MECHANICS OF AIRSPEED

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INTRODUCTION

The basic principles of airspeed measurement, as well as the more common practical problems, are reviewed. The construction of an airspeed indicator calibrator is described. Although it is difficult to find very much beyond rudimentary definitions that has been written on the subject of airspeed, this paper should by no means be considered a rigorous, last minute treatment of the subject. It is, however, quite comprehensive, even though it is intended to serve a fairly wide non-technical audience.

My intention in writing this paper was to provide a worthwhile resource on the mechanics of airspeed measurement, as well as to offer a more or less do-it-yourself project in which the reader can actually apply the principles learned in a meaningful way.

BASIC RELATIONSHIPS

The total energy (TE) of an object is the sum of the kinetic energy (KE) and the potential energy (PE) or:

$$TE = PE + KE$$

The total energy of an airstream is no different and is equivalent to the total pressure of the airstream (H). This total pressure is equal to the sum of the kinetic and potential energies of the airstream. The absolute or static pressure of the undisturbed air (p) is equivalent to the potential energy of the airstream. The dynamic pressure of the airflow (q) is equivalent to the kinetic energy of the airstream. We can now write an equivalent expression for the total pressure of the airstream in terms of the dynamic and static pressures:

$$H = p + q$$

The static pressure is found simply by measuring the absolute pressure of the airstream. This is analogous to measuring the pressure altitude. The kinetic in reality is found by subtracting the static pressure from the total pressure; more on this later. The kinetic energy can be related by Bernoulli's familiar equation for incompressible flow:

$$\text{Kinetic Energy} = \frac{\text{Mass x (Velocity)}^2}{2}$$

or: $$KE = \tfrac{1}{2}mV^2$$

The kinetic energy of one cubic foot of air is:

$$KE = \tfrac{1}{2}\rho V^2$$

where ρ, the Greek letter rho, is the symbol for the unit density of air (or, for example, the mass of one cubic foot of air) and V is the relative velocity of the air or the true speed through the air mass, more commonly called the True Airspeed or TAS.

The kinetic energy of the airstream is one of the most important terms in aerodynamics and is called "dynamic pressure" with the shorthand notation "q". We can now rewrite Bernoulli's equation for incompressible flow as follows:

$$q = \tfrac{1}{2}\rho V^2$$

or:

$$q = \tfrac{1}{2}\rho(\mathrm{TAS})^2$$

It is this kinetic energy of the air (relative to the airplane) that the pilot is interested in gauging in order to know his speed through the air mass. The remainder of this paper discusses the problems associated with this "gauging".

Pitot-Static Systems

If a symmetrical object is aligned with the airflow, the airflow will stagnate or drop to zero velocity at the nose and tail stagnation points. Since the total energy will remain constant (in incompressible flow), the airstream dynamic pressure will be converted to a static pressure, or what looks like and can be measured like static pressure, at the stagnation point as shown in Fig. 1. If we put a hole at the stagnation point and attach a gauge, we can measure the total pressure, H. This pressure is called the ram of pitot pressure. If we also provide a hole parallel to the airstream so that it is unaffected by the dynamic pressure, and attach a gauge, we can measure the ambient or static pressure of the airstream, p. However, we want to measure airspeed which is a function of dynamic pressure. Therefore, we must find the difference between the stagnation pressure (pitot pressure) and the ambient pressure (static pressure) or:

$$q = H - p$$

Figure 2 illustrates three common variations of the basic pitot-static system used to measure airspeed. The gauge (airspeed indicator) measures the difference between the total and static pressures. This difference, of course, is graduated in some unit of speed; mph, knots, etc. This is why airspeed indicators are called differential pressure instruments.

Equivalent Airspeed

Airspeed indicators are graduated so as to read true airspeed in standard sea level conditions. However, because airplanes rarely fly in standard day sea level conditions, the airspeed indicator will rarely indicate the true speed through the air. Neglecting, for the moment, pitot system error, static system error, instrument error, and compressibility error, the pilot will read an equivalent airspeed on the dial.

The equivalent airspeed (EAS) is the same as that flight speed or true airspeed in the standard sea level air mass which would produce the same dynamic pressure and, hence, the same indicator reading as that at the actual flight level. The true airspeed (TAS) results when the equivalent airspeed is corrected for variations in air density between flight level and standard sea level conditions. Since the airspeed indicator is calibrated for the dynamic pressures corresponding to true airspeeds in standard sea level conditions, any non-standard variation in air density must be corrected for.

In order to relate EAS to TAS, we must know the air density for both the standard sea level conditions (ρ_o) and the air density at flight level (ρ). If, for example, we have a TAS at flight level conditions that produces a dynamic pressure that is equal to a sea level dynamic pressure produced by an equivalent sea level true airspeed, and we know the respective air densities, we can mathematically relate TAS to EAS:

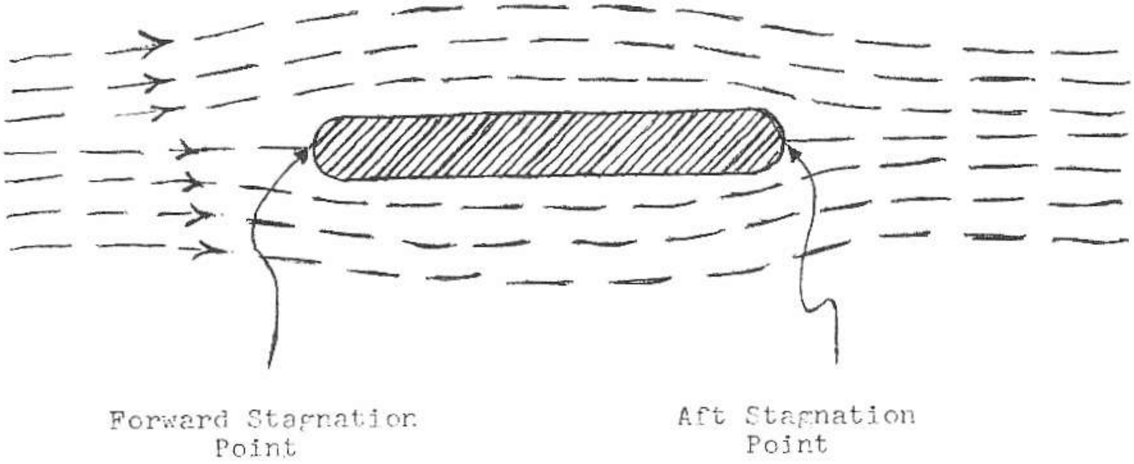
$q = \tfrac{1}{2}\rho(\mathrm{TAS})^2$ (Dynamic pressure and true airspeed at flight level)

$q = \tfrac{1}{2}\rho_o(\mathrm{EAS})^2$ (Same dynamic pressure produced by an equivalent sea level true airspeed)

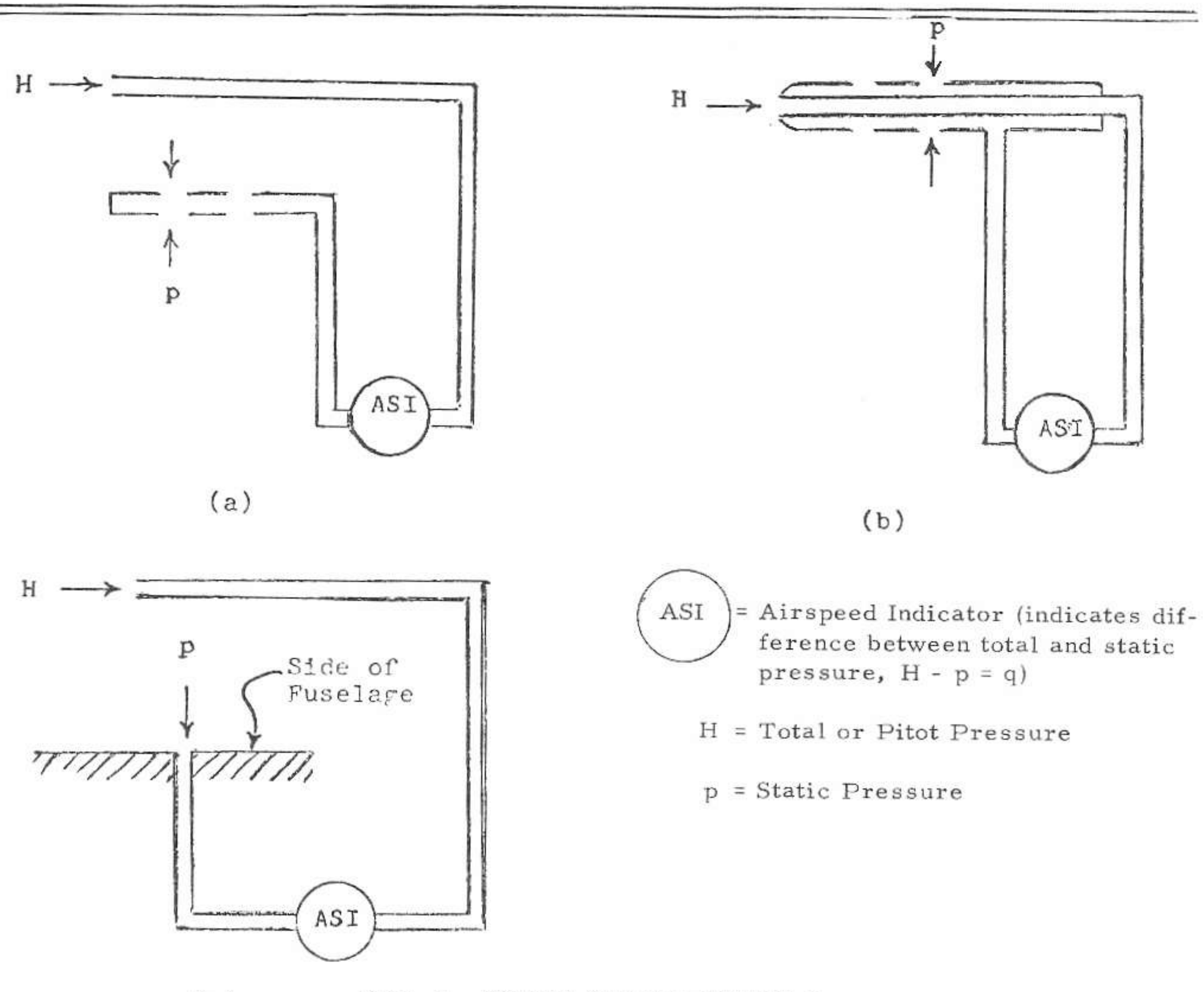
Since the dynamic pressures are equal, we can now equate EAS and TAS:

$$\tfrac{1}{2}\rho(\mathrm{TAS})^2 = \tfrac{1}{2}\rho_o(\mathrm{EAS})^2$$

FIG. 1. STAGNATION POINT



(Stagnation pressure is airstream total pressures, $H = p + q$)



(a)

(b)

ASI = Airspeed Indicator (indicates difference between total and static pressure, $H - p = q$)

H = Total or Pitot Pressure

p = Static Pressure

(c) FIG. 2. PITOT-STATIC SYSTEMS

From this equation, we can solve for the TAS in terms of: the EAS (from our airspeed indicator), the standard sea level air density, ρ_o (a standard value), and the flight level air density, ρ (which we compute using the flight level pressure altitude and temperature). In other words:

$$\text{TAS} = \frac{\text{EAS}}{\sqrt{\frac{\rho}{\rho_o}}}$$

or:

$$\text{TAS} = \sqrt{\frac{\rho_o}{\rho}}\ \text{EAS}$$

By substituting this new value for TAS in the expression for dynamic pressure, we get the following equation for flight level conditions:

$$q = \tfrac{1}{2}\rho\left(\sqrt{\frac{\rho_o}{\rho}}\ \text{EAS}\right)^2$$

or:

$$q = \tfrac{1}{2}\rho_o(\text{EAS})^2$$

AIRSPEED CALIBRATION

In order to calibrate a particular pitot-static system so that the correct dynamic pressure can be known, special equipment and careful flight test procedures are required. However, given the proper correction data pitot and static pressure sensing errors and an unchanged aircraft and pitot-static configuration, the only error in determining the correct dynamic pressure for a particular flight speed will be that error contributed by the airspeed indicator itself. This error can be considerable, but only a couple of miles per hour error can be, if not dangerous, at least disconcerting.

In order to calibrate the airspeed indicator, we need a simple but accurate differential pressure gauge. A manometer, similar to that used by many doctors to measure blood pressure, can serve nicely. Because water is much less dense than the mercury used in the doctor's manometer, it is much more practical for measuring the relatively low pressures found in the pitot tube. Below are the conversion factors needed to convert the basic equation for dynamic pressure ($q = \frac{1}{2}\rho V^2$) so that we can equate the height of the water in the manometer column to the equivalent sea level airspeed read on the airspeed indicator (reference: International Civil Aviation Organization (ICAO) standard atmosphere data as of Nov. 7, 1952 and The International System of Units, Physical Constants and Conversion Factors, NASA SP-7012):

ρ_o = 0.0012250 grams per cubic meter

1 mm water pressure (60° F) = 9.79685 newtons per square meter

1 mile per hour = 0.44704 meters per second

1 knot = 0.5144444 meters per second

Using these conversion factors, we can now equate the dynamic pressure, in terms of mm of water pressure, to the equivalent sea level true airspeed (neglecting, for the moment, the compressibility effect). This gives us:

$$q = 0.0124943 \times (\text{EAS})^2$$

where q is measured in mm of water pressure and EAS is in mph;

or: $$q = 0.0165461 \times (\text{EAS})^2$$

where q is still measured in mm of water pressure but EAS is in knots.

The early airspeed indicators were graduated according to the formula for incompressible flow:

$$V = \sqrt{\frac{2q}{\rho_o}}$$

which, of course, comes from our earlier equation for dynamic pressure at sea level ($q = \frac{1}{2}\rho_o V^2$). This is perfectly adequate for slow speeds and low altitudes. However, most modern airspeed indicators are graduated in accordance with a formula which includes a correction factor, f_o, which corrects the airspeed reading for compressibility error in sea level conditions.

The effective pressure actuating the indicator is called the "impact pressure" and is given the symbol, q_c, to distinguish it from the dynamic pressure, q, for incompressible flow. To compensate for the increase in pitot pressure due to compressibility in sea level conditions, we graduate the indicator in the following manner:

$$V = f_o \times \sqrt{\frac{2q_c}{\rho_o}}$$

where: V = calibrated airspeed, CAS, at sea level (dial reading)

ρ_o = sea level air density

q_c = effective impact pressure which includes the compressibility effect. q_c is always larger than q.

f_o = the "f factor" which corrects for the magnified dynamic pressure due to compressibility effect at the stagnation point in sea level conditions

The "f factor" comes from Bernoulli's equation for compressible flow. (The mechanics of compressible flow are beyond the scope of this paper, but are covered more completely in any good textbook on aerodynamics.) The f factor can be approximated reasonably well up to approximately Mach 2.0, or twice the speed of sound, with the following expression (reference: Aerodynamics of Supersonic Flight):

$$f = \frac{1}{\sqrt{1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \ldots}}$$

where M is the airspeed in terms of Mach number

$$(M = \frac{\text{TAS}}{\text{speed of sound}})$$

The speed of sound at sea level is approximately 761 mph (647 knots); therefore, we can see that at 76 mph M = 0.1, at 152 mph M = 0.2, etc.

At sea level, our calculated pitot pressure (q) will be too low, particularly at the higher speeds. It must be increased by $\left(\frac{1}{f_o}\right)^2$

where f_o is the sea level correction that is included in the airspeed dial graduation. This adjustment for the dynamic pressure is commonly called the Mach factor (MF) which is approximated with the following expression:

$$MF = (1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \ldots)$$

The corrected dynamic pressure (this is the pressure actually found in the pitot tube, neglecting sensing errors) is sometimes referred to as the "compressible q". Notice that:

$$q_c = MF \times q$$

Figure 3 contains the corrected pressures that should be used when checking indicators whose dials have been adjusted for sea level compressibility error. This calibration data is to be used with the manometer described in the next section.

The first column of Fig. 3a and 3b contains the equivalent airspeed corresponding to the indicator dial readings. The low speeds are offered in case the reader is interested in wind speed measurement. The second column contains the corresponding corrected dynamic pressure (q_c) in mm of water pressure. It is this pressure that should be used to set up the simulated pitot pressure, in order to compare the resulting indicator reading with the corresponding EAS in column one. The difference will be the indicator error.

Figure 4 is a sample calibration chart for a particular airspeed indicator in a form that can be conveniently used to supplement data in the aircraft owner's manual.

If the airspeed indicator is not corrected for compressibility effect in sea level conditions, it will read high, even at sea level. Figures 5a and 5b illustrate the error that would result with an uncorrected indicator. The first column is the speed that would be read if the

(mph)	mm water
2	0.05
4	0.2
6	0.45
8	0.8
10	1.25
12	1.8
14	2.45
16	3.2
18	4.05
20	5
22	6.05
24	7.2
26	8.45
28	9.8
30	11.25
35	15.31
40	20
45	25.32
50	31.27
55	37.84
60	45.05
65	52.88
70	61.35
75	70.45
80	80.18
85	90.55
90	101.56
95	113.2
100	125.48
110	151.97
120	181.04
130	212.7
140	246.97
150	283.86
160	323.4
170	365.61
180	410.51
190	458.12
200	508.46
210	561.57
220	617.46
230	676.18
240	737.74
250	802.19
260	869.55
270	939.86
280	1013.15
290	1089.47
300	1168.85

3a

(Graduated in <u>mph</u>)

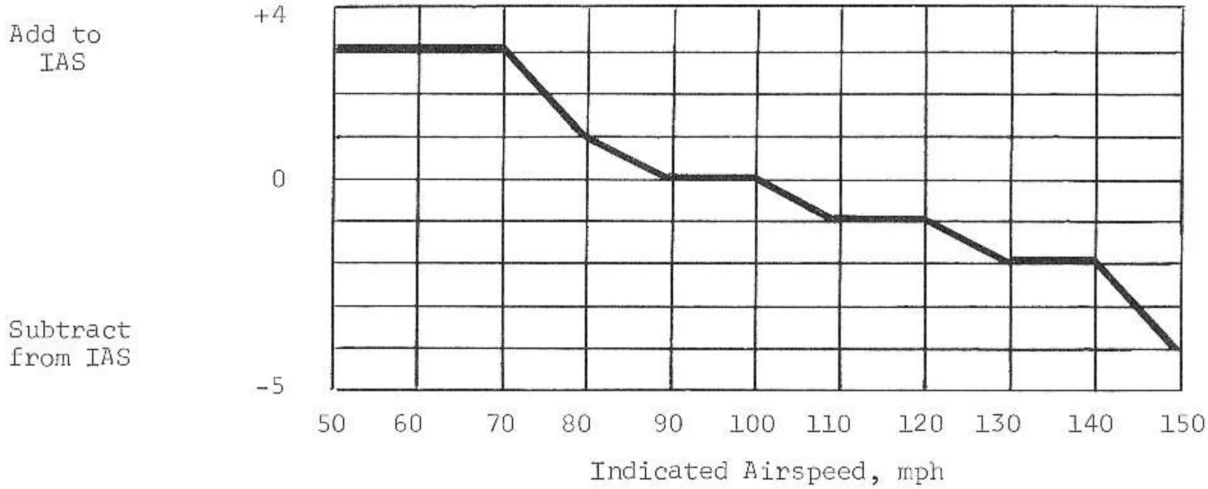
(knots)	mm water
2	0.07
4	0.26
6	0.6
8	1.06
10	1.65
12	2.38
14	3.24
16	4.24
18	5.36
20	6.62
22	8.01
24	9.53
26	11.19
28	12.98
30	14.9
35	20.28
40	26.5
45	33.55
50	41.43
55	50.14
60	59.69
65	70.08
70	81.31
75	93.38
80	106.3
85	120.06
90	134.67
95	150.14
100	166.45
110	201.66
120	240.32
130	282.46
140	328.12
150	377.32
160	430.1
170	486.49
180	546.55
190	610.3
200	677.81
210	749.1
220	824.25
230	903.29
240	986.29
250	1073.31
260	1164.4
270	1259.64
280	1359.09
290	1462.82
300	1570.91

3b

(Graduated in <u>knots</u>)

FIGURE 3

CALIBRATION CHART FOR AIRSPEED INDICATORS
GRADUATED IN EITHER MPH OR KNOTS
MEASURED AGAINST MILLIMETERS OF WATER PRESSURE



(IAS ± Correction = BAS)

FIGURE 4

SUGGESTED AIRCRAFT AIRSPEED INDICATOR CALIBRATION CHART FOR CONVERTING INDICATED AIRSPEED (IAS) TO BASIC AIRSPEED (BAS)

indicator was uncorrected for sea level compressibility effect. The third column is the actual equivalent sea level true airspeed. The middle column is the "f factor" or the compressibility correction factor in sea level conditions or f_o. The "f factor" (in this case, f_o) is multiplied times the uncorrected reading (first column) to give the actual equivalent reading (third column) just as the pilot multiplies the CAS times the "f" correction to get EAS. For example, uncorrected, the indicator would read 240 mph for a particular dynamic pressure; when the dial is corrected for sea level compressibility effect, the same dynamic pressure will produce a dial reading of only 237 mph.

Note that the "f" correction found on the pilot's flight computer (see Fig. 9) is diminished from the equation for the "f" mentioned earlier, by the f_o term that is already incorporated in the airspeed dial graduation. Note also from Fig. 5 that the dial correction is less than 1% for indicated airspeeds less than approximately 200 mph.

Each airspeed indicator has its own set of peculiar characteristics which cause it to differ from any other airspeed indicator. These differences may be caused by slightly different hairspring tensions, flexibility of the diaphragm accuracy of the indicator's dial markings, or even the effect of temperature on the different metals in the indicator mechanism. Change in temperature can cause an instrument error due to the variance in the coefficient of expansion of the different metals comprising the working mechanism. This error can be removed by the installation of a bimetallic compensator within the mechanical linkage. This bimetallic compensator is installed and set at the factory, thereby eliminating the temperature error within the instrument.

The airspeed observed on the dial, or the indicated airspeed (IAS) which has been corrected for instrument error, is called the basic airspeed or BAS (reference: Air Force Manual 51-40, Air Navigation). Although this term does not exist in the FAA lexicon, the author feels that it is necessary in order to reconcile the following

CAS	×	f_o	=	EAS
50		0.9995		49.973
60		0.9992		59.953
70		0.9989		69.926
80		0.9986		79.889
90		0.9983		89.842
100		0.9978		99.784
110		0.9974		109.713
120		0.9969		119.627
130		0.9964		129.527
140		0.9958		139.409
150		0.9952		149.274
160		0.9945		159.119
170		0.9938		168.944
180		0.993		178.747
190		0.9923		188.527
200		0.9914		198.283
210		0.9905		208.014
220		0.9896		217.718
230		0.9887		227.394
240		0.9877		237.042
250		0.9866		246.659
260		0.9856		256.244
270		0.9844		265.798
280		0.9833		275.317
290		0.9821		284.802
300		0.9808		294.251

5a

(For Dials Graduated in mph)

CAS	×	f_o	=	EAS
50		0.9993		49.962
60		0.9989		59.935
70		0.9985		69.897
80		0.9981		79.847
90		0.9976		89.782
100		0.997		99.702
110		0.9964		109.603
120		0.9957		119.485
130		0.995		129.346
140		0.9942		139.183
150		0.9933		148.996
160		0.9924		158.783
170		0.9914		168.541
180		0.9904		178.27
190		0.9893		187.967
200		0.9882		197.631
210		0.987		207.26
220		0.9857		216.852
230		0.9844		226.406
240		0.983		235.921
250		0.9816		245.395
260		0.9801		254.825
270		0.9786		264.211
280		0.977		273.551
290		0.9753		282.844
300		0.9736		292.088

5b

(For Dials Graduated in knots)

FIGURE 5

AIRSPEED DIAL CORRECTION FOR COMPRESSIBILITY
EFFECT IN SEA LEVEL CONDITIONS

fairly common discrepancy: The aircraft owner or operator's manual will usually contain airspeed correction data to convert: "IAS to CAS". This correction is normally determined in flight tests using carefully calibrated equipment (and, therefore, does not contain individual instrument error correction) as this correction is intended to apply to an entire model or series of aircraft. This "IAS to CAS" correction, then, assumes that all the airspeed indicators will have no error. The Air Force introduces what it calls basic airspeed which is the indicator reading corrected for instrument error only. Basic airspeed is the correct equivalent airspeed (neglecting compressibility) based on the difference between the actual pitot and static pressure, even though these pressures themselves might be in error. It is these pressure sensing errors that are determined in the manufacturer's calibration flight tests.

Manometer Construction and Operation

The apparatus described in this paper is not intended as a substitute for any certified calibration equipment, and any calibration data obtained for a particular aircraft should be considered strictly unofficial. However, any significant instrument error uncovered by the procedures described here should be cause to have the aircraft instrument checked at an FAA certified instrument calibration facility by a person suitably qualified and certified.

The manometer type airspeed calibration device whose construction is described here can be used either in the vertical position as a conventional "U-tube" type, measuring pressure differential up to 1,000 mm of water pressure (approximately 280 mph) or it can be inclined so that pressures up to 100 mm of water pressure (approximately 90 mph) can be more precisely measured. This expanded scale for low-range speed is useful for the low range of all airspeed indicators, but in particular those found in helicopters, sailplanes, and other slow flying aircraft. Because of its low range sensitivity and accuracy, the inclined manometer makes an excellent device for measuring wind speeds. Both a pitot tube and a static pressure probe (similar to those shown in Fig. 2a) will be necessary. A simple experiment is suggested where the wind gradient near the surface is determined. This gradient, or shear, can be an important and often troublesome factor as an aircraft descends through it for a landing.

The manometer shown in both Fig. 6 and Fig. 8 was made from inexpensive material found locally. Simple tools and a little imagination will also come in handy. The heart of the manometer consists of two glass tubes (which probably can be found in the local school chemistry lab) and a "meter stick" (which any good stationery supply store should have in stock). One other necessary item, at least for the inclined manometer, is a good spirit level. All the parts should be readily identified from the accompanying pictures. Although care and accuracy are musts, there is no reason why a less elaborate instrument than shown wouldn't be perfectly adequate.

Vertical Manometer

To construct the manometer shown in Fig. 6, mount a "U" made out of clear tubing which has provision for reading the difference between the two legs with the meter stick or a meter scale that has 1 mm increments. Fill the "U" half full of water, in which you have added a small amount of food coloring (to improve visibility), and a very small amount of photographer's "Photo-flo" or clear liquid detergent (to act as a wetting agent). A simple stand should be provided so that the manometer can be easily read, as well as held in the correct vertical position.

Connect one side of the "U" to the aircraft's pitot tube through a tee fitting. At the tee, connect a short length of flexible tubing. This will be used as the "blow tube". Be sure that all connections are air tight and that any drain holes are sealed up. (Don't forget to unseal them when you have finished.) Blow gently into the blow tube and trap some pressure in the line by squeezing off the line (a clamp or clothes pin will come in handy). This pressure should be as high as possible, without exceeding the manometer scale or "pegging" the airspeed indicator. By holding this pressure for a couple of minutes, you can get a check on the integrity of the pitot system plumbing. If there is any drop in this pressure, you will know that there is a

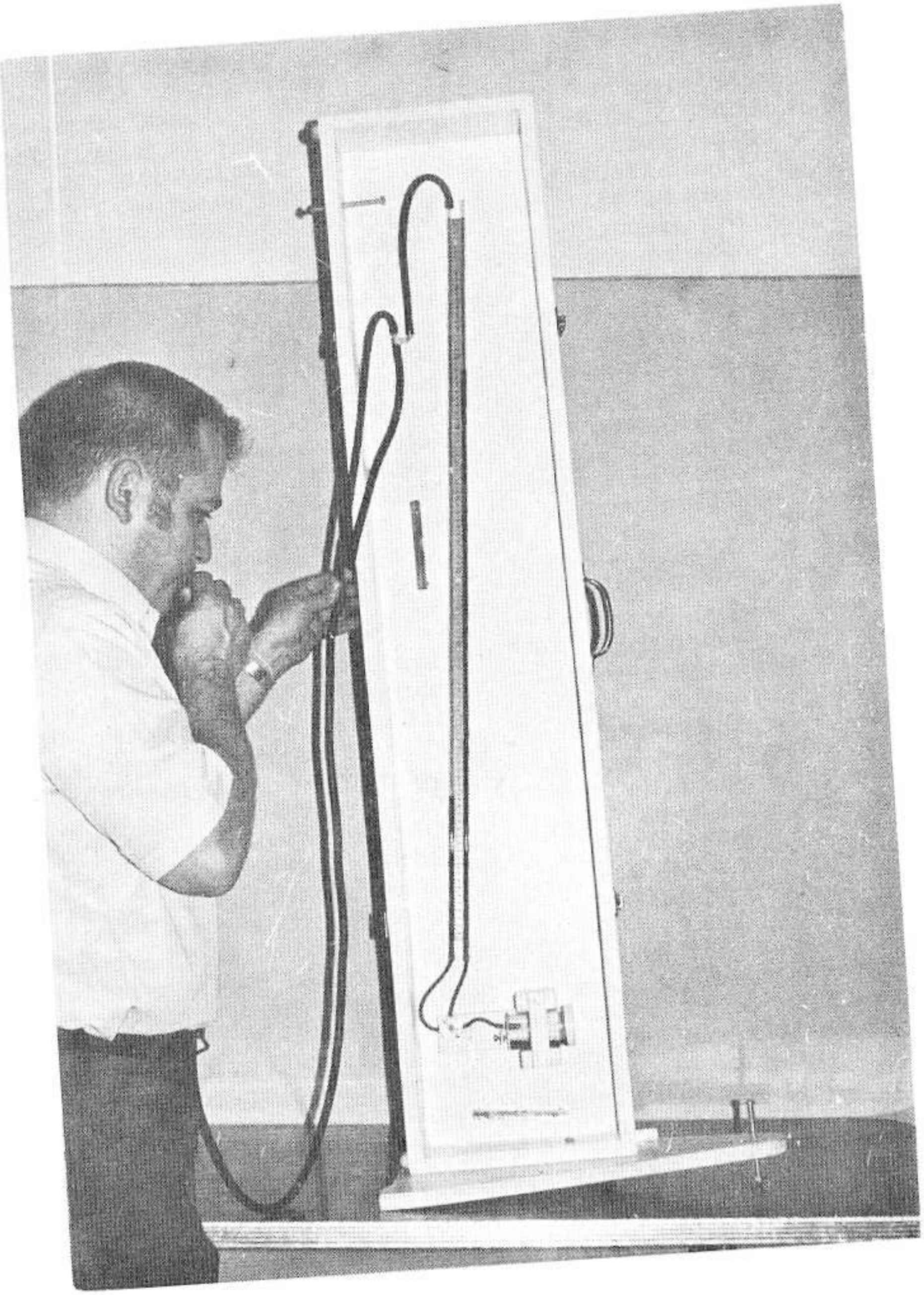


FIG. 6. VERTICAL MANOMETER AIRSPEED CALIBRATOR

leak somewhere that should be fixed before you continue the calibration procedure. Caution: Even a light wind can cause errors in the manometer reading, so it is suggested that the calibration be done inside, or at least when no wind is blowing.

Inclined Manometer

From Fig. 3, we can see that the dynamic pressure for airspeeds below 90 mph will be less than 100 mm of water pressure, or just one tenth of the total scale of the vertical manometer. For better measuring accuracy for the important speeds below 90 mph, we can expand the scale by inclining the manometer tube so that the maximum vertical differential is now 100 mm instead of 1,000 mm of water. (Note: The reader will probably have access to different materials and skills than the author, so the following should be used only as a guide.)

The use of a well to replace the second leg of the manometer allows for much simpler operation, but introduces error caused by the variation in the height of the well which must be accounted for either in the design of the manometer or by a correction applied to each reading. The former is obviously the more desired. If, for example, the area of the well is 1,000 times the area of the manometer tube, then the well will rise one thousandth of the length of the tube drop. For a 1,000 mm (full scale) change in the column length (from the top end to the bottom end), the well will rise 1.0 mm. The pressure read on the bottom end of the meter scale (with a 1.0 to 10 slope) will be 1.0 mm too high because of the rise of 1 mm in the well. The pressure will really be 101 mm of water instead of 100 mm. To compensate for this error, we reduce the manometer tube elevation from 100 mm to 99 mm. This allows us to use the scale reading directly; of course, the full scale 1 meter becomes 0.1 meter (see Fig. 7 for a further illustration).

In a second example, if the area of the well is 100 times that of the tube, then the well will rise 10 mm when the water is at the bottom end of the scale. To compensate for this error, we have to reduce the manometer tube elevation from 100 mm to 90 mm. Again, this correction allows us to read the millimeter scale directly, without any intermediate corrections. This latter example (well area 100 times the tube area) represents the apparatus shown in Fig. 8, where the key materials used were a length of relatively common 7-mm glass tubing which has an inside diameter of 0.200 inches and a plastic pill bottle which has an inside diameter of 2.00 inches. An optional 3-way valve (obtained at a medical supply store) is shown in Fig. 8 that allows the apparatus to be used in either the vertical or inclined position by a simple change of the valve position.

Correction for Variation in Temperature

Temperature here, of course, refers to the temperature of the manometer and the liquid within it. Temperature affects the density of the water in the manometer, the length of the scale used for measuring the column height, as well as the overall volume of the manometer. So many of these factors will vary, depending on the materials used in construction, that it would be virtually impossible to account for all of them here. The reader is referred to the Manual of Barometry for an idea of the complexity of the effect of temperature on the manometer reading. It is sufficient to say that small deviations from the 60° F reference temperature (the temperature at which the density of water is calculated; see fourth page of this article) will have little effect on our calibration.

Correction for Variation in Gravity

The gravity at the location of the manometer is a factor governing the weight of the column of water in the manometer which counterbalances, and is used to measure, the simulated pitot pressure. Since gravity is affected by latitude and altitude as well as other local anomalies and, therefore, generally varies from place to place, the direct readings of the manometer will not be comparable if it is not corrected for gravity.

In order to provide a uniform comparable gravity basis for pressure data, various international organizations have agreed to adopt a standard acceleration of gravity denoted by g_o and given the value of 980.665 cm/sec^2. The local acceleration of gravity is denoted by g_ℓ. In order to correct for variations in gravity, sometimes called "reduction to standard

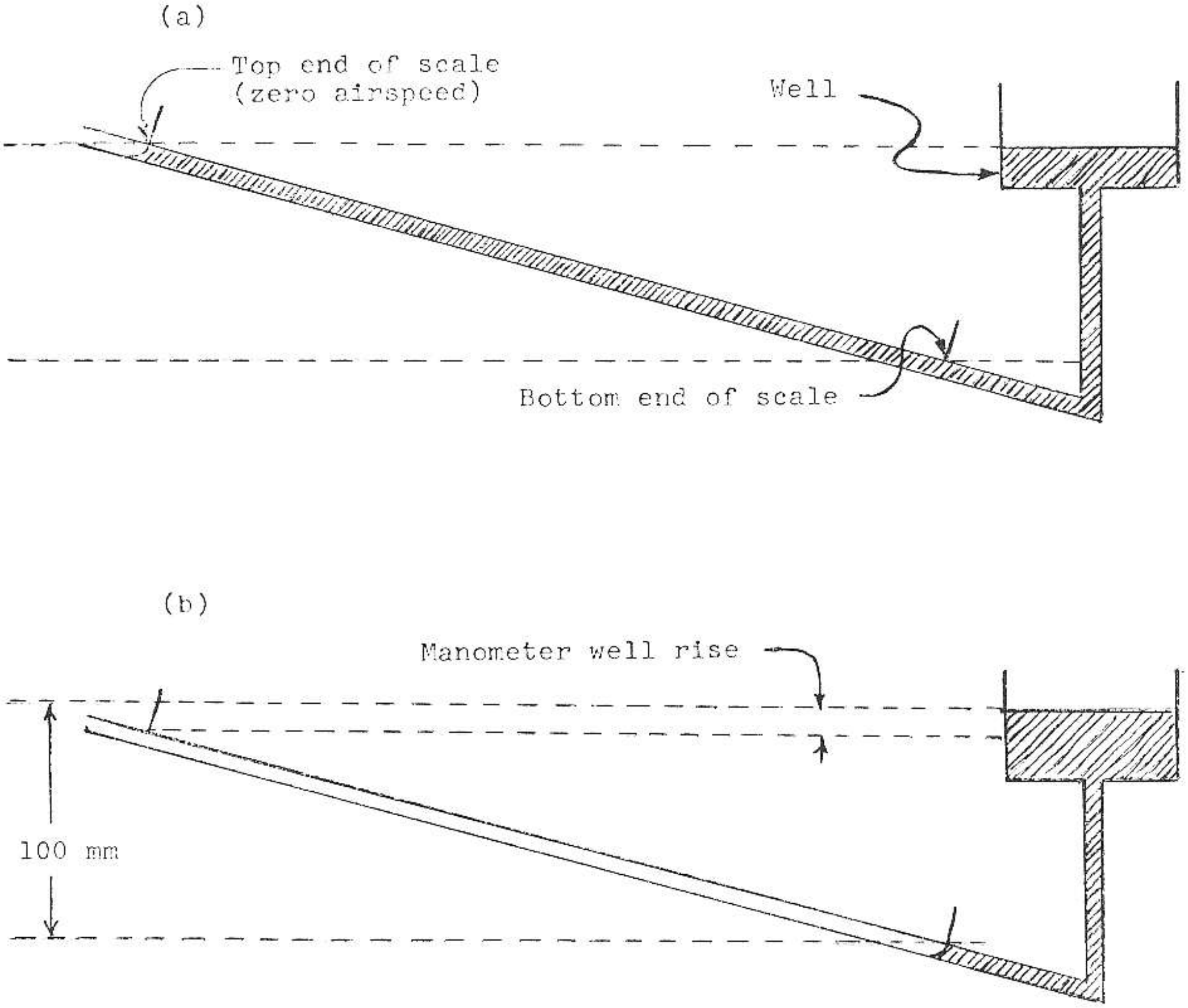


FIG. 7. CORRECTION OF MANOMETER DESIGN FOR VARIATION IN WELL FLIGHT

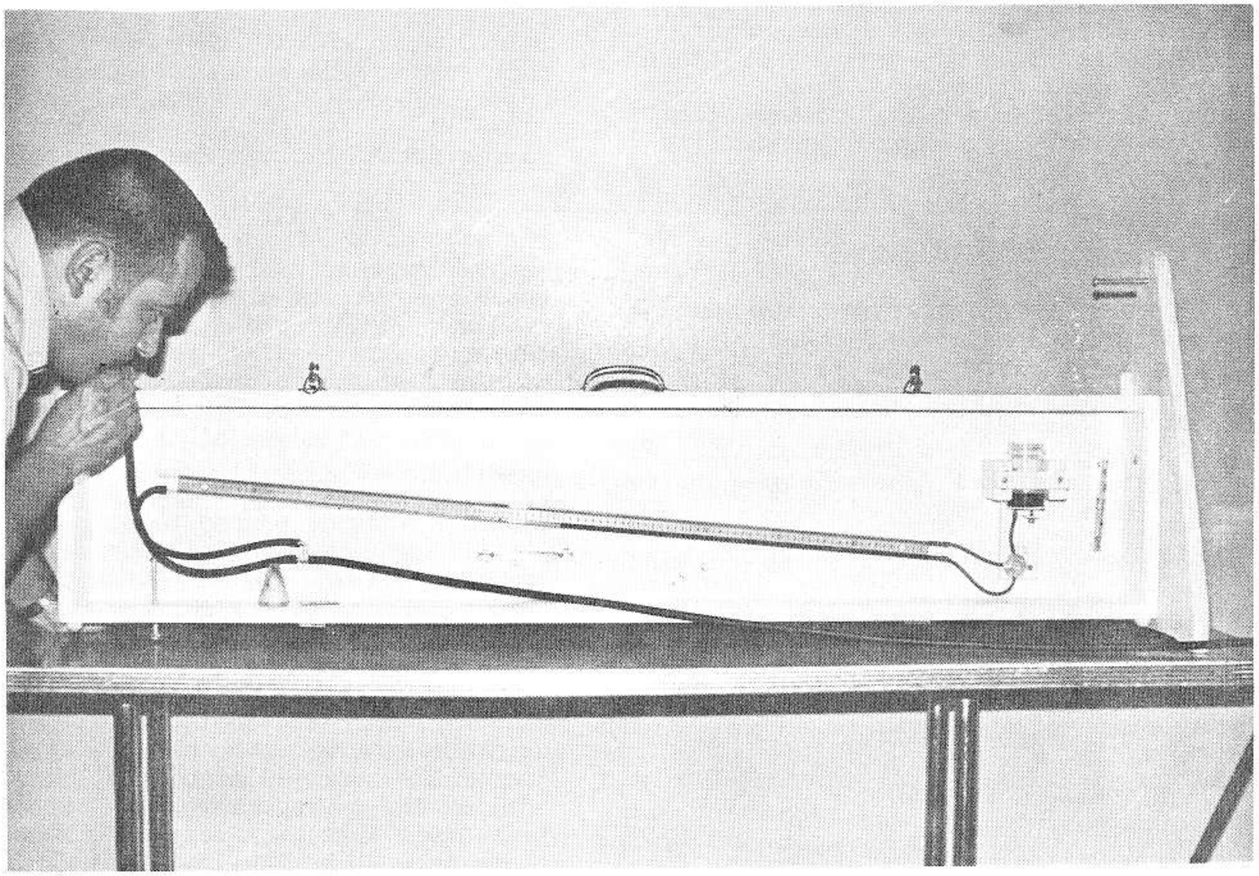


FIG. 8. INCLINED MANOMETER AIRSPEED CALIBRATOR

gravity", the following expression is used:

$$\text{Corrected Value} = \left(1 + \frac{g_\ell - g_o}{g_o}\right) \times \text{Manometer Reading}$$

However, unless the local gravity is known (from such sources as the local weather station) or you happen to have a gravimeter handy, the uncorrected manometer reading will probably be very satisfactory since the gravity variation will not normally exceed 0.1 or 0.2 percent. The reader should, however, realize how so many factors can interact to complicate life.

AIRSPEED ERRORS

In actual installations, the reading observed on the airspeed indicator (IAS) will normally differ from the equivalent airspeed (EAS) for any one or more of the following reasons:

(1) Mechanical errors in the instrument.

(2) The static system does not sense the true static pressure.

(3) The pitot system does not sense the true pitot pressure.

(4) Leaks or restrictions in the pitot-static system plumbing will cause errors.

(5) At high speed, the compressibility effect will magnify the air density at the pitot tube.

(6) Turbulent air will cause erroneous readings.

(7) If the aircraft is climbing or descending or accelerating (changing speed), there will be lag errors in the pitot-static system as well as the indicator.

Static pressure error and, to a lesser degree, pitot pressure error are generally the most serious and are collectively called "position error". This is caused by the pitot and static sensors being poorly located or positioned to sense the correct pressures. The best locations for these sensors are usually determined for each aircraft design during the manufacturer's flight tests.

From the equation for total pressure, we can see that the dynamic pressure, q, is the difference between the total pressure and the static pressure ($q = H - p$). We can see that, if the static pressure is too low, the dynamic pressure will be too large and, hence, the airspeed reading will be too high. Depending on the aircraft, if the static port in the indicator vents into the cabin, the airspeed will read slightly high because of the lower pressure inside most unpressurized light plane cockpits.

When the static ports are located on the side of the fuselage, they should be located symmetrically on both sides; otherwise, as the plane slips or skids sideways through the air, the pilot will get erroneous readings because of the high or low static pressure feeding the airspeed indicator. In this situation, lateral misalignment of the pitot tube with the airstream will also cause error. We can see the problem arising if a pilot, for some reason, wanted to slip the airplane to a landing. Unfortunately, most airspeed systems are very inaccurate in this flight configuration and, as a result, this maneuver can be a very precarious one.

Just like the devious used car dealer who turns back the odometer, the devious used (or new, for that matter) airplane dealer can easily distort the static hole to give the unsuspecting buyer the false impression that he is buying a faster airplane than he really is.

The angle of attack, as well as the angle of sideslip, can have a significant effect on the airspeed reading. Most pilots have noticed the extremely low airspeed readings during slow flight and stalls. This is generally because the pitot tube is not aligned with and, hence, not sensing the correct total airstream pressure. In flight testing, a device will be used to swivel the pitot tube so that it is aligned with the airstream. At other times, a shroud will be placed around the pitot tube to make it relatively insensitive to misalignment with the airstream.

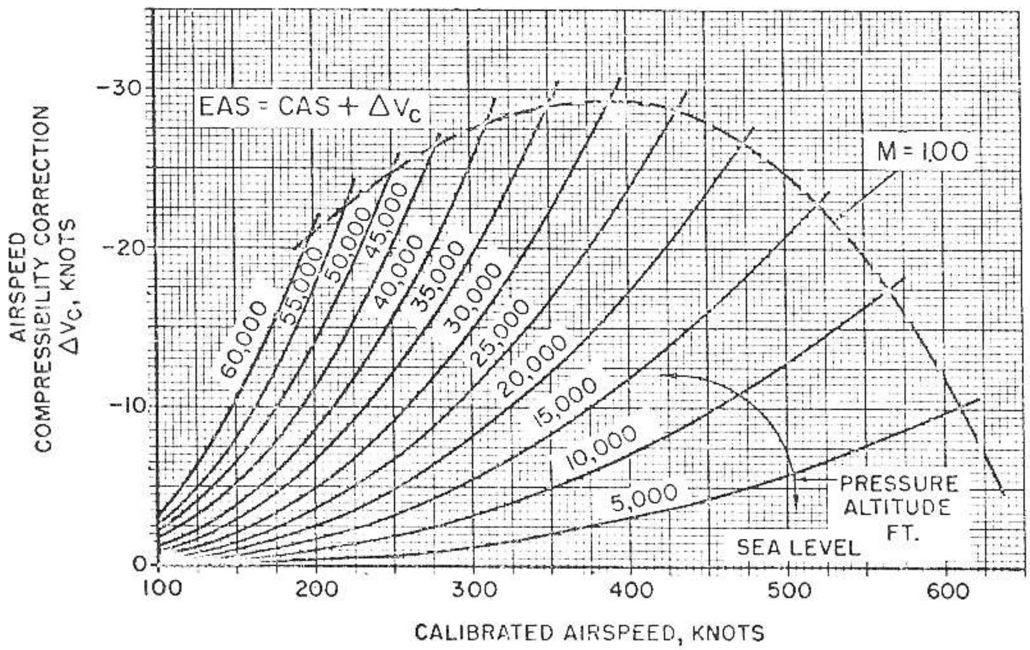


FIGURE 9

CORRECTION FOR COMPRESSIBILITY EFFECT
(REFERENCE: <u>AERODYNAMICS FOR NAVAL AVIATORS</u>)

The air in which the pitot tube is located is just as important as its alignment with the airflow. If the pitot tube was placed directly over the wing, it would sense a much higher airspeed because of the relatively faster airflow over the wing. In order to ensure the location of the pitot tube in an undisturbed region, it has been recommended (by the NACA) that the pitot tube be mounted about one chord length in front of the wing, far from any prop blast. However, it is much cheaper to mount a short tube under the wing (where it is also protected from the weather, as well as people) and then provide a calibration chart to correct the resulting errors.

Any nicks, bends, or other distortions in the opening of the pitot tube can also cause errors because the stagnation point may not be centered on the pitot tube opening. It should be easy to see that most errors in the pitot system will cause the indicator to read low.

Although we have not been treating the airflow as incompressible (which, of course, it is) for speeds below about 200 mph and below altitudes of about 20,000 feet, there is little difference between the density of the air in the pitot tube and the undisturbed ambient air, at least as far as the pilot is concerned. Within this envelope, we can treat the airflow as incompressible and use the relatively simple expression for incompressible flow ($q = \frac{1}{2}\rho V^2$). However, with faster and higher flying aircraft, compressibility effect does become significant and is a major subject in itself (also see Airspeed Calibration section). As mentioned earlier, most airspeed indicators are already corrected for compressibility effect in sea level conditions; however, the readings must be corrected for compressibility when the conditions are not standard.

Fig. 9 shows the amount of correction required to be applied to an indicator reading that has already been corrected for sea level compressibility. When the CAS is corrected for compressibility effect using this "f factor", the result will be the equivalent airspeed (EAS) which is related to the true airspeed (TAS) as we have seen earlier:

$$\text{TAS} = \sqrt{\frac{\rho_o}{\rho}}\ \text{EAS}$$

This expression can be solved easily (on the pilot's flight computer) by knowing the flight level pressure altitude and temperature.

In addition to the various considerations mentioned above, prior to flight, any protective cover should, of course, be removed. You should also check out the anti-ice system (pitot heat), if icing is even a remote possibility during the flight. Care should be exercised in this regard, as pitot heat has been known to distort the pitot tube opening when left on too long without sufficient airstream cooling. There is also the possibility of burning the heating element out with prolonged ground use, such as forgetting to shut it off after landing.

DEFINITION OF TERMS USED IN THIS PAPER

ρ = Flight level air density.

ρ_o = Standard day sea level air density (ρ_o = 0.0012250 grams per cubic meter).

p = Static air pressure measured at rest in the undisturbed atmosphere. Also equivalent to the potential energy (PE) of the airstream.

q = Dynamic air pressure is the difference between the total and static air pressures, assuming air to be an incompressible fluid. Also equivalent to the kinetic energy (KE) of the airstream.

H = Total pressure is the pressure acting at the forward stagnation point. It is the sum of the dynamic and static pressures ($H = p + q$). Also called the ram or pitot pressure.

IAS = Indicated airspeed is the uncorrected speed observed on the airspeed indicator dial.

BAS = Basic airspeed is the indicated airspeed corrected for instrument error (reference: Air Force Manual 51-40). It is the CAS, based on the aircraft's actual sensed pitot and static pressures, or what you will get when you calibrate the indicator as described in this paper.

CAS = Calibrated airspeed as defined by the FAA (reference: FAR Part 1) is the indicated airspeed corrected for position and instrument errors. Calibrated airspeed was at one time referred to (by the FAA) as the true indicated airspeed or TIAS. An ambiguity concerning calibrated airspeed should be noted: Most aircraft operating manuals will contain charts for converting "IAS to CAS". These corrections are obtained from flight test data with an accurately calibrated airspeed indicator for an entire model series of aircraft. Therefore, these charts will not normally include the individual instrument correction. The Air Force defines calibrated airspeed as the basic airspeed corrected for position error; this allows for insertion of the separately determined instrument correction (reference: Air Force Manual 51-40).

EAS = Equivalent airspeed is the equivalent true airspeed associated with the same dynamic pressure in the standard sea level air mass and is the calibrated airspeed corrected for compressibility effect. Note that, for speeds less than about 200 knots and altitudes below about 20,000 feet, there is relatively little compressibility so, for all practical purposes, in this region, CAS = EAS.

TAS = True airspeed is the equivalent airspeed corrected for variations in air density and is the actual speed through the air. In the standard sea level air mass where $\rho = \rho_o$, true airspeed equals equivalent airspeed (TAS = EAS). There are two factors which determine nonstandard air density: First, is the difference in pressure between the flight level and the standard sea level air pressures. (To the pilot, this is related to the pressure altitude computation used in determining true airspeed.) Second, is the difference in temperature between the standard sea level temperature and that found at flight level.

DAS = Density airspeed is calibrated airspeed corrected only for variations in density. If compressibility is ignored, then density airspeed is taken as the true airspeed. This is the general practice for moderate speeds and altitudes. Although not a standard part of FAA terminology, density airspeed is defined by the military (reference: Air Force Manual 51-40 and Navy H. O. Pub. No. 216).

f = "f factor" or the compressibility factor used to correct calibrated airspeed for compressibility error in non-standard conditions (CAS × f = EAS). This correction is found on most flight computers and becomes quite significant in the faster and higher flying aircraft. For flight conditions above the standard sea level conditions, the compressibility effect will cause the airspeed indicator to read too high, so we can see that the "f factor" will always be less than 1.0.

f_o = The compressibility correction for standard sea level conditions only. Most airspeed indicators are graduated so as to read correctly in sea level conditions; f_o is this correction. Without this dial correction, the indicator would normally read too high.

M = Mach number and is the ratio between the speed of the aircraft and the speed of sound:

$$M = \frac{\text{TAS}}{\text{Speed of Sound}}$$

q_c = is sometimes called the "compressible q" and is the actual pressure found in the pitot tube less the static pressure, the result of compressibility, also called the "impact pressure". q_c is related to the incompressible q by the Mach factor: $q_c = q \times MF$.

MF = Mach factor as seen from above, relates q_c and q. It gives us the apparent increase in the dynamic pressure caused by the compressibility effect.

Standard atmosphere = A hypothetical vertical distribution of the atmospheric temperature, pressure and density which, by international agreement, is considered to be representative of the atmosphere for pressure-altimeter calibration and other purposes.

Standard temperature = The temperature of the air existing in a standard atmosphere. This temperature is equal to +15° C (+59° F) at sea level. At altitude, standard temperature decreases at a constant rate (1.98° C per 1,000 feet) to -56.50° C at 36,089 feet and remains essentially constant to above 100,000 feet.

Standard sea level pressure = Is defined by international agreement as 760 millimeters of mercury pressure (or the more familiar, 29.9213 inches of mercury).

Position error = Error in sensing the correct pitot and static pressures due to improper location and alignment of the pitot and static probes.

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END OF PART II