumbing" in the aircraft fuselage associated with the accessing the pressure transducer to the ambient atmosphere. *Static Source Error Correction* (SSEC) refers to the factors supplied for each variant of an aircraft by the manufacturer to correct for these plumbing-related errors.

Temperature must also be measured to accurately convert a static pressure reading to an altitude. This is performed by a total temperature probe, the measurement from which also must be corrected for effects caused by the movement of the aircraft.

Airspeed

As with altitude, measuring air speed with a pressure transducer is conceptually straightforward. Bernoulli's formula for total pressure in a compressible flow gives us a relationship between airspeed and "impact pressure" for subsonic speeds,

$$q_c = p\ \{(1 + ((\gamma - 1)/2\gamma)(\rho/p)V^2)\ \exp\ (\gamma/\gamma\text{-}1) - 1\}$$

and for supersonic speeds

$$q_c = ((1+\gamma)/2)\ \ (V/a\ )^2\ p\left[\frac{(\gamma + 1)^2}{4\gamma - 2(\gamma - 1)(a/v)^{2}}\right] \exp\ (1/\gamma\text{-}1) - p$$

In these equations, q_c is the impact pressure p_t - p, measured by the transducer plumbed to the forward-pointing pitot tube, V the true airspeed, γ the ratio of specific heat of air at a constant pressure to specific heat at a constant volume, ρ the mass density of ambient air, and "a" the speed of sound in ambient air.

Altitude		Acceleration due to gravity	Pressure scale height	Number density	Particle speed	Collision frequency	Mean free path	Molecular weight	Temperature	Pressure	Density	Sound speed	Dynamic viscosity	Kinematic viscosity	Thermal conductivity
Z(m)	H(m)	g(m/s²)	H_p(m)	n(m⁻³)	V(m/s	ν(s⁻¹)	L(m)	M(kg/kmol)	T(K)	P(mb)	ρ(kg/m³)	C(m/s)	μ (N·s/m²)	η (m³/s)	(J/m·s·K)
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
4500	4497	9.7928	7589.7	1.6156(+25)	435.05	4.1602(+9)	1.0457(-7)	28.964	258.921	5.7752(+2)	7.7704(-1)	322.57	1.6448(-5)	2.1167(-5)	2.3028(-5)
5000	4996	9.7912	7495.7	1.5312(+25)	432.31	3.9180(+9)	1.1034(-7)	28.964	255.676	5.4048(+2)	7.3643(-1)	320.55	1.6282(-5)	2.2110(-5)	2.2765(-5)
5500	5495	9.7897	7401.8	1.4502(+25)	429.56	3.6871(+9)	1.1650(-7)	28.964	252.431	5.0539(+2)	6.9747(-1)	318.50	1.6116(-5)	2.3107(-5)	2.2500(-5)
6000	5994	9.7882	7307.8	1.3725(+25)	426.79	3.4671(+9)	1.2310(-7)	28.964	249.187	4.7217(+2)	6.6011(-1)	316.45	1.5949(-5)	2.4161(-5)	2.2236(-5)
6500	6493	9.7866	7213.8	1.2980(+25)	424.00	3.2577(+9)	1.3016(-7)	28.964	245.943	4.4075(+2)	6.6431(-1)	314.39	1.5781(-5)	2.5278(-5)	2.1970(-5)
7000	6992	9.7851	7119.8	1.2267(+25)	421.20	3.0584(+9)	1.3772(-7)	28.964	242.700	4.1105(+2)	5.9002(-1)	312.31	1.5612(-5)	2.6461(-5)	2.1703(-5)
7500	7491	9.7836	7025.8	1.1585(+25)	418.37	2.8689(+9)	1.4583(-7)	28.964	239.457	3.8299(+2)	5.5719(-1)	310.21	1.5442(-5)	2.7714(-5)	2.1436(-5)
8000	7990	9.7820	6931.7	1.0932(+25)	415.53	2.6888(+9)	1.5454(-7)	28.964	236.215	3.5651(+2)	5.2579(-1)	308.11	1.5271(-5)	2.9044(-5)	2.1168(-5)
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Table 1—Excerpt of altitude versus pressure table from "U.S. Standard Atmosphere."

Impact Pressure q_c In Inches of Mercury for Values of Calibrated Airspeed V_c in Miles Per Hour

Calibrated Airspeed, Vc, mph	0	1	2	3	4	5	6	7	8	9
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
100	.363029	.370347	.377736	.385239	.392785	.400406	.408111	.415888	.423736	.451639
110	.439637	.447433	.455874	.464097	.472391	.480772	.489213	.497731	.506328	.515008
120	.525742	.532566	.541464	.550443	.559480	.568606	.577797	.587070	.596414	.605837
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

Table 2—Excerpt of airspeed versus impact pressure, form NASA Technical Note D-822.

NASA's Technical Note D-822 provides extensive tabulations of impact pressure in inches of mercury and pounds per square foot for values of airspeed in miles per hour and knots. A short excerpt from these tables is shown in Table 2.

Pressure measurements for airspeed are analogous to altitude in that several types of measurement are possible, and error sources must be considered. For example, airspeed indicators are calibrated for standard sea-level conditions, and the measured air speed is the true airspeed. Pressure and density vary under other conditions, and a correction factor to yield true air speed from the "calibrated" air speed must be utilized:

$$V = V_c \, (f/ f_o) \sqrt{\rho_o/\rho}$$

In this equation, V is true airspeed, V_c is calibrated air speed, f and f_o are compressibility factors at the actual reading point and sea-level, respectively, and ρ and ρ_o are mass density of air at the actual reading point and sea-level.

Pressure Transducer Selection for Air Data Instruments

Selecting a pressure transducer which is suitable for modern air data instruments requires that the designer consider the parametric specifications for the measurements, transducer interface to the system, and the suitability of the transducer for the environmental conditions of the aircraft.

Accuracy

Air data instruments are used in the full range of aircraft types; commercial and military, large commercial transports to small general aviation, experimentals, helicopters, UAVs, and other vehicles. There are also *primary* and *secondary* air data systems. Tabulating the accuracy specifications for all of these possibilities is beyond the scope of this note, but a brief discussion of some of the requirements is useful.

The SAE defines a minimum performance standard for primary air data computer accuracy (3), as measured at room temperature. At 50,000 ft, the allowable tolerance is +/-125 ft, which converts to 0.010 psi (0.020 inHg). For a 17 psi full scale transducer, this is 0.059% of full scale. At 5,000 ft, the allowable tolerance is +/- 25 ft; equivalent accuracy is 0.012 psi (0.024"Hg), or 0.068% of 17 psi.

Note that the SAE standard specifies the total error allowed in the altitude measurement. This error budget must be divided between the basic transducer accuracy, residual uncorrected SSEC, and signal processing errors, and consider the change with time, or drift, of these parameters (see below, "Long Term Stability"). The ideal air data pressure transducer should therefore achieve higher accuracies than those stated above on the assumption that the rest of the system is not error-free.

An emerging standard for air data instruments is called "Reduced Vertical Separation Measurement" (RVSM). This will allow higher density of aircraft on well-traveled air routes, for example, over the North Atlantic between the U.S. and Europe. RVSM requirements call for tighter tolerance bands. For example, at 50,000 ft, the RVSM tolerance is +/- 50 ft, requiring higher transducer accuracies.

Selection of a pressure transducer which supports the minimum accuracy standards is, of course, a prerequisite for air data instrument design. It is possible to pay several thousand dollars for a highly-accurate transducer, however, and achieving the necessary accuracy at a reasonable cost allows a competitive instrument price.

Measurement Resolution, Linearity

Sufficient resolution to support the absolute accuracy of the pressure measurement is a basic requirement for the transducer. For a transducer offering 0.05% accuracy, resolution of a factor of ten smaller, 0.005% or better, is the typical "rule of thumb."

A minimum resolution is also necessary for vertical speed calculations. SAE AS8002 (3) specifies a 0.003 inHg threshold for transducers measuring vertical speeds. This is .0087% of 17 psi full scale transducer.

Another important consideration for making vertical speed measurements with digital output is the "localized linearity" of the transducer. Linearity specifications typically deal

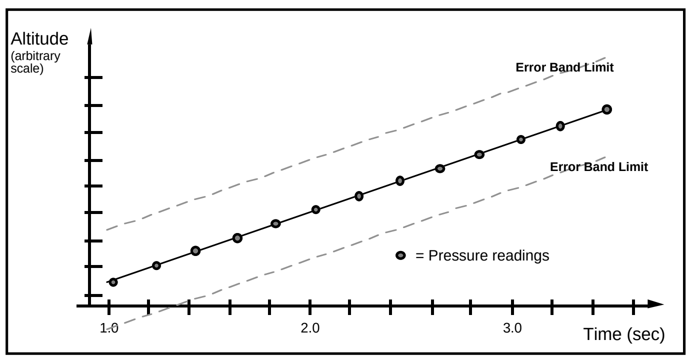


Figure 1a—Ideal linear pressure characteristic for vertical speed measurements.

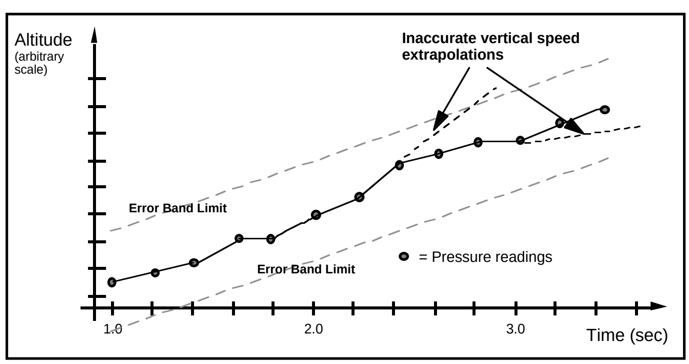


Figure 1b—Local nonlinearities cause vertical speed computation errors even with resolution and absolute accuracy within specification.

with the entire span of the transducer, from lowest pressure to highest pressure. Vertical speed measurements require that short duration changes in altitude produce consistent pressure reading deltas, since these readings are continuously averaged and extrapolated to a rate of ascent or descent. While a transducer may have a satisfactory overall linearity and be operating well within its error band, digitization errors may cause local nonlinearities which result in incorrect extrapolations of vertical speed. This concept is shown in Figures 1a and 1b. In the Honeywell PPT, the digitization algorithm has been specifically tailored to insure that the local linearity is sufficient to support vertical speed accuracy requirements.

Long Term Stability

Stability refers to the change in the accuracy with time. Typically, long term stability is defined in percent of full scale drift per year. A low rate of drift can be of equal importance to small "time zero" errors. While it is extremely unlikely that an unstable transducer could cause a failure, since most critical aircraft systems are redundant and repeatedly cross-checked, unstable transducers can result in excessive maintenance costs, unacceptable periods "on the ground", and increased pilot workload.

When selecting a pressure transducer, it is necessary to assess the effect of the specified accuracy drift per year on the overall system performance. It is also desirable to know the environmental conditions under which that drift was evaluated.

Electrical Interface

As noted earlier, the availability of high performance, low cost microprocessors and memory gives the instrument designer the building blocks for a digital air data computer. However, the transducer world still deals largely with analog output signals, and analog-to-digital conversion is required. A transducer such as the Honeywell PPT with a direct digital output offers several advantages:

- Accuracy is not lost converting analog to digital signals. A/D converters have temperature, voltage and other environmental sensitivities which can degrade signals. Conversion errors of +/- 0.02% or more are possible, even with careful design.
- A digital output in standard ASCII decimal format simplifies the programming interface to the signal processing electronics.
- Some digital output transducers, such as the PPT, allow selection of the pressure units for the digital output, e.g., inches of Hg, psi, millibar, etc. This reduces downstream processing for converting the measurement.

Environmental Compatibility

Designing an air data instrument to function reliably for many years is a primary challenge for systems designers. The Federal Aviation Administration and several professional bodies have issued standards and guidelines which should be referenced to understand the design guidelines, tests and conditions necessary to demonstrate a satisfactory design. (See "References") Air data instrument design test results are submitted to the FAA and approved via a "Technical Standard Order" (TSO), which then enables the manufacturer to sell the product to aircraft makers.

The Radio Technical Commission for Aeronautics (RTCA) provides two documents related to the design and verification of airborne equipment. Document RTCA 628-95/SC180-047, "Design Assurance Guidance for Airborne Electronic Hardware," describes design guidelines. Document RTCA/DO-160C, "Environment Conditions and Test Procedures for Airborne Equipment," defines the test procedures and conditions necessary to demonstrate suitability for the airborne environment. The list of conditions which must be evaluated, each covered by a section of DO-160C, is extensive:

Temperature and Altitude
Magnetic Effect
Temperature Variation
Power Input
Humidity
Voltage Spike
Shock
Audio Frequency Conducted Susceptibility
Vibration
Induced Signal Susceptibility
Explosion Proofness
Radio Frequency Susceptibility
Water proofness
Emission of Radio Frequence Energy
Fluid Susceptibility
Lightning Induced Transient Susceptibility
Sand and Dust
Lightning Direct Effects
Fungus Resistance
Icing
Salt Spray

Conclusion

The following points summarize some of the key messages presented in this note:

- Deriving important aircraft navigation and flight parameters from pressure measurements is conceptually straightforward. As with many design challenges, the "devil is in the details." Careful attention must be paid to errors caused by the effects of the aircraft moving through the atmosphere, its physical configuration, and the change of key physical parameters with altitude and temperature such as air density, air compressibility, and gravity.
- The availability of powerful, low cost microprocessors and memory has eased the task of designing the signal processing necessary for high performance air data computers.

Figure 2—Honeywell Precision Pressure Transducer. Available in absolute, gauge and differential models with pressure ranges suitable for altitude, airspeed and other air data measurements.

- Even with the sophisticated digital signal processing provided by the microprocessors, the performance of air data instruments is still strongly dictated by the pressure transducer characteristics; basic accuracy, resolution, long term stability, and reliability in the spectrum of environmental conditions encountered in aircraft operation.

- Digital output pressure transducers, all else being equal, provide higher performance and easier integration into air data instruments.

- The overriding challenge to today's air data designer is to design a high performance, reliable, appropriately–featured instrument which can be profitably sold at an a price attractive to the marketplace. Again, the focus is on the pressure transducer as the major contributor to the cost of the instrument. The transducer must offer high value—the right combination of high performance and attractive price. Honeywell's Precision Pressure Transducer (Figure 2) is flying today in air data instruments from major manufacturers. It offers the cost-effective solution that avionics engineers seek for air data requirements.

REFERENCES

(1) All equations are taken from NASA Technical Note D-822, "Tables of Airspeed, Altitude and Mach Number Based on Latest International Values for Atmospheric Properties and Physical Constraints", Aug. 1961, NASA, Washington. Available from NTIS, US Dept. of Commerce.

(2) "US Standard Atmosphere, 1976", NOAA/NASA, NOAA-S/T 76-1562, Washington, D.C., 1976.

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Customer Service Representative
(612) 954-2888 fax: (612) 954-2582
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