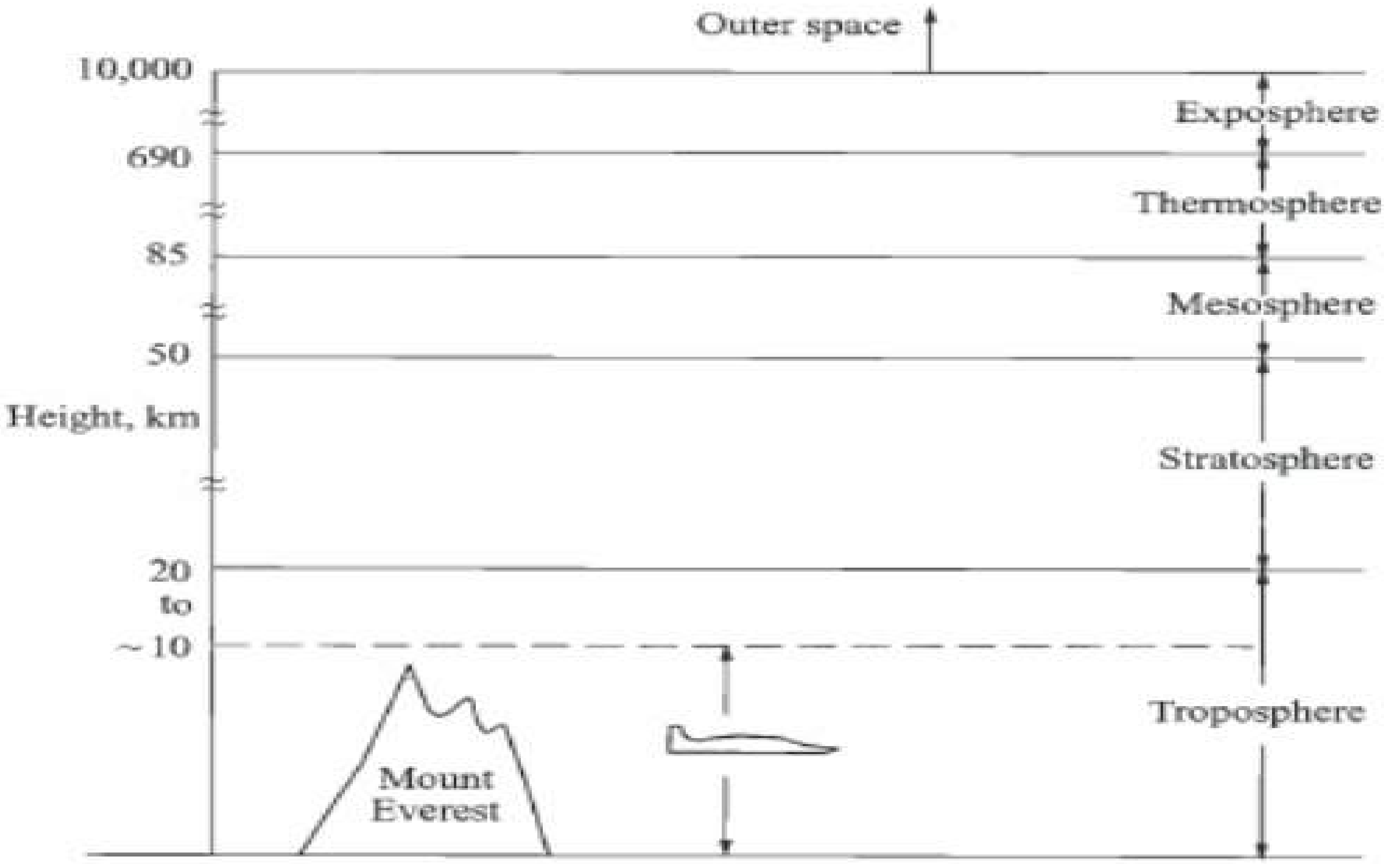
Air Data Instruments

Earth's Atmosphere

- Most of the aircraft fly in the troposphere which extends up to an altitude of about 36,000 feet or 11 km (6.8 miles) above the earth's surface. Figure shows the different layers of atmosphere



- Earth's atmosphere is a layer of gases surrounding surface and it is held in position by earth's gravitational force.
- The atmosphere has about 78% of nitrogen, 21% of oxygen, about 1% argon, 0.04% of carbon dioxide, trace amount of other gases, and a variable (up to 1%) amount of water vapour.
- Three-fourths of atmosphere is within or above 10 km of troposphere, directly above earth's surface. Tropos in Greek means 'turning' or 'mixing'. Most of the aircraft fly within this altitude. Troposphere has a large amount of mixing, due to solar heating at the surface.
- The hot air being lighter rises, the atmospheric pressure decreases and so the air expands and the temperature of air mass decreases. The rate at which the temperature decrease is called the lapse rate

International Standard Atmosphere (ISA)

All aircraft follow the same standardized model of the atmosphere- called International Standard Atmosphere (ISA).

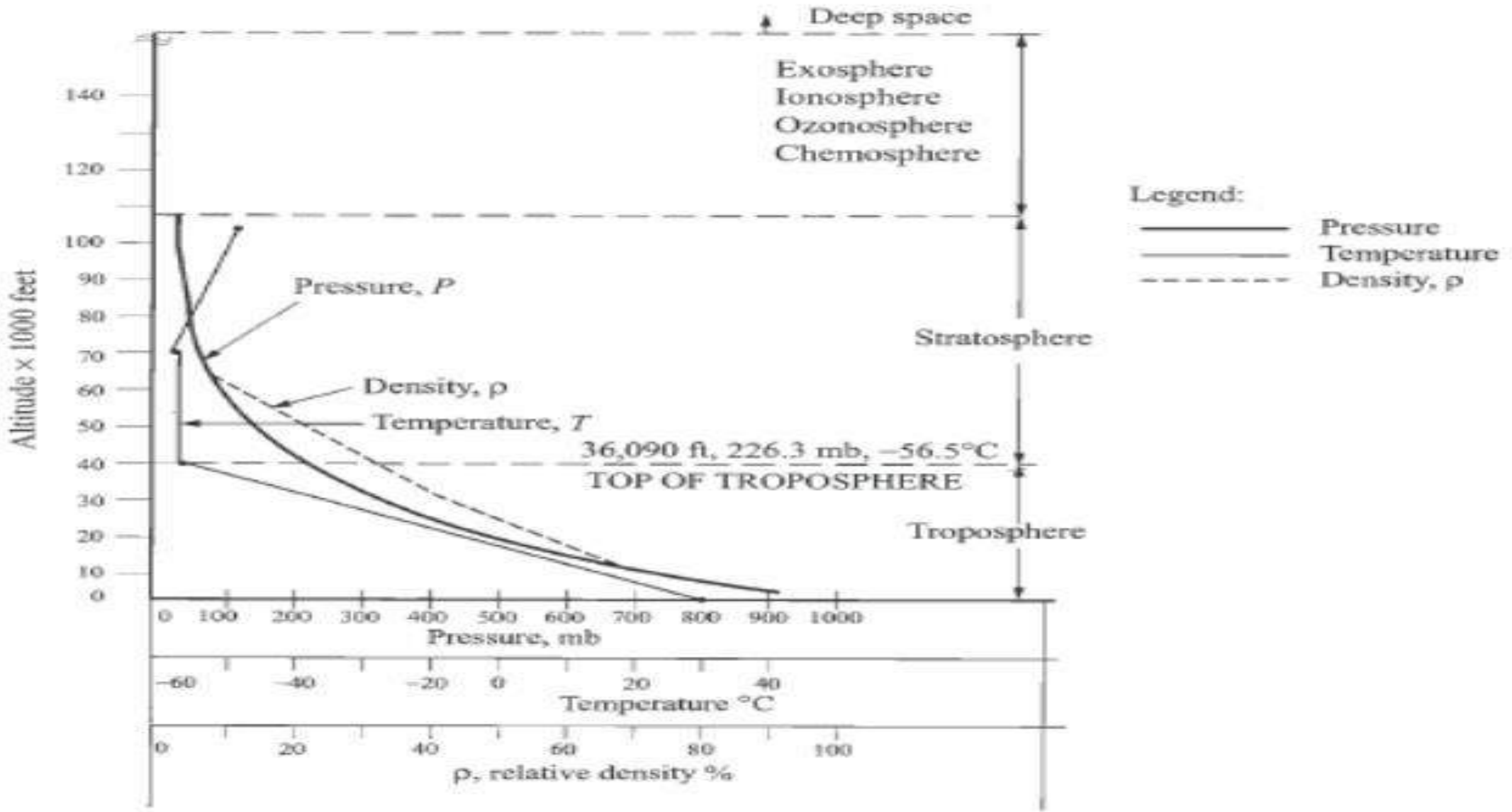
The standardized ISA model serves to maintain the vertical separation of aircraft, to prevent mid-air collisions, particularly in congested air routes of trans-Atlantic flights.

Atmospheric Variations with Altitude

Atmospheric pressure falls as height increases.

The standard atmosphere at mean-sea-level is assumed to be 1013.25 mb. (14.7 psi, or 29.921 inches Mercury or 10132.5 pascals). 1 mb = 10 pascals.

The transition to deep space is gradual. Almost all aircraft usually fly within the troposphere. i.e. at altitudes less than 36,000 feet


Deep space
Exosphere
Ionosphere
Ozonosphere
Chemosphere
Legend:
Pressure
Temperature
Density, ρ
Stratosphere
Troposphere
Pressure, P
Density, ρ
Temperature, T
36,090 ft, 226.3 mb, −56.5°C
TOP OF TROPOSPHERE
Altitude × 1000 feet
140
120
100
90
80
70
60
50
40
30
20
10
0
0 100 200 300 400 500 600 700 800 900 1000
Pressure, mb
−60 −40 −20 0 20 40
Temperature °C
0 20 40 60 80 100
ρ, relative density %

- In ISA model, temperature is assumed to be 15°C at mean-sea-level and falling at a uniform rate of -1.98°C for every 1000 feet up to tropopause (36,090 feet). This is called the lapse rate
- Above tropopause the atmospheric temperature is assumed to be constant at -56.5°C, up to about 70,000 feet. Temperature starts rising again above 70,000 feet.

- The following International Standard Atmosphere model has been arrived after extensive studies and research:

1. Atmospheric pressure at mean-sea-level is 1013.25 mb,
2. Temperature at mean-sea-level is 15°C.

Air Data Instruments

The three basic air data instruments are:

- Altitude Indicator (ALTI), sensing the flight altitude.
- Air Speed Indicator (ASI), to know the aircraft speed.
- Vertical Speed Indicator (VSI), to indicate rate of ascent or descent of the aircraft.

The following vital information should always be presented to both pilot and co-pilot in the Main Instrument Panel (MIP) in the prime zone of his vision:

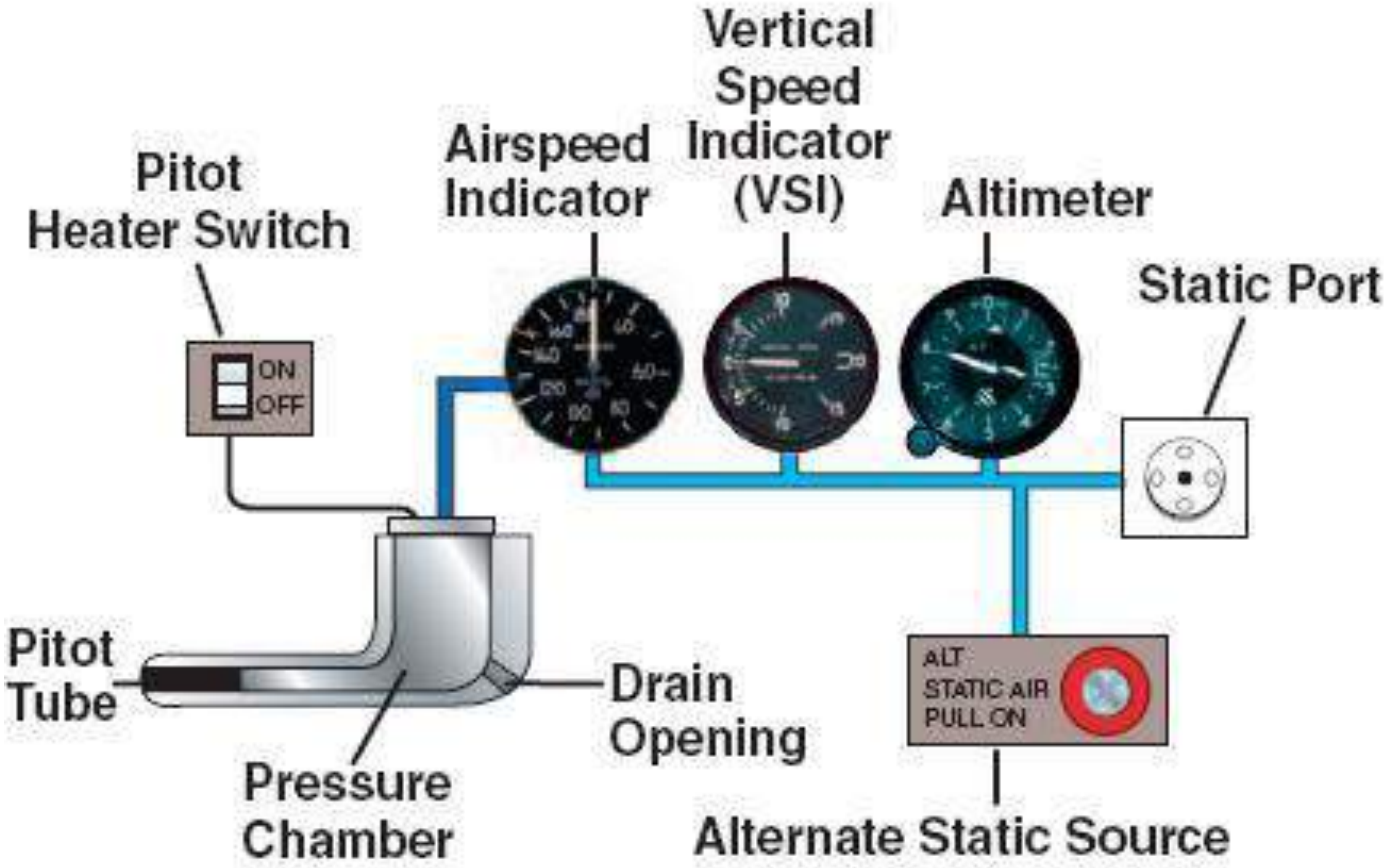
1. Air speed, mph/knots
2. Altitude, feet
3. Vertical speed, feet/mm.

- The three air data instruments-ALTI, AST and VSI, are based on the measurement of pitot and static pressures.
- Pitot tube is used to sense the Pt, the total or pitot pressure. A static port is used to measure the prevalent atmospheric static pressure.
- Air speed is sensed as a difference in total pressure, Pt and static pressure Ps.

FREE PILOT TRAINING

- Pitot pressure, also called total pressure is defined for subsonic (below speed of sound) flight as the pressure of air brought to rest (stagnation pressure).
- Static pressure is defined as the undisturbed (ambient) air pressure through which the aircraft is moving. It is the absolute pressure which would be present, locally, without any pressure fluctuations or disturbances due to the moving aircraft.
- Static pressure measurement is more difficult and challenging than pitot pressure measurement. There will be significant influence of the moving aircraft on the atmosphere through which it flies. Measuring static pressure accurately in this dynamic environment has always posed severe measurement problems.

Pitot-Static System



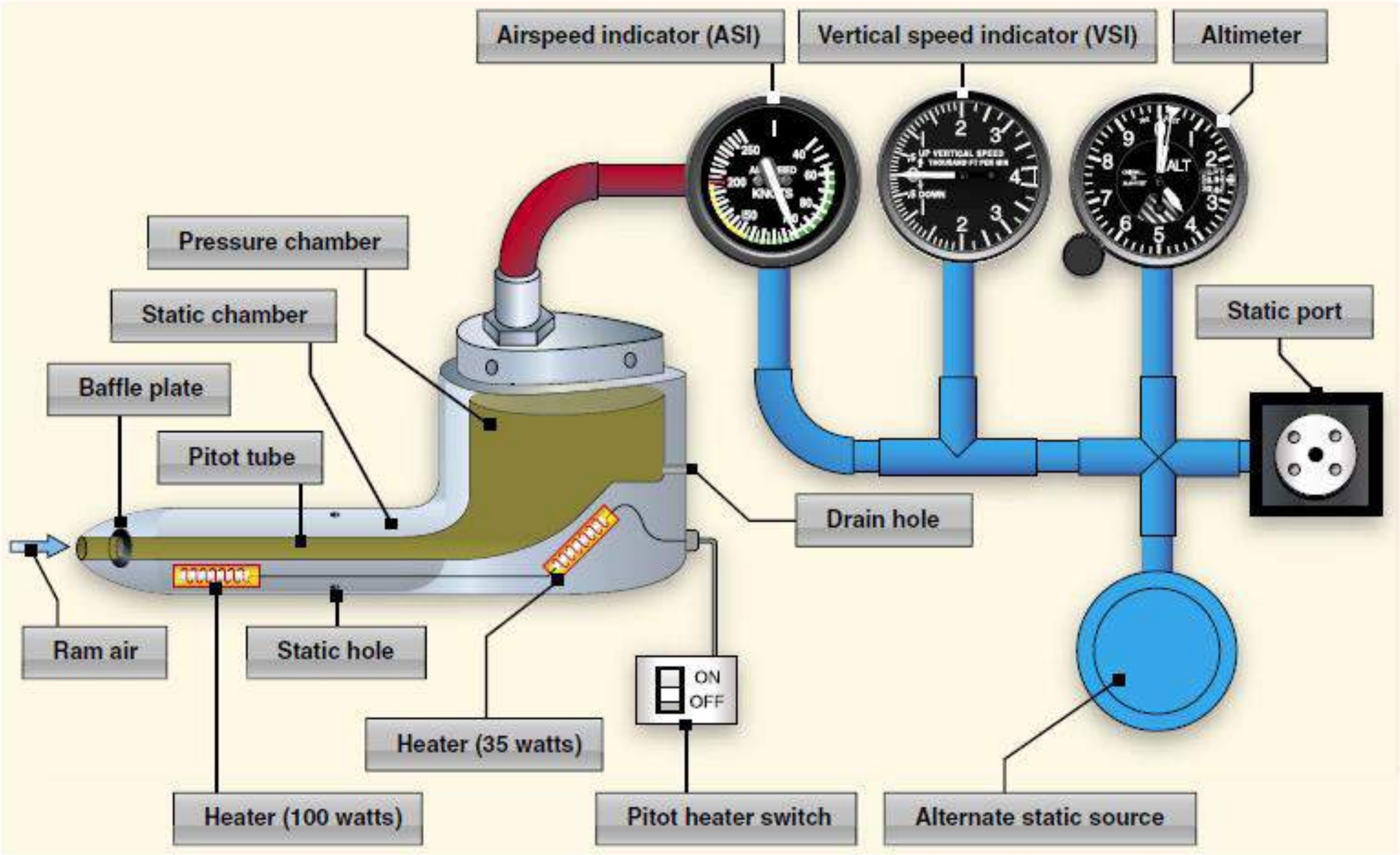


Figure 7-1. *Pitot-static system and instruments.*

Impact Pressure Chamber and Lines

- The pitot tube is utilized to measure the total combined pressures that are present when an aircraft moves through the air.
- Static pressure, also known as ambient pressure, is always present whether an aircraft is moving or at rest.
- It is simply the barometric pressure in the local area.
- Dynamic pressure is present only when an aircraft is in motion; therefore, it can be thought of as a pressure due to motion.

Static Pressure Chamber and Lines

- The static chamber is vented through small holes to the free undisturbed air on the side(s) of the aircraft.

- As the atmospheric pressure changes, the pressure is able to move freely in and out of the instruments through the small lines which connect the instruments into the static system.

- An alternate static source is provided in some aircraft to provide static pressure should the primary static source become blocked.

- The alternate static source is normally found inside of the flight deck. The air pressure inside the flight deck is lower than the exterior pressure.

- **When the alternate static source pressure is used, the following instrument indications are observed:**

1. The altimeter indicates a slightly higher altitude than actual.

2. The ASI indicates an airspeed greater than the actual airspeed.

3. The VSI shows a momentary climb and then stabilizes if the altitude is held constant.

The basic principle of operation depends on Bernoulli's theorem which states that "the total energy remains constant in a fluid flow." Total energy comprises (1) pressure energy, (2) kinetic energy $\left(\frac{1}{2}\rho V^2\right)$ and (3) potential energy (ρgh).

i.e. $$\text{Total energy} = p + \frac{1}{2}\rho V^2 + \rho gh = \text{constant} \quad \text{(Bernoulli's equation)} \tag{3.1}$$

where,

p = pressure
ρ = density of the fluid, assumed constant
V = velocity of aircraft relative to wind
g = acceleration due to gravity, and

Figure 3.1 represents a tube through which an ideal fluid passes through at a steady rate.

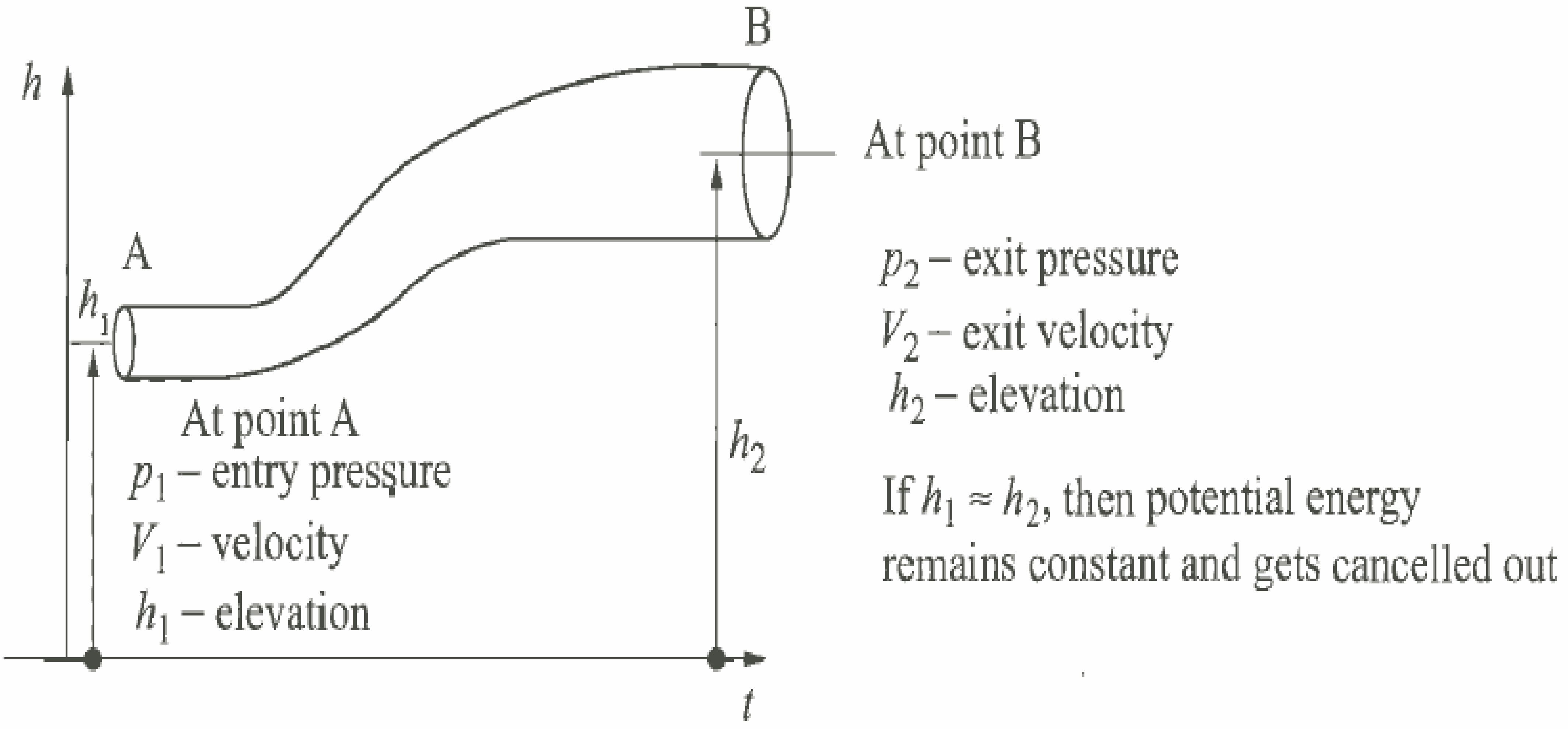


Fig. 3.1 Fluid flow in a tube.

The total energy is conserved, i.e.

$$\underbrace{p_1}_{\substack{\text{pressure}\\\text{energy}}} + \underbrace{\frac{1}{2}\rho V_1^2}_{\substack{\text{kinetic}\\\text{energy}}} + \underbrace{\rho g h_1}_{\substack{\text{potential}\\\text{energy}}} = \underbrace{p_2}_{\substack{\text{pressure}\\\text{energy}}} + \underbrace{\frac{1}{2}\rho V_2^2}_{\substack{\text{kinetic}\\\text{energy}}} + \underbrace{\rho g h_2}_{\substack{\text{potential}\\\text{energy}}}$$

If the fluid flows horizontally, then $h_1 = h_2$, then potential energy (ρgh component) remains constant and gets cancelled out. Equation (3.1) then becomes:

$$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}V_2^2 \tag{3.2}$$

which tells us that

- If the speed of a fluid decreases/increases as it travels along as horizontal stream line, the pressure of the fluid must increase/decrease.

Pitot Pressure

In an ideal fluid, *total energy* is the sum of potential energy (ρgh) (assumed constant), kinetic energy $\left(\frac{1}{2}\rho V^2\right)$ and pressure energy (p), and it remains constant. Potential energy is assumed to be constant in the vicinity of measurement, at a flight altitude, h. Thus potential energy can be lumped together with other constants; making

$$\therefore \quad p + \frac{1}{2}\rho V^2 = \text{constant} \tag{3.3}$$

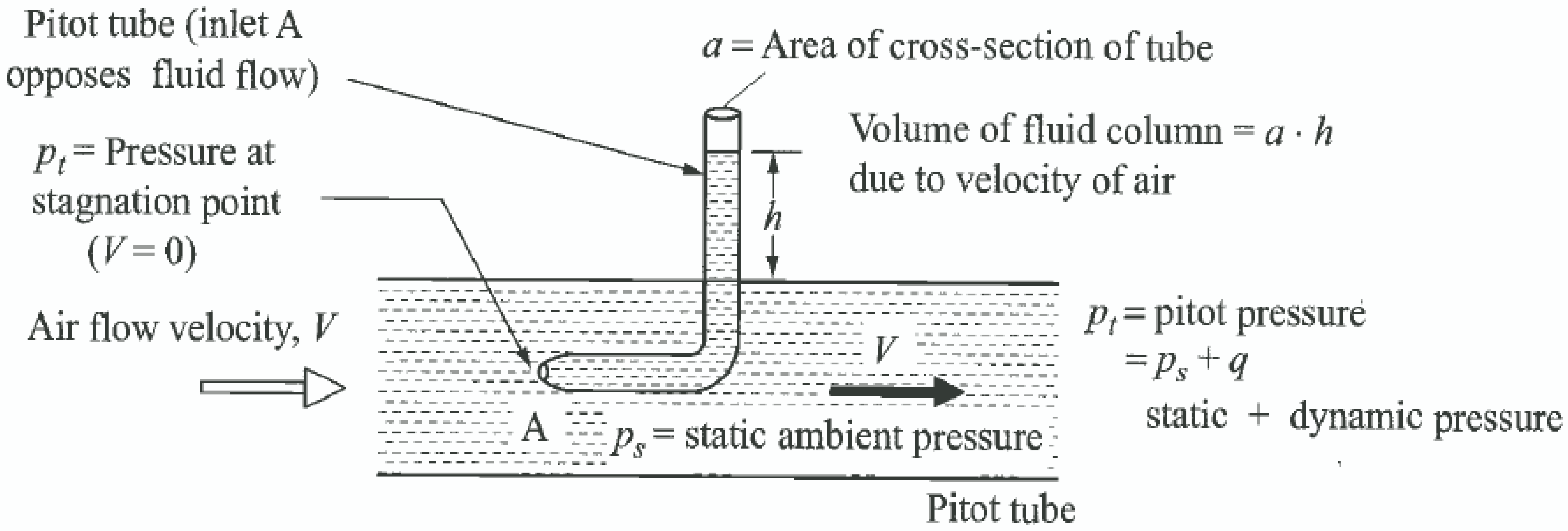


Fig. 3.2 Total (pitot) pressure.

- Pitot pressure is the total stagnation pressure at point A, where the fluid is brought to rest. This point A is called stagnation point, where the fluid is brought to rest or stagnates.
- When the fluid is flowing at a certain velocity V, and is suddenly stagnated at Pitot probe, then the velocity head is converted to pressure head where h is the height of rise of fluid in pitot tube, and m = mass of the raised fluid column,

Then p, pressure $= \dfrac{\text{force}}{\text{area}} = \dfrac{mg}{a} \cdot \dfrac{h}{h} = \dfrac{mgh}{(a \cdot h)} = \dfrac{mgh}{V} = \rho g h$, since $\rho = (m/v)$

and $$gh = \frac{p}{\rho}$$

where a = area of cross-section of capillary tube
and h = height rise due to flow velocity
ρ = density of air

$$\text{Potential energy} = \text{Kinetic energy}$$

i.e. $$mgh = \frac{1}{2} m V^2$$

substituting from Equation 3.4a, $gh = \dfrac{p}{\rho}$ we have $\dfrac{m \cdot p}{\rho} = \dfrac{1}{2} m V^2$

$\therefore \quad p = \dfrac{1}{2} \rho V^2$. This is called the dynamic pressure, represented by alphabet q.

- In an ideal fluid, total energy is the sum of potential, kinetic and pressure energies.

Total energy = Potential energy + Kinetic energy + Pressure energy

- Potential energy is the energy of air particle at a particular height above the earth's surface and for an aircraft flying at a certain altitude, potential energy is assumed to be constant and therefore is not considered any further.
- This makes the sum of KE and PE constant

The pitot tube measures the total pressure, p_t, which is equal to

$$p_t = p_s + q = p_s + \frac{1}{2}\rho V^2 \tag{3.8}$$

All the air data instruments depend on the measurement of p_t, total pressure and p_s = ambient static pressure. The dynamic pressure q, then is derived from:

$$q = p_t - p_s \tag{3.9}$$

and since q = 1/2 ρV^2, velocity of airflow can be indicated by sensing ($p_t - p_s$)—a differential pressure measurement.

Finally, note that p_t the total pressure is measured using the pitot tube. The static pressure, p_s, the pressure of the surrounding static air is measured separately using static ports, which is not sensitive to dynamic pressure, q, by making the static ports, tangential to airflow as shown below in Figure 3.3. Accurate static measurement is difficult and also most important.

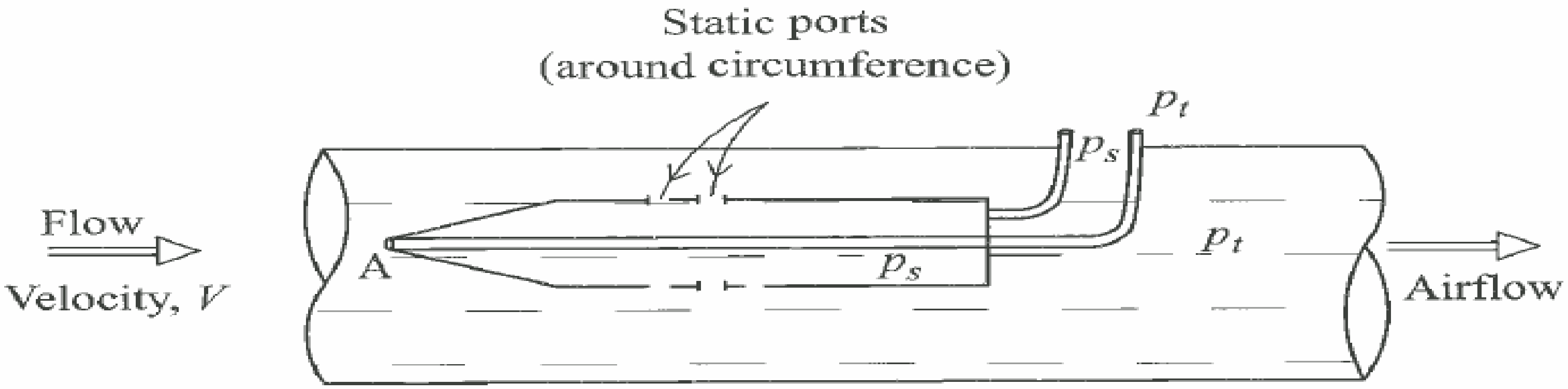


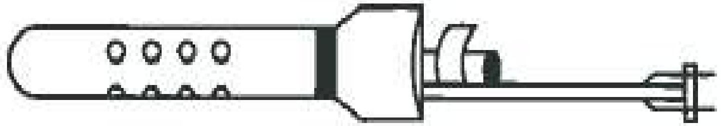
Fig. 3.3 Combined pitot-static tube.

Summarising, the pitot tube measures total pressure, p_t which is the sum of static pressure, p_s and dynamic pressure, $q = 1/2\ \rho V^2$. This constitutes the basic principle used in all air data instruments. Static pressure, p_s is carefully sensed through static ports. Dynamic pressure, due to flow velocity V is then computed as:

$q = 1/2\ \rho V^2 = p_s - p_t \rightarrow$ a differential pressure measurement in an Air Speed Indicator (ASI).

Figure shows some more common pitot and pitot-static probes.

(a) Fuselage side mounting pitot probe



(b) Nose boom mounting pitot probe

(c) Fuselage nose mountable pitot-static probe

(d) Aerodynamically compensated pitot-static probe

- Static ports are worst affected by wrong positioning of the probe in the aircraft.
- Shock waves (abrupt pressure changes) are caused by high speed air flowing past an abrupt change in shape of the probe, which should be minimized.
- The airflow past the probe must be "laminar"-i.e. airflow must be in smooth lines (need not be straight) past the aerodynamically shaped body of either the probe or even the aircraft.

- Airflow past an aerodynamically shaped body depends on several factors such as:

1. Shape of the probe/aircraft
2. Diameter of the probe
3. Air speed, and
4. Angle of attack (AOA)

- If static port holes are located at a position where they are exposed to shock waves, static pressure measurement will be erroneous due to turbulent cross-flows, and therefore inaccurate.

Shock wave errors are minimized by:

1. Decreasing the probe diameter; however the diameter cannot be reduced indefinitely because a slender probe is prone to oscillations due to airflow; also electrical power wires to anti-icing heater need certain minimum diameter to be accommodated.

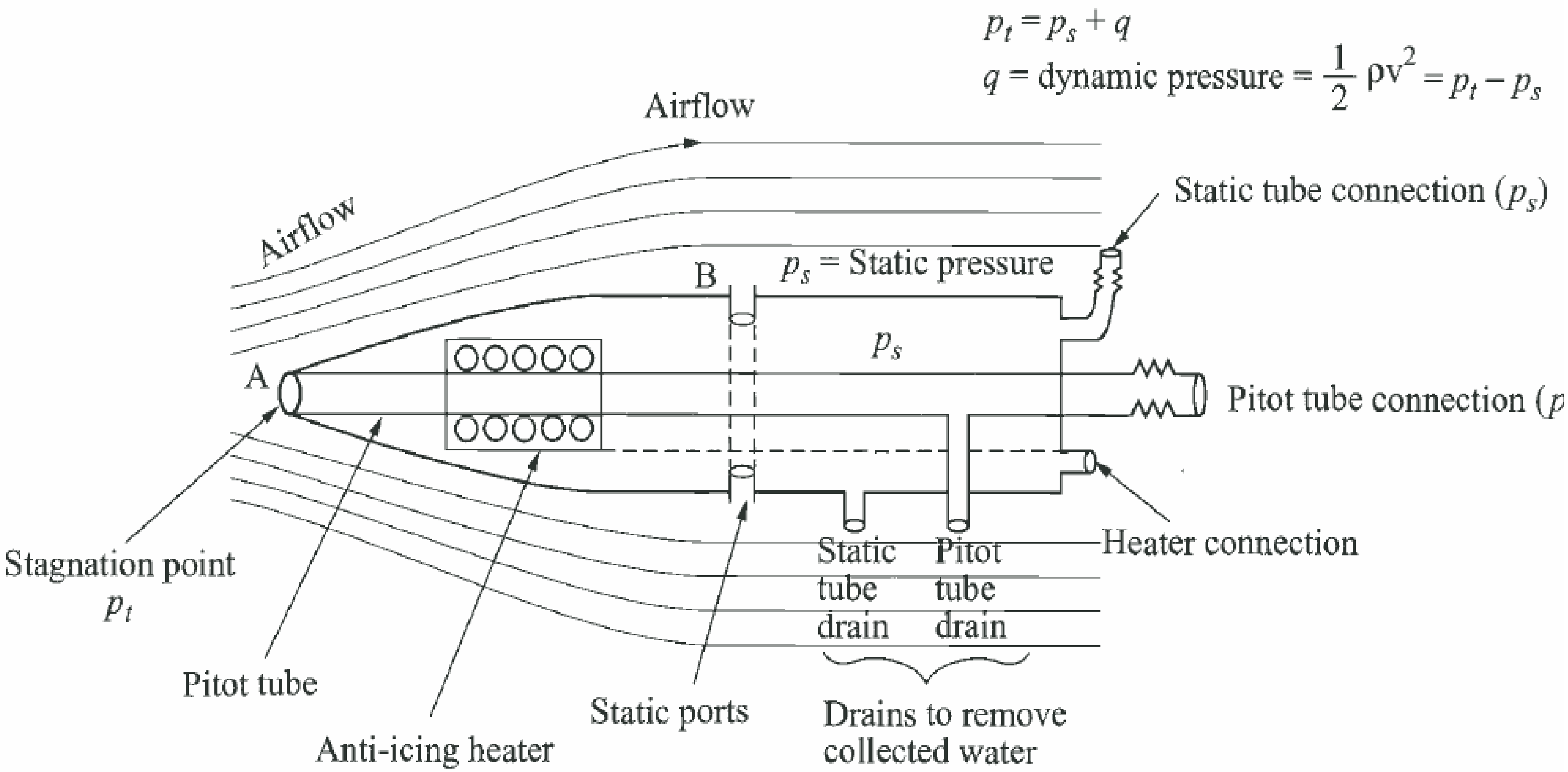
2. Static ports can be judiciously located at two stations S1 and S2, along the probe length, so that some holes at least are in the region of undisturbed airflow.

Static pressure measurement is also affected by angle-of-attack.

There are two types of probe based on static port configuration, namely:

1. Combined pitot-static probe.
2. Separate pitot and static probe

Combined Pitot and Static Probe



- In this probe shown in Figure , both total pressure and static pressure are sensed in the same pitot-static tube.
- Static ports are co-located with the pitot tube, and is not separate.
- Note that the total pressure, Pt is called as total pressure, pitot pressure, or stagnation pressure.
- The basic pitot tube consists of a capillary tube with a smaller diameter opening, A, which faces the airflow, moving at a certain velocity, V. The flow is brought to rest at the tip of the probe and the flow velocity gets converted into a pressure head.

Separate Static Ports

- Combining static ports in the pitot probe introduces errors due to position error:

(i) caused by probe vibrations, and

(ii) errors introduced at different angles of attack.

- Therefore separate ports are used. A typical static port is shown in Figure

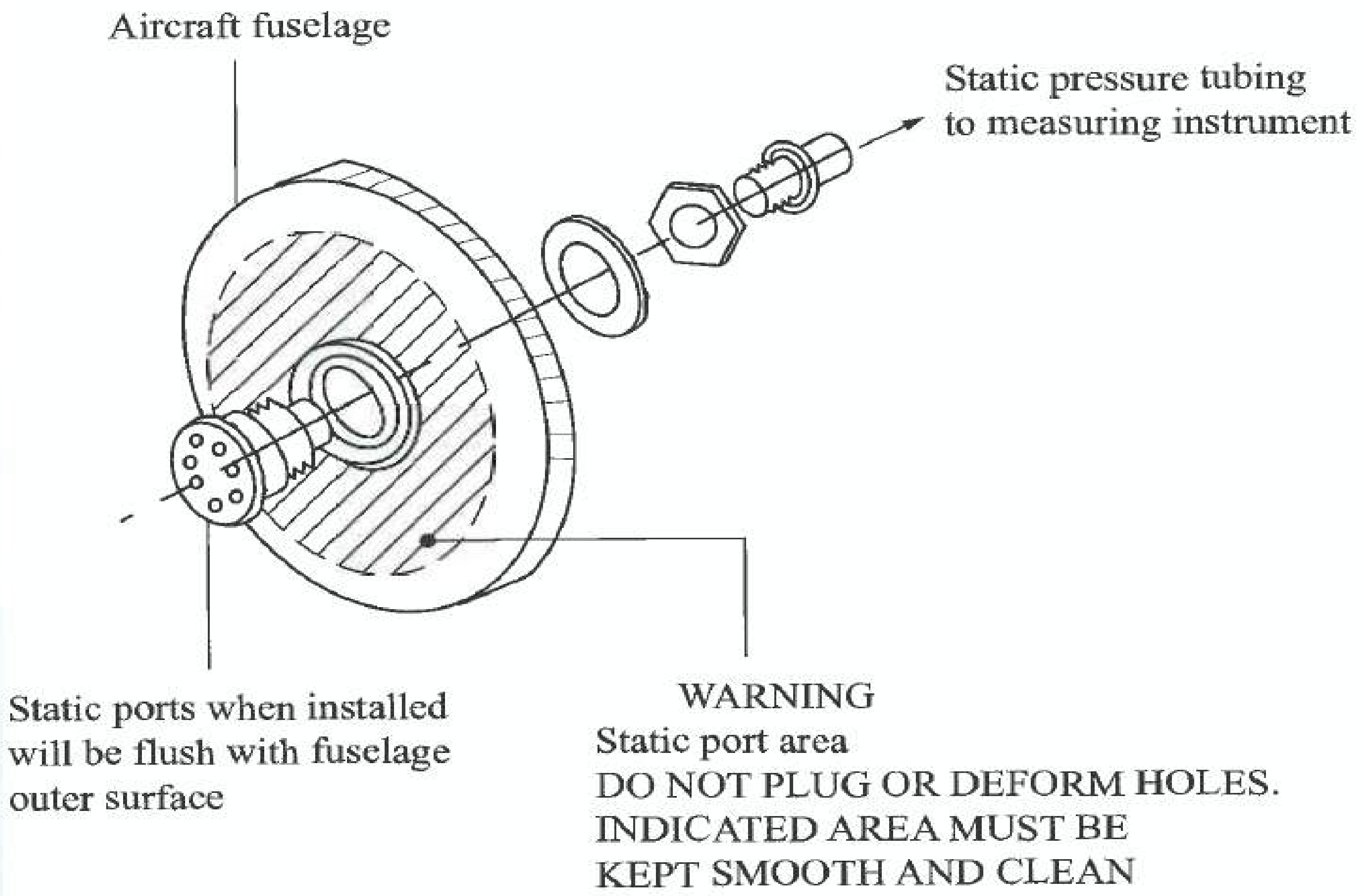


Fig. 3.10 Separate static port, mounted flush with fuselage.

- Even separate static port suffers from repeatability problems. Flush static ports suffer from port installation variances and also from imperfections in the fuselage skin around the static port.
- Therefore, to achieve high repeatability of the static pressure measurement, between different aircraft requires very tight manufacturing tolerances, during the construction of the fuselage.

- The pressure coefficient Δp/q is the ratio of (local static pressure-free stream static pressure) and the dynamic pressure q, as given by the equation

$$\frac{\Delta p}{q} = \frac{\text{local static pressure} - \text{free stream static pressure}}{\text{dynamic pressure, } q}$$

Locations of Combined Probe and Static Ports

- Proper location of combined pitot and static probe, or static port in the aircraft is necessary to sense the static pressure accurately. The location is decided after studying the flow pattern of the aircraft model in a transonic wind tunnel.
- The location should be at a place where there are no large scale perturbations of airflow and the location depends on: the type of aircraft (civil or military) speed (subsonic or supersonic) and aerodynamic characteristics. The location cannot therefore be generalized.
- However, there are typical areas which are preferred under a wing, wing tip, in front of vertical stabiliser tip, left or right of fuselage nose, as shown in Figure

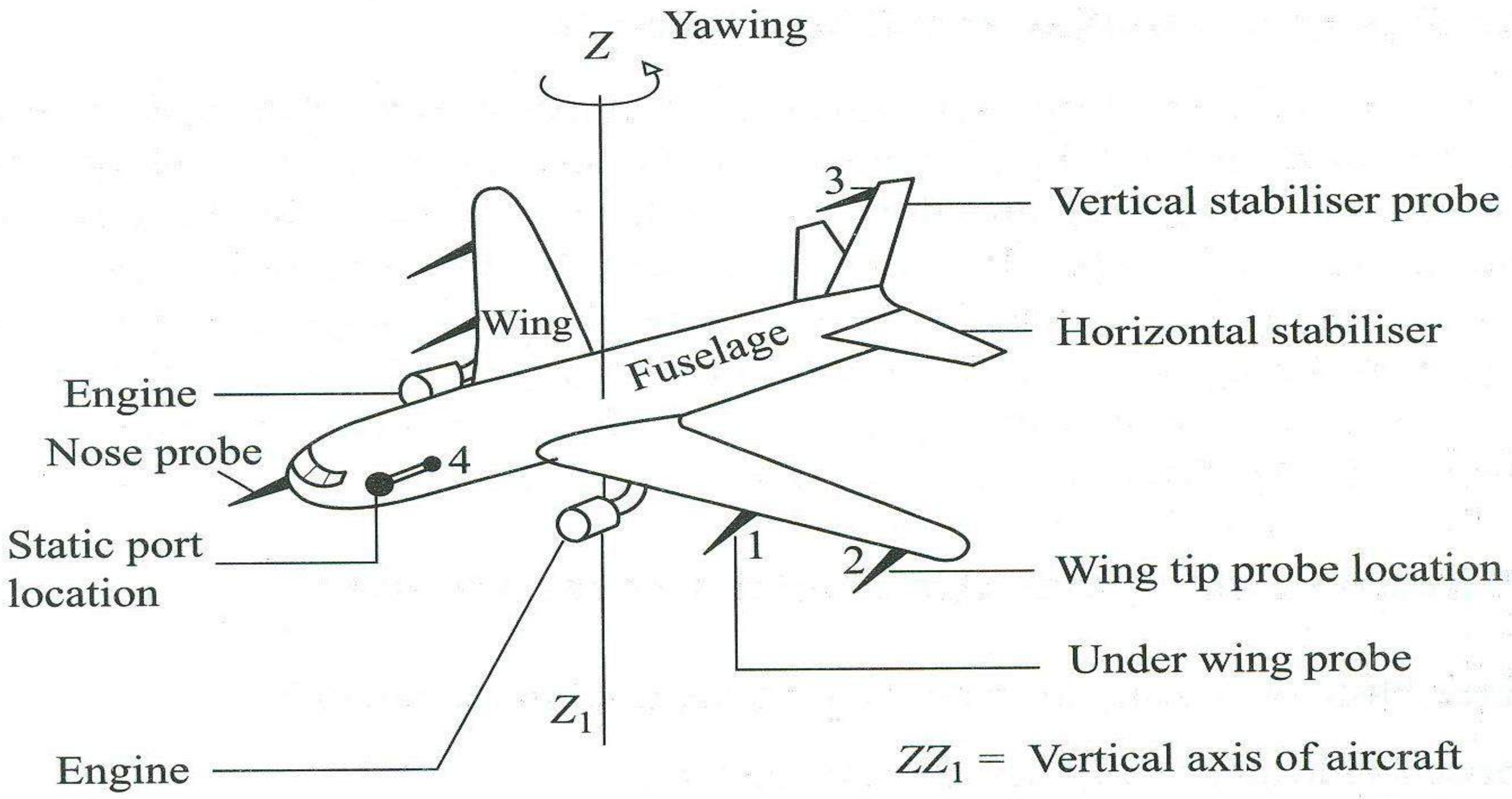


Fig. 3.11 Preferred locations of pitot-static tube and static ports in the aircraft.

Position Error

- Position error is caused by the difference between local static pressure (at the point of sensing)and the free-stream static pressure. Some difference always exists because the airplane is moving in the static atmosphere, causing flow disturbances, and we are attempting to measure the static atmospheric pressure.
- Figure shows how this error changes along the length of a subsonic aircraft. This pressure distribution is not constant and varies with Mach number and angle of attack.

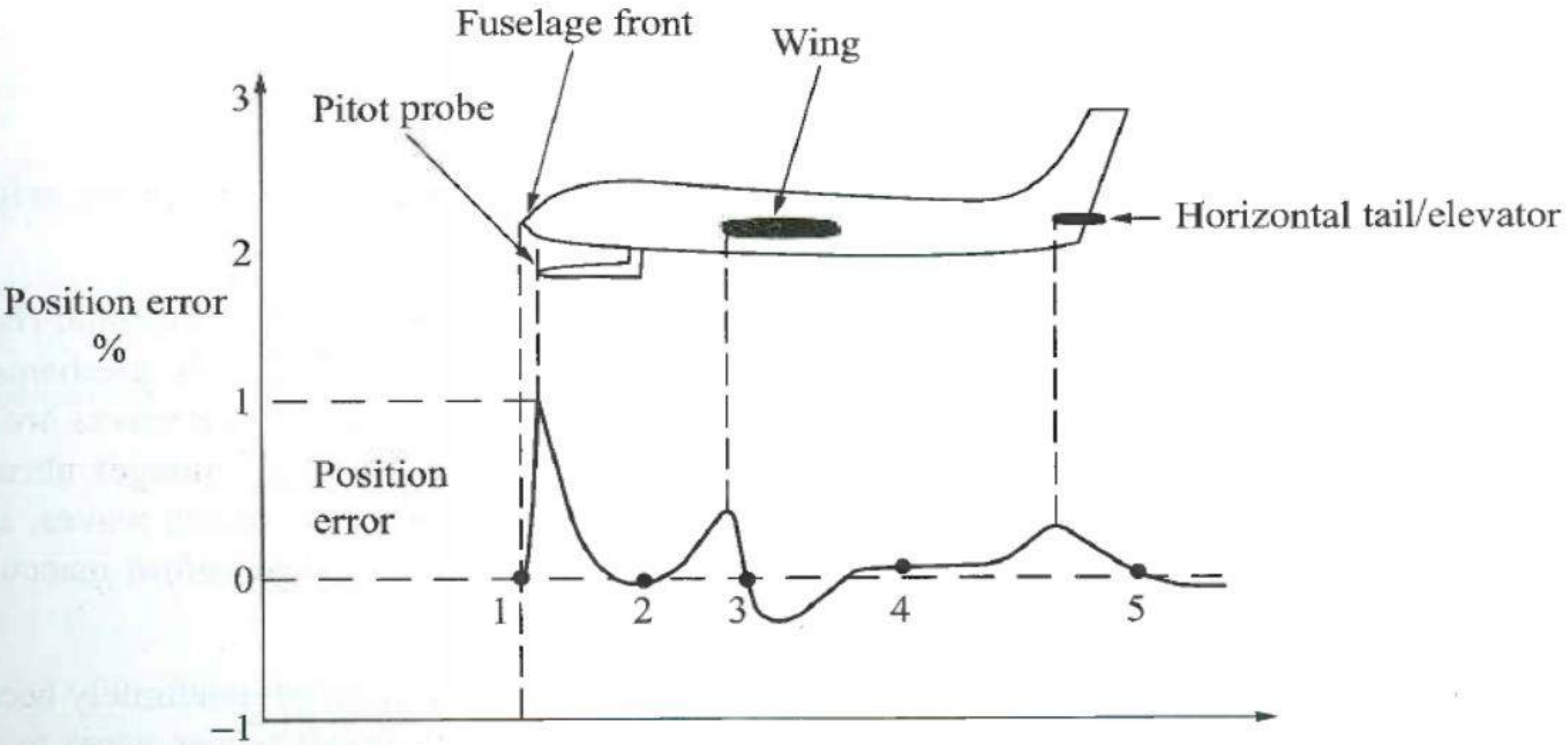


Fig. 3.8 Percentage position error along the length of the aircraft points 1 to 5 indicate positions of least error and therefore are the best possible locations of pitot-static probe in an aircraft.

Types of Air Data Instruments

- There are two types used to measure air data depending on the size and complexity of the aircraft, and the utilization of air data:

1. Pneumatic type (used in older and smaller aircraft)
2. Air data computer (used in large civil transport aircraft, as well as in supersonic aircraft).

Pneumatic Air Data Instruments

- In the pneumatic type, total and static pressures are sensed using tubing directly connected to sensitive mechanical pressure gauges.
- This type is satisfactory in a small aircraft, where the length of tubing is small and air datas are not required by other subsystems.

Air Data Computer

- Pneumatic air data instruments are not suited for large transport aircraft.
- This is due to large distances involved from the sensing point to indicators in cockpit.
- Larger distances require complex routing, and lengthy pneumatic tubes which add to increased weight and serious maintenance problems. Further they produce significant pneumatic lag errors.
- Air data computer (ADC), on the other hand, removes the above restrictions by having the ADC located close to the sensors with the added advantage of large fan-out via electrical cables to many subsystems which require air data..

- ADC receives its primary inputs from the aircraft's pitot and static systems and temperature sensor to display static air temperature or total air temperature.
- These pressures and temperatures are converted into electrical signals with shortest distance from sensing point to the transducer and then used for computation.

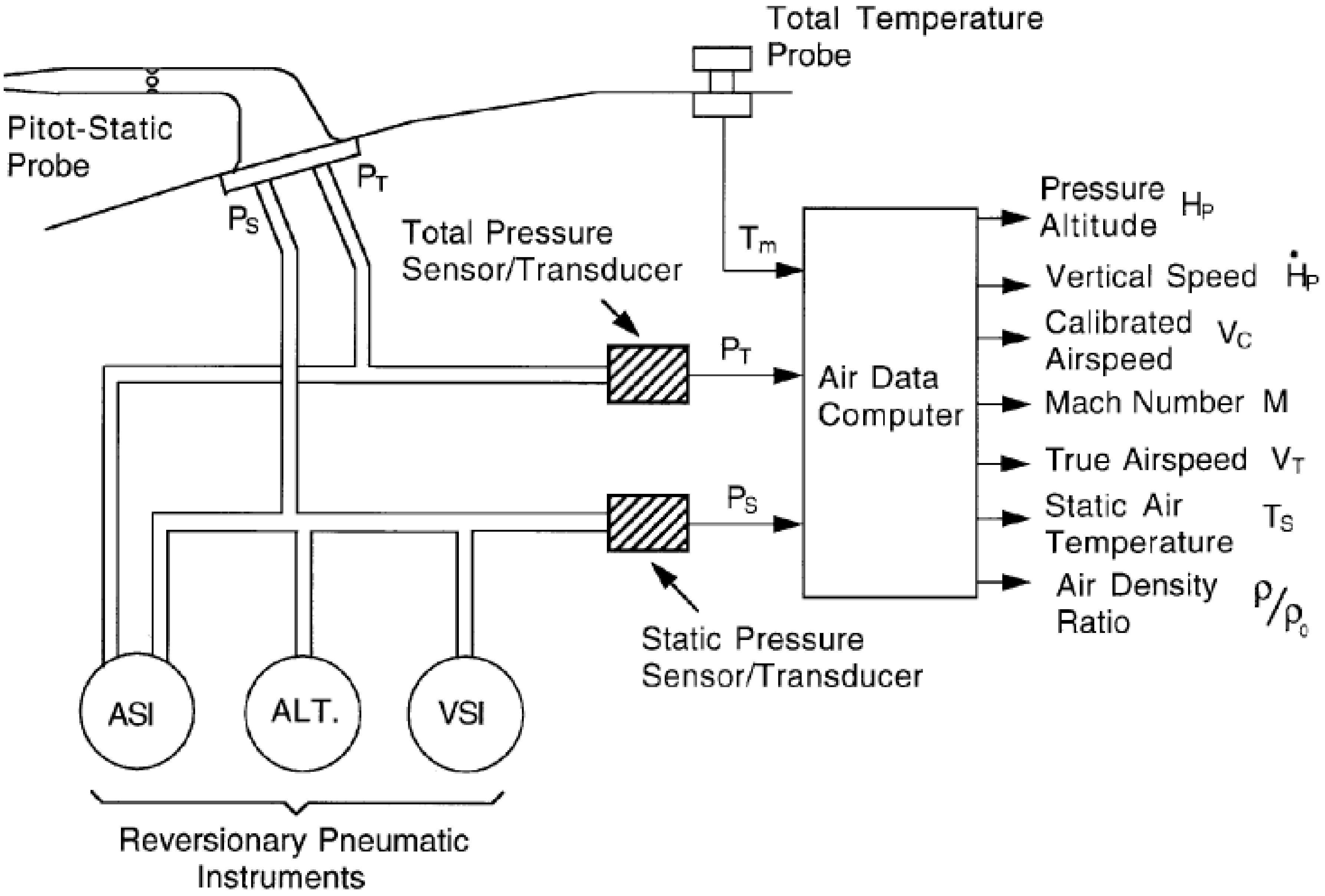
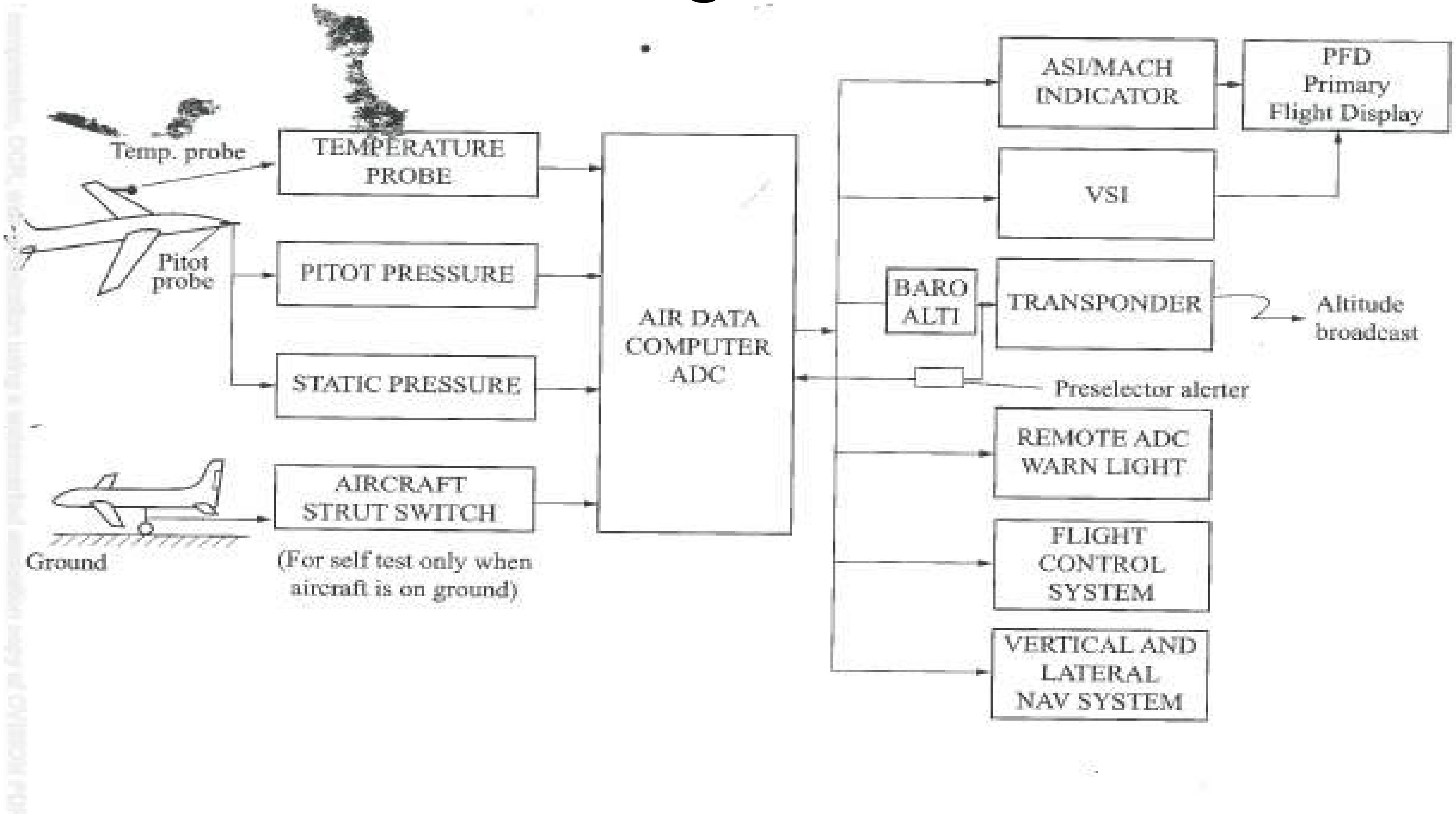
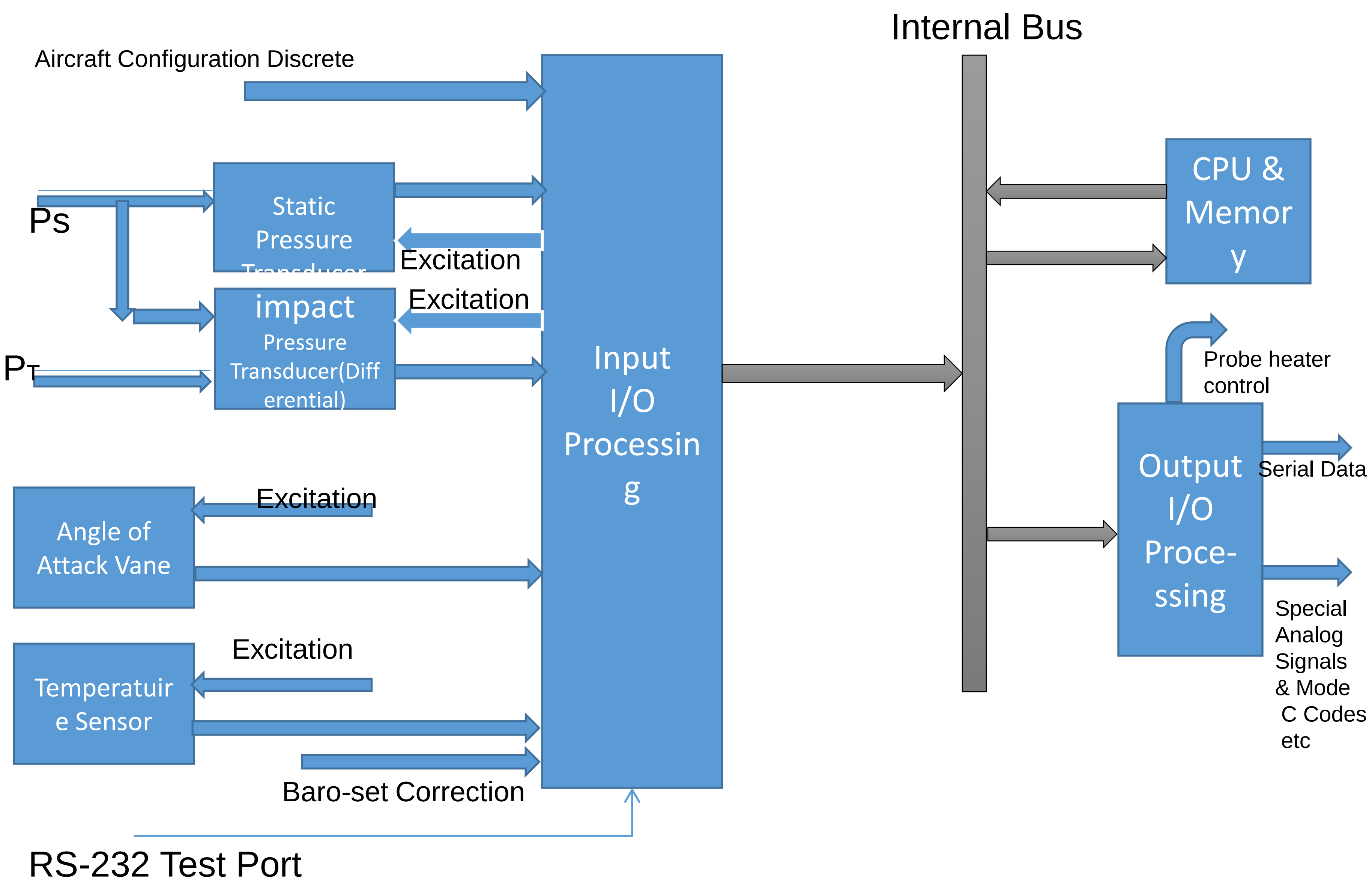


Fig. 7.1 Basic air data system.

Block Diagram of ADC



Functional Block Diagram of Digital Air-Data Computer



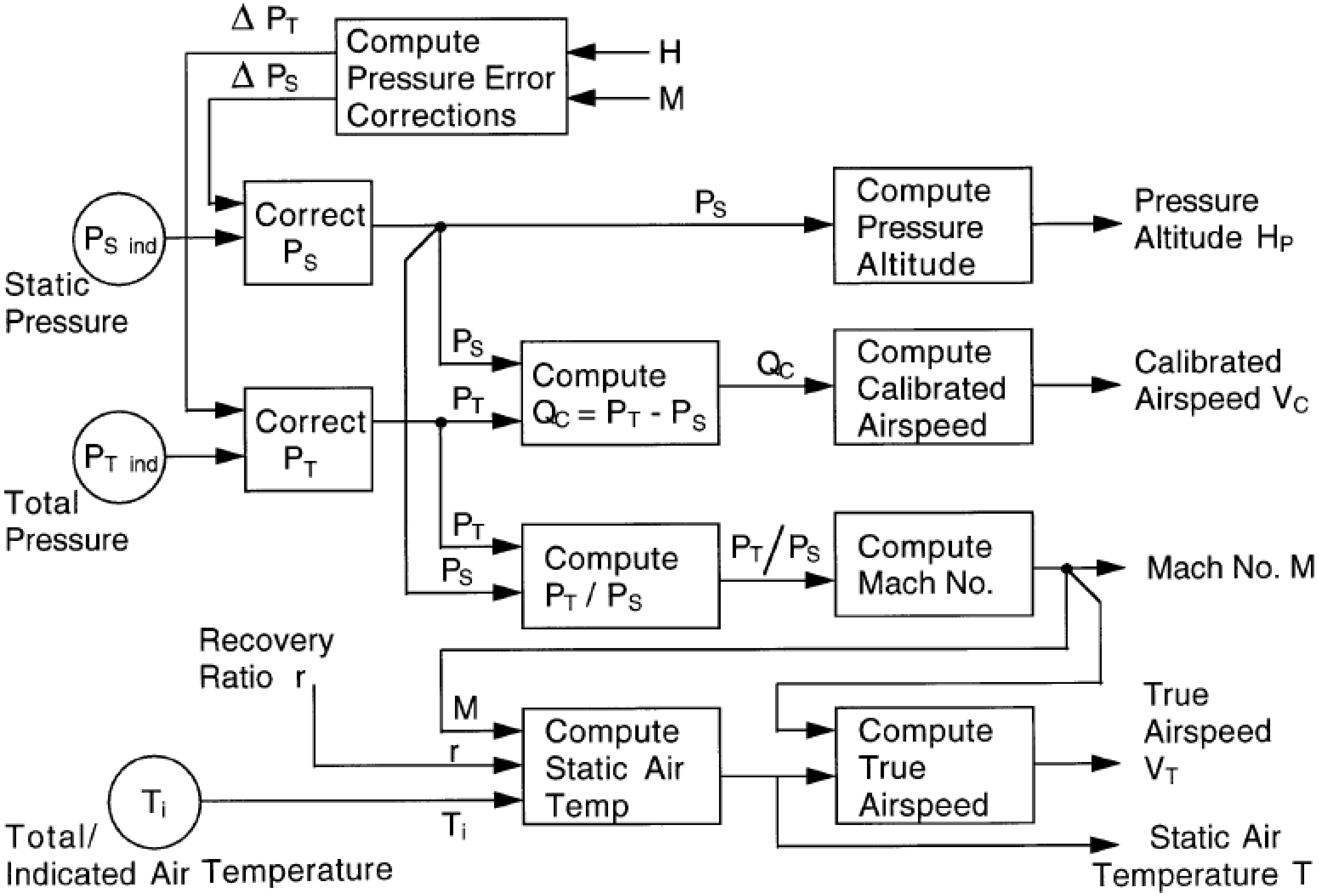


Fig. 7.15 Air data computation flow diagram.

- Computed results from these inputs: pitot and static pressures, temperature and strut switch are converted into digital form and transmitted electrically to many subsystems via data buses, which require air data, such as: altimeter, vertical speed indicators, to the flight control systems, navigation system and to other subsystems like transponder to broadcast altitude data.

- ADC also provides many warnings, which include-over speed warning, air data computer valid signal to flight control system.
- ADC is located usually in the avionics bay below the pilot, such that pneumatic lengths are minimum

Some of the advantages of ADC are:

1. Reduces weight by minimizing tubing and cabling lengths.

2. Reduced maintenance because of solid-state reliability in signal conditioners in ADC.

3. Signal conditioning and processing are easy: corrections for pressure error, barometric pressure changes compressibility effects can be easily computed.

4. Electrical signal handling is easier than pneumatic type, because of flexibility of routing.

- **Two basic quantities which are fundamental for the piloting of any aircraft from a light aircraft to a supersonic fighter** are the ***pressure altitude***, and the ***calibrated airspeed*.**

- **Pressure altitude** is the height of the aircraft above sea level derived from the measurement of the static pressure assuming a standard atmosphere.

- **Calibrated airspeed** is indicated airspeed corrected for instrument errors and position error (due to incorrect pressure at the static port caused by airflow disruption).

Air Data for Key Sub-systems

- ***Air traffic control transponder*** – Pressure altitude is supplied to the air traffic control (ATC) transponder for automatic reporting to the air traffic ground control system.
  - The ATC authorities specify the flight levels which aircraft must maintain in '*controlled airspace*' in terms of pressure altitude and these are set so that there is a minimum of 1,000 ft vertical separation between aircraft flying in the vicinity of each other.

- ***Flight control systems*** – Calibrated airspeed and pressure altitude information is required by the flight control system (FCS).
  - This is to enable automatic adjustment to be made to the gains (or 'gearings') of the FCS with airspeed and height to compensate for the wide variation in control effectiveness and aircraft response over the flight envelope.

- ***Autopilot system*** – A number of autopilot control modes require air data information, e.g., ‘height acquire/hold’, ‘Mach number acquire/hold’ and ‘airspeed acquire/hold’ (auto-throttle system).

- ***Navigation system*** – Pressure altitude and true airspeed are required by the navigation system. Pressure altitude is required for navigation in the vertical plane.
    - It can be combined (or mixed) with the inertially derived information from the inertial navigation system (INS) to provide vertical velocity and altitude information which is superior to either source on its own.

- ***Flight management system*** – The flight management system requires information on all the air data quantities: pressure altitude, vertical speed, Mach number, static air temperature, true airspeed and calibrated airspeed.

- Air data information is essential for the FMS to maintain the aircraft on the most fuel efficient flight path and for achieving 4D flight management (3D position and time).

- ***Engine control systems*** – Height and calibrated airspeed information is required by the engine control systems.

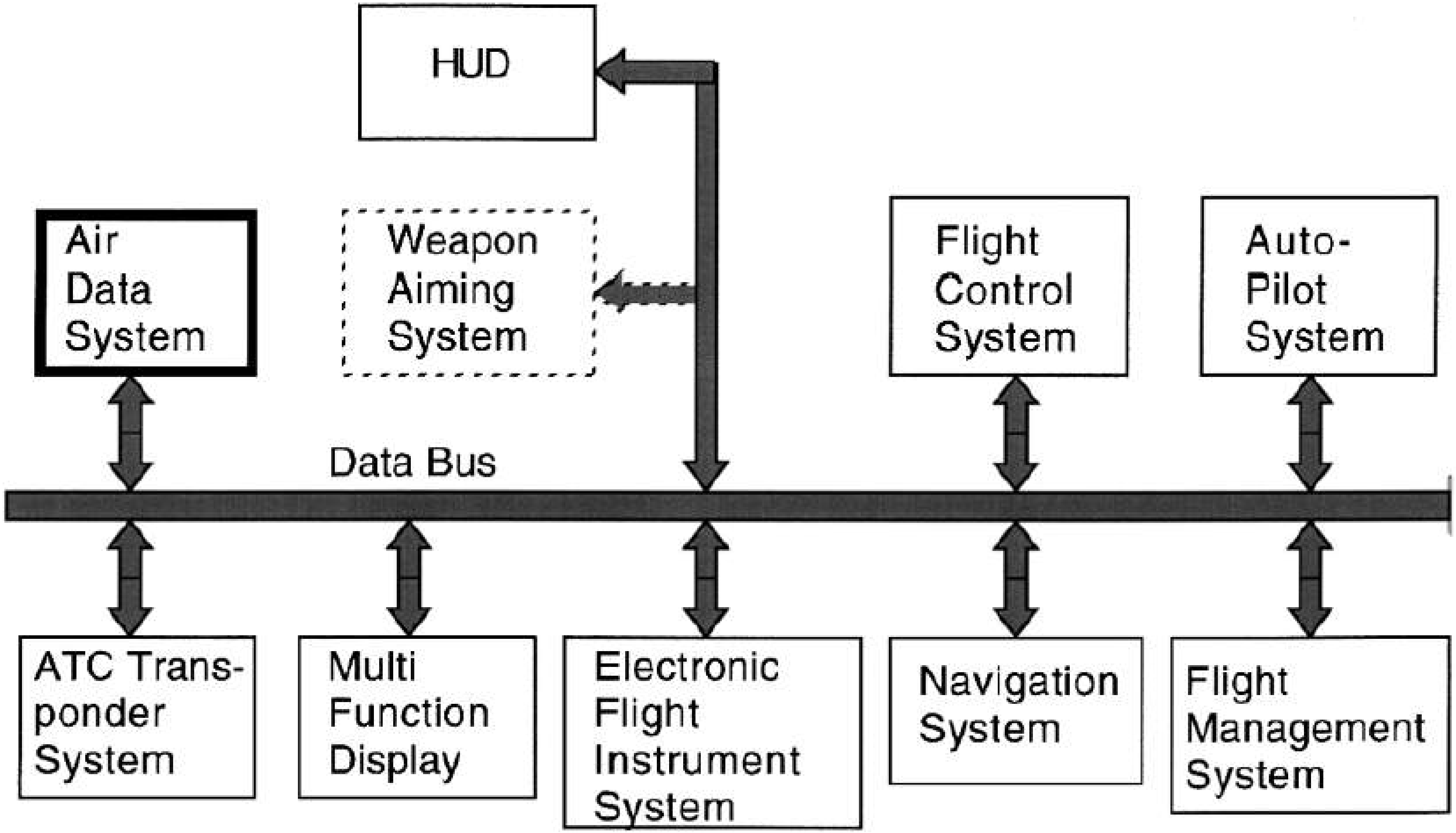


Fig. 7.2 Flow of air data to key avionic sub-systems (redundancy omitted for clarity).

- **In Flight Blockage of Pitot -** When this first happens, if the aircraft is in steady flight the pilot will not realize there is a problem because the ice simply seals the pressure inside the Expandable Capsule When the aircraft descends for landing however the pressure inside the capsule will remain constant, whether the aircraft accelerates, or decelerates.

- As the aircraft descends the static pressure will increase. This will squeeze the expandable capsule.

- Thus, the indicated airspeed will decrease as the aircraft descends regardless of the actual airspeed.
- The opposite would happen if the aircraft climbed.

- **In Flight Blockage of Static Vent** - As long as the aircraft remains at the same altitude the Airspeed indicator works normally since the correct static pressure is sealed in the case.

- When the aircraft descends the static pressure in the case will be lower than it should be.

- Thus, the airspeed will begin to read progressively higher as the aircraft descends. If the aircraft climbs the airspeed will begin to read progressively lower.

what a pilot should do

- **DO** consider pitot heat and alternate static sources as mandatory instruments for flight in actual instrument conditions.

- **DO** conduct a careful preflight of all instrument systems.

- **DO** keep your scan moving and identify any instrument(s) that give you conflicting information.

- **DO** identify the instrument or system that is in error by determining what makes sense and what doesn't.

- **DO** eliminate the offending instrument or system from your attention. Carrying instrument covers to cover the inoperative instruments can keep them from becoming a constant source of distraction. Remember, your scan will tend to pick up the abnormal.

- **DO** consider a backup altimeter for serious instrument flying. Even the altimeter watches are good enough to keep you out of the terrain. Sky diving altimeters are also useful as a backup in an emergency.

- **DON'T** allow your attention to become fixated on any one instrument or system. If you can't figure out why an instrument is giving you the reading it is, there's a good chance there's a problem. Integrate the readings from all other instruments and determine which instrument is lying to you. Eliminate it.

Pitot-Static System Maintenance

- Pressure test
  - Apply vacuum to equivalent altitude of 1,000 feet
  - No more than 100 feet loss in 1 minute
  - Altimeter may be used to make test
- Clean entry holes, drain holes and static ports
- Check pitot heater
  - Look at electric drain and temperature
- Trouble shoot by isolating sections
- A static leak will cause low readings on altimeter and airspeed indicator

Altimeter

The altimeter is an instrument that measures the height of an aircraft above a given pressure level. Since the altimeter is the only instrument that is capable of indicating altitude, this is one of the most vital instruments installed in the aircraft. To use the altimeter effectively, the pilot must understand the operation of the instrument, as well as the errors associated with the altimeter and how each effect the indication.

Principle of Operation

The pressure altimeter is an aneroid barometer that measures the pressure of the atmosphere at the level where the altimeter is located, and presents an altitude indication in feet. The altimeter uses static pressure as its source of operation. Air is denser at sea level than aloft—as altitude increases, atmospheric pressure decreases. This difference in pressure at various levels causes the altimeter to indicate changes in altitude.

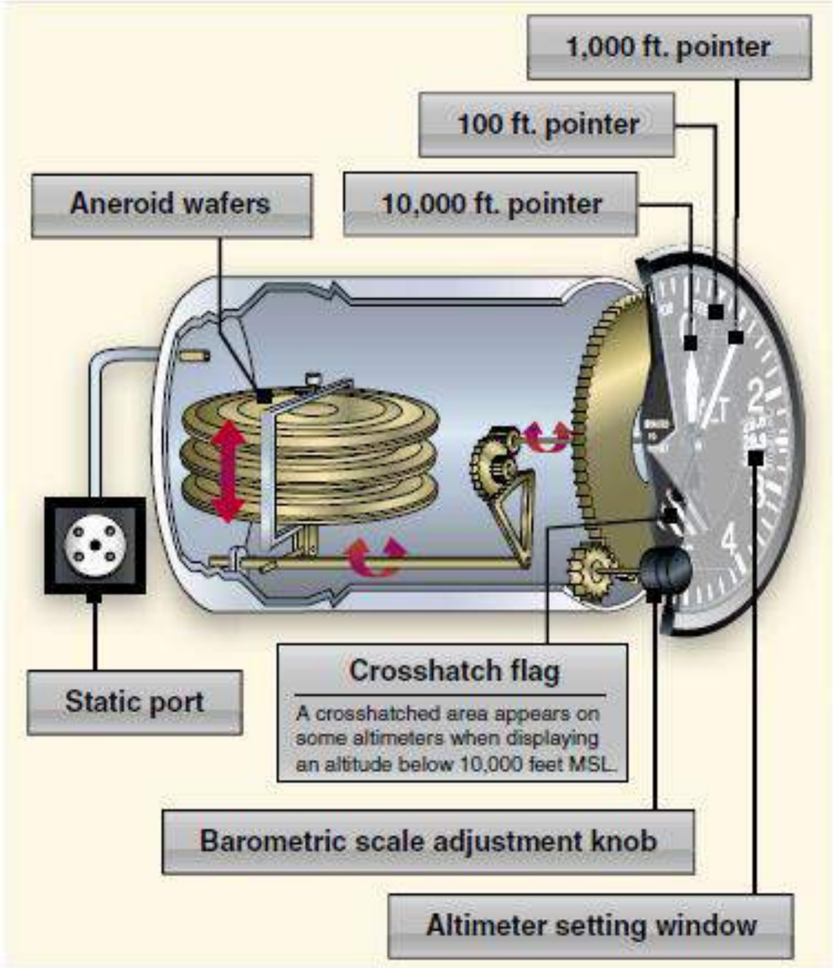


Figure 7-2. *Altimeter.*

https://youtu.be/OiVCX04YJMY

HOW IT WORKS

Altimeter

Pilots are mainly concerned with five types of altitudes:

1. **Indicated altitude—read** directly from the altimeter (uncorrected) when it is set to the current altimeter setting.

2. **True altitude—the** vertical distance of the aircraft above sea level—the actual altitude. It is often expressed as feet above mean sea level (MSL). Airport, terrain, and obstacle elevations on aeronautical charts are true altitudes.

3**. Absolute altitude—the** vertical distance of an aircraft above the terrain, or above ground level (AGL).

4. **Pressure altitude—the** altitude indicated when the altimeter setting window (barometric scale) is adjusted to 29.92 "Hg. This is the altitude above the standard datum plane, which is a theoretical plane where air pressure (corrected to 15 °C) equals 29.92" Hg. Pressure altitude is used to compute density altitude, true altitude, true airspeed (TAS), and other performance data.

5. **Density altitude—**pressure altitude corrected for variations from standard temperature. When conditions are standard, pressure altitude and density altitude are the same. If the temperature is above standard, the density altitude is higher than pressure altitude. If the temperature is below standard, the density altitude is lower than pressure altitude. This is an important altitude because it is directly related to the aircraft’s performance.

Vertical Speed Indicator (VSI)

The VSI, which is sometimes called a vertical velocity indicator (VVI), indicates whether the aircraft is climbing, descending, or in level flight. The rate of climb or descent is indicated in feet per minute (fpm). If properly calibrated, the VSI indicates zero in level flight.

Principle of Operation

- Although the VSI operates solely from static pressure, it is a differential pressure instrument.
- It contains a diaphragm with connecting linkage and gearing to the indicator pointer inside an airtight case.
- The inside of the diaphragm is connected directly to the static line of the pitot-static system. The area outside the diaphragm, which is inside the instrument case, is also connected to the static line, but through a restricted orifice (calibrated leak).

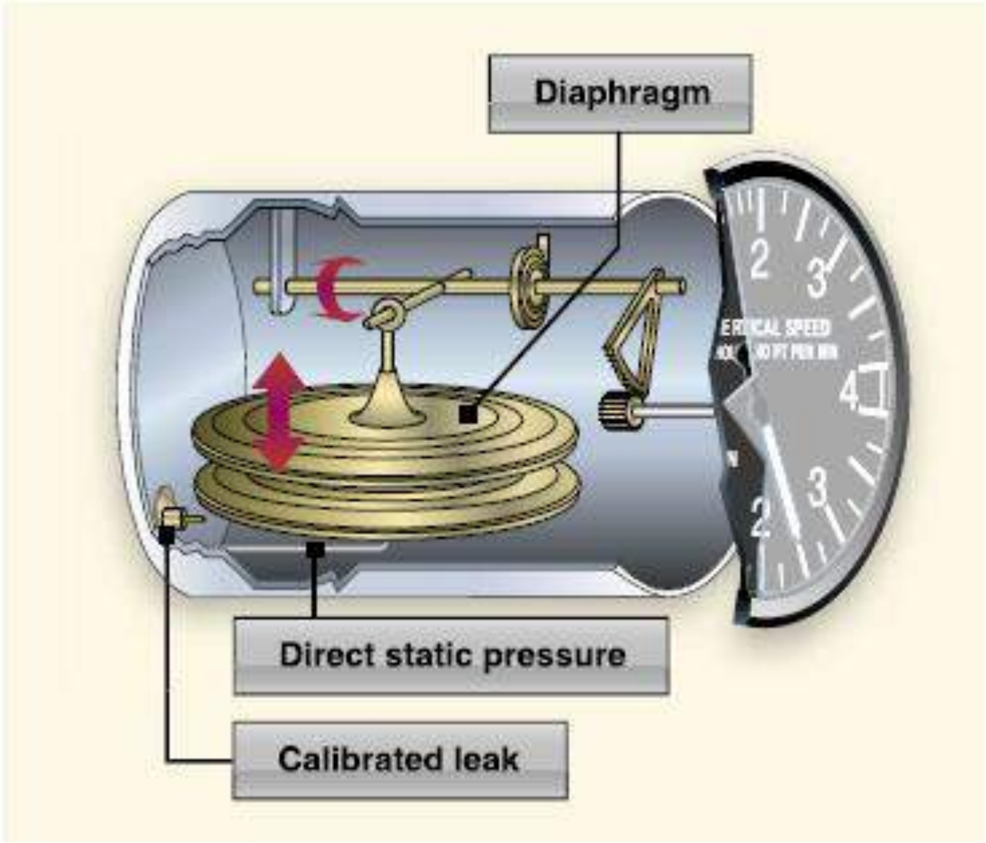


Figure 7-5. *Vertical speed indicator (VSI).*

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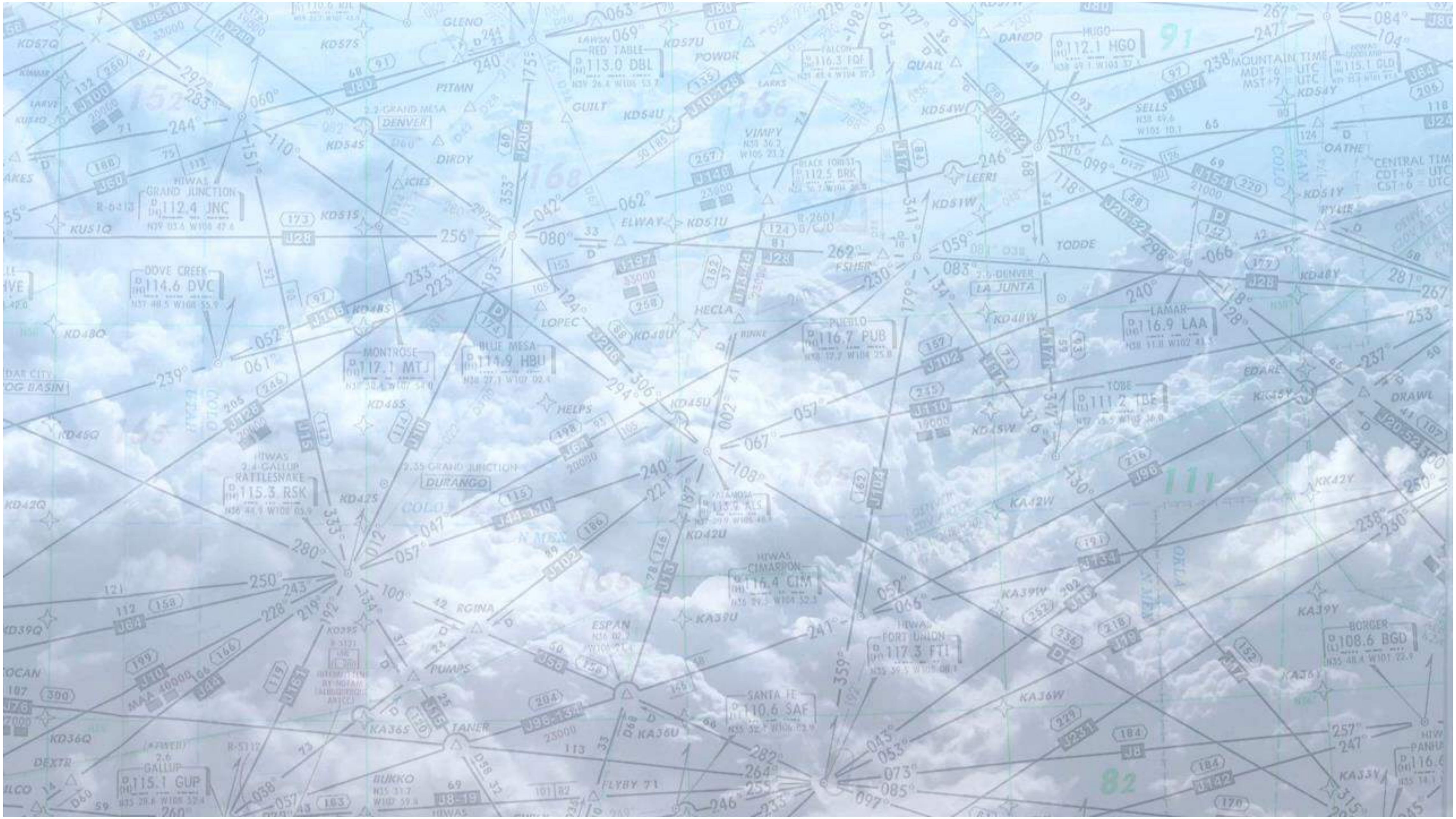

RED TABLE
113.0 DBL
HUGO
112.1 HGO
FALCON
116.3 FQF
MOUNTAIN TIME
MDT+6 = UTC
MST+7 = UTC
GRAND JUNCTION
112.4 JNC
BLACK FOREST
112.5 BRK
CENTRAL TIME
CDT+5 = UTC
CST+6 = UTC
DOVE CREEK
114.6 DVC
LA JUNTA
LAMAR
116.9 LAA
PUEBLO
116.7 PUB
MONTROSE
117.1 MTJ
BLUE MESA
113.9 HBU
TOBE
111.2 TBE
RATTLESNAKE
115.3 RSK
DURANGO
CIMARRON
116.4 CIM
FORT UNION
117.3 FTI
BORGER
108.6 BGD
SANTA FE
110.6 SAF
GALLUP
115.1 GUP

- Both the diaphragm and the case receive air from the static line at existing atmospheric pressure.
- The diaphragm receives unrestricted air while the case receives the static pressure via the metered leak.
- When the aircraft is on the ground or in level flight, the pressures inside the diaphragm and the instrument case are equal and the pointer is at the zero indication.
- When the aircraft climbs or descends, the pressure inside the diaphragm changes immediately, but due to the metering action of the restricted passage, the case pressure remains higher or lower for a short time, causing the diaphragm to contract or expand.
- This causes a pressure differential that is indicated on the instrument needle as a climb or descent.
- When the pressure differential stabilizes at a definite ratio, the needle indicates the rate of altitude change.
- **The VSI displays two different types of information:**
  - Trend information shows an immediate indication of an increase or decrease in the aircraft’s rate of climb or descent.
  - Rate information shows a stabilized rate of change in altitude.

Airspeed Indicator (ASI)

- The ASI is a sensitive, differential pressure gauge which measures and promptly indicates the difference between pitot (impact/dynamic pressure) and static pressure.
- These two pressures are equal when the aircraft is parked on the ground in calm air.
- When the aircraft moves through the air, the pressure on the pitot line becomes greater than the pressure in the static lines.
- This difference in pressure is registered by the airspeed pointer on the face of the instrument, which is calibrated in miles per hour, knots (nautical miles per hour), or both.

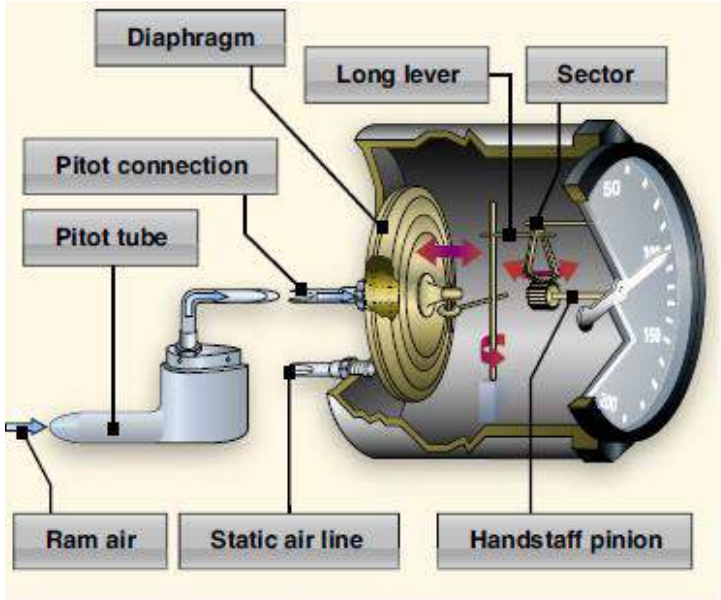

Figure 7-7. *Airspeed indicator (ASI).*

- When the pressure differential stabilizes at a definite ratio, the needle indicates the rate of altitude change.

https://youtu.be/lyyc_CurfUs

The VSI displays two different types of information:

• Trend information shows an immediate indication of an increase or decrease in the aircraft’s rate of climb or descent.

• Rate information shows a stabilized rate of change in altitude.

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- **Indicated airspeed (IAS)—**the direct instrument reading obtained from the ASI, uncorrected for variations in atmospheric density, installation error, or instrument error. Manufacturers use this airspeed as the basis for determining aircraft performance. Takeoff, landing, and stall speeds listed in the AFM/ POH are IAS and do not normally vary with altitude or temperature.

- **Calibrated airspeed (CAS)—**IAS corrected for installation error and instrument error. Although manufacturers attempt to keep airspeed errors to a minimum, it is not possible to eliminate all errors throughout the airspeed operating range. At certain airspeeds and with certain flap settings, the installation and instrument errors may total several knots. This error is generally greatest at low airspeeds. In the cruising and higher airspeed ranges, IAS and CAS are approximately the same. Refer to the airspeed calibration chart to correct for possible airspeed errors.

- **True airspeed (TAS)—**CAS corrected for altitude and nonstandard temperature. Because air density decreases with an increase in altitude, an aircraft has to be flown faster at higher altitudes to cause the same pressure difference between pitot impact pressure and static pressure. Therefore, for a given CAS, TAS increases as altitude increases; or for a given TAS, CAS decreases as altitude increases.

- **Groundspeed (GS)—**the actual speed of the airplane over the ground. It is TAS adjusted for wind. GS decreases with a headwind, and increases with a tailwind.

ASIs on single-engine small aircraft include the following standard color-coded markings:

• **White arc—commonly** referred to as the flap operating range since its lower limit represents the full flap stall speed and its upper limit provides the maximum flap speed. Approaches and landings are usually flown at speeds within the white arc.

• **Lower limit of white arc (VS0)—**the stalling speed or the minimum steady flight speed in the landing configuration. In small aircraft, this is the power-off stall speed at the maximum landing weight in the landing configuration (gear and flaps down).

• **Upper limit of the white arc (VFE)—**the maximum speed with the flaps extended.

• **Green arc—the** normal operating range of the aircraft. Most flying occurs within this range.

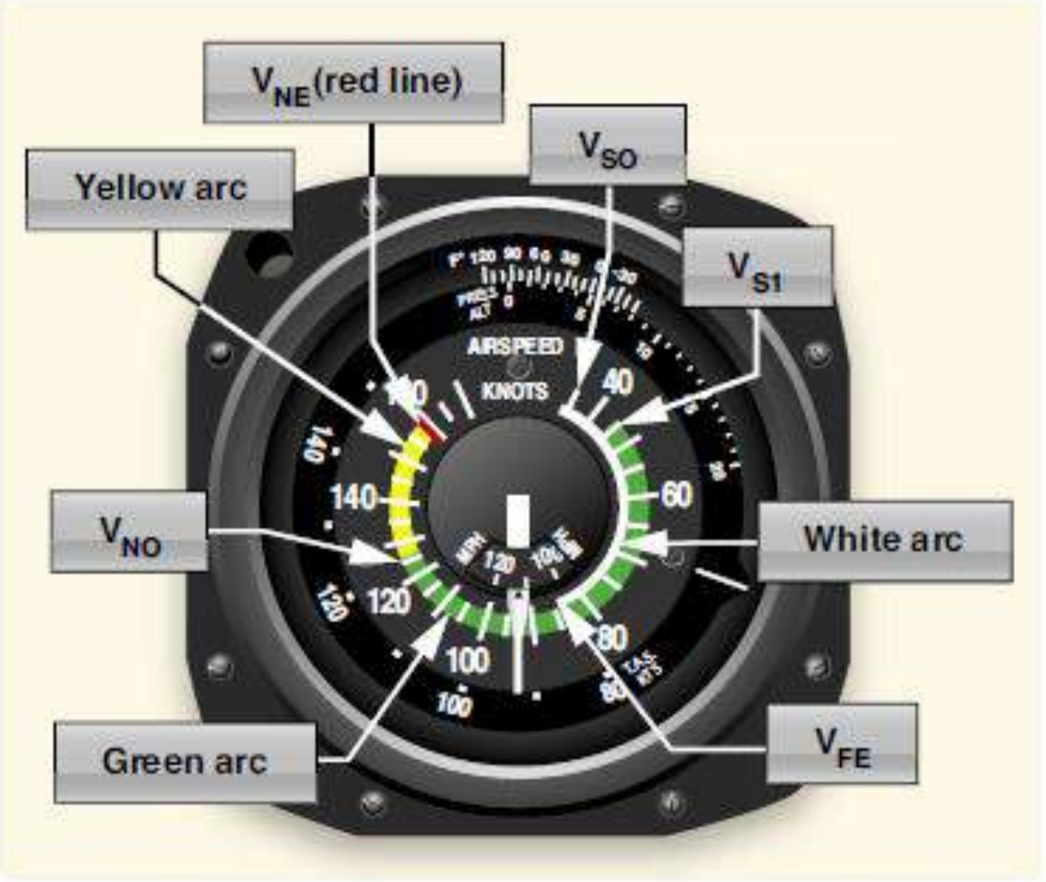


Figure 7-8. *Airspeed indicator (ASI).*

Airspeed Indicator Markings

- Aircraft weighing 12,500 pounds or less, manufactured after 1945, and certificated by the FAA, are required to have ASIs marked in accordance with a **standard color-coded marking system.**

- **This system of color-coded markings enables a pilot to determine at a glance certain airspeed limitations that are important to the safe operation of the aircraft.**

- For example, if during the **execution of a maneuver, it is noted that the airspeed needle is in the yellow arc and rapidly approaching the red line**, the immediate reaction should be to reduce airspeed.

• **Lower limit of green arc (VS1)—**the stalling speed or the minimum steady flight speed obtained in a specified configuration. For most aircraft, this is the power-off stall speed at the maximum takeoff weight in the clean configuration (gear up, if retractable, and flaps up).

• **Upper limit of green arc (VNO)—**the maximum structural cruising speed. Do not exceed this speed except in smooth air.

• **Yellow arc—caution** range. Fly within this range only in smooth air, and then, only with caution.

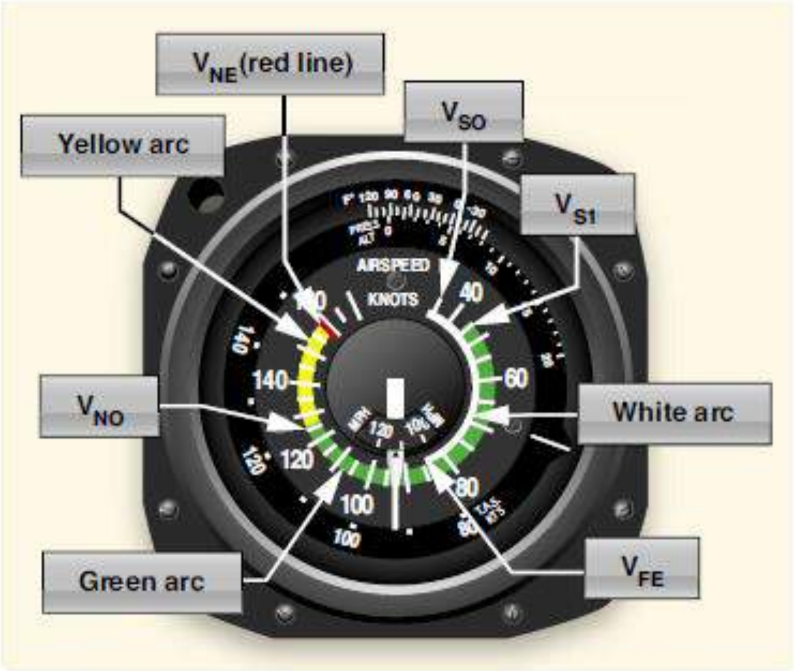


Figure 7-8. *Airspeed indicator (ASI).*

Other Airspeed Limitations

Some important airspeed limitations are not marked on the face of the ASI, but are found on placards and in the AFM/POH.

These airspeeds include:

• **Design maneuvering speed (VA)—**the maximum speed at which the **structural design's limit load can be imposed (either by gusts or full deflection of the control surfaces) without causing structural damage.** It is important to consider weight when referencing this speed. For example, VA may be 100 knots when an airplane is heavily loaded, but only 90 knots when the load is light.

• **Landing gear operating speed (VLO)—**the maximum speed for extending or retracting the landing gear if flying an aircraft with retractable landing gear.

• **Landing gear extended speed (VLE)—**the maximum speed at which an aircraft can be safely flown with the landing gear extended.

• **Best angle-of-climb speed (VX)—**the airspeed at which an aircraft gains the greatest amount of altitude in a given distance. It is used during a **short-field takeoff to clear an obstacle**.

- **Best rate-of-climb speed (VY)—**the airspeed that provides the most altitude gain in a given period of time.

- **Single-engine best rate-of-climb (VYSE)—**the best rate-of-climb or minimum rate-of-sink in a light twin-engine aircraft with one engine inoperative. It is marked on the ASI with a blue line. VYSE is commonly referred to as “Blue Line.”

- **Minimum control speed (VMC)—**the minimum flight speed at which a light, twin-engine aircraft can be satisfactorily controlled when an engine suddenly becomes inoperative and the remaining engine is at takeoff power.


Attitude Indicator
Slip Skid Indicator
Altimeter
Vertical Speed Indicator (VSI)
Air Speed Indicator
Turn Indicator
Horizontal Situation Indicator
Slip/Skid Indicator
Turn Rate Indicator Tick Marks
Turn Rate Trend Vector

Pressure Altitude

- The static pressure can be computed at suitable increments of altitude from −914.4 m (−3,000 ft) to 32,004 m (105,000 ft approx.) and the data stored in a table look-up store using the appropriate formulae relating static pressure and altitude.

(a) Troposphere −914 m to 11,000 m (−3,000 ft to 36,089 ft)

$$P_S = 1{,}013.25(1 - 2.25577 \times 10^{-5} H_P)^{5.255879}$$

(b) Stratosphere 11,000 m to 20,000 m (36,089 ft to 65,617 ft)

$$P_S = 226.32\, e^{-1.576885 \times 10^{-4}(H_P - 11{,}000)}$$

(c) Chemosphere 20,000 m to 32,000 m (65,617 ft to 105,000 ft)

$$P_S = 54.7482[1 + 4.61574 \times 10^{-6}(H_P - 20{,}000)]^{-34.163215}$$

Vertical Speed, dH_P/dt

- The vertical speed or rate of change of altitude, dH_P/dt, is derived from the rate of change of static pressure, dP_s/dt, using the basic formulae relating the differentials dH and dP_S in equation (7.3), viz.

$$-\frac{dp}{P} = \frac{g}{R_a T} dH \tag{7.3}$$

$$dH = -\frac{R_a T}{g_0} \frac{1}{P_s} dP_S$$

$$\dot{H}_P = -\frac{R_a T_S}{g_0} \frac{1}{P_S} \dot{P}_S$$

  - This can be computed from the actual measured and corrected air temperature value or from the standard atmosphere temperature. The latter is the usual case so that H_P is purely a function of P_S.

(a) Troposphere

$$\dot{H}_P = 8434.51(1 - 2.25577 \times 10^{-5} H_P)\frac{1}{P_S}\dot{P}_S$$

(b) Stratosphere

$$\dot{H}_P = 6341.62\frac{1}{P_S}\dot{P}_S$$

- **Mach number:-**The pressure ratio, P_T / P_S , can be computed at suitable increments of Mach number and the results stored in a table look-up store using the appropriate formulae.

(a) Subsonic speeds

$$\frac{P_T}{P_S} = (1 + 0.2M^2)^{3.5}$$

(b) Supersonic speeds

$$\frac{P_T}{P_S} = \frac{166.92M^2}{(7M^2 - 1)^{2.5}}$$

- ***Calibrated Airspeed***
- The impact pressure, Q_C, can be computed at suitable increments over the range of calibrated airspeeds, say 25 m/s (50 knots) to 400 m/s (800 knots) and the results stored in a table look-up store using the appropriate formulae.

(a) $V_C \leq 340.3$ m/s (661.5 knots)

$$Q_C = 101.325\left[1 + 0.2\left(\frac{V_C}{340.294}\right)^{3.5} - 1\right]\mathrm{kN/m^2}$$

(b) $V_C \geq 340.3$ m/s (661.5 knots)

$$Q_C = 101.325\left[\frac{166.92\left(\frac{V_C}{340.294}\right)^7}{\left[7\left(\frac{V_C}{340.294}\right)^2 - 1\right]^{2.5}} - 1\right]$$

Static Air Temperature

The static air temperature, T_S, is derived by computing the correction factor $1/(1 + r0.2\ M^2)$ and multiplying the measured (indicated) air temperature, T_m, by this correction factor, viz.

$$T_S = \frac{T_m}{(1 + r0.2M^2)}$$

True Airspeed

The true airspeed, V_T, is derived from the computed Mach number and the computed static air temperature, T_S, viz.

$$V_T = 20.0468\ M\sqrt{T_S}$$

7.3.3 *Air Density versus Altitude Relationship*

The relationship between air density, ρ, and altitude, H, is derived from the equation relating P_S and H and using the gas law

$$P_S = \rho R_a T$$

to eliminate P_S.

For example, in the troposphere

$$P_S = P_{S0}\left(1 - \frac{L}{T_0}H\right)^{g_0/LR_a}$$

$T = T_0 - LH$. Hence

$$\frac{\rho}{\rho_0} = \left(1 - \frac{L}{T_0}H\right)^{(g_0/LR_a)-1} \tag{7.14}$$

where ρ_0 is the density at standard sea level conditions $= P_{S0}/R_aT_0$. The ratio ρ/ρ_0 is referred to as the *density reduction factor*.

7.4.2.2 Pressure Sensor Technology

Two basic types of pressure sensor have now become well established in modern digital air data systems. Although there are other types of pressure sensor in service, attention has been concentrated on these two types as they account for most of the modern systems. The two main types can be divided into:

(a) Vibrating pressure sensors.
(b) Solid state capsule pressure sensors.

(a) *Vibrating pressure sensors*
The basic concept of this family of sensors is to sense the input pressure by the change it produces in the natural resonant frequency of a vibrating mechanical system.

The output of the sensor is thus a frequency which is directly related to the pressure being measured. This frequency can be easily measured digitally with very high resolution and accuracy without the need for precision analogue to digital conversion circuitry. This confers a significant advantage as it enables a very simple and very accurate interface to be achieved with a micro-processor for the subsequent air data computation.

The vibrating cylinder sensor is shown schematically in Figure 7.10. The pressure sensing element consists of a thin walled cylinder with the input pressure acting on the inside of the cylinder and with the outside at zero vacuum reference pressure. The cylinder is maintained in a hoop mode of vibration by making it part of a feedback oscillator by sensing the cylinder wall displacement, processing and amplifying the signal and feeding it back to a suitable force producing device. Electromagnetic drive and pick-off coils are used so that there is no contact with the vibrating cylinder.

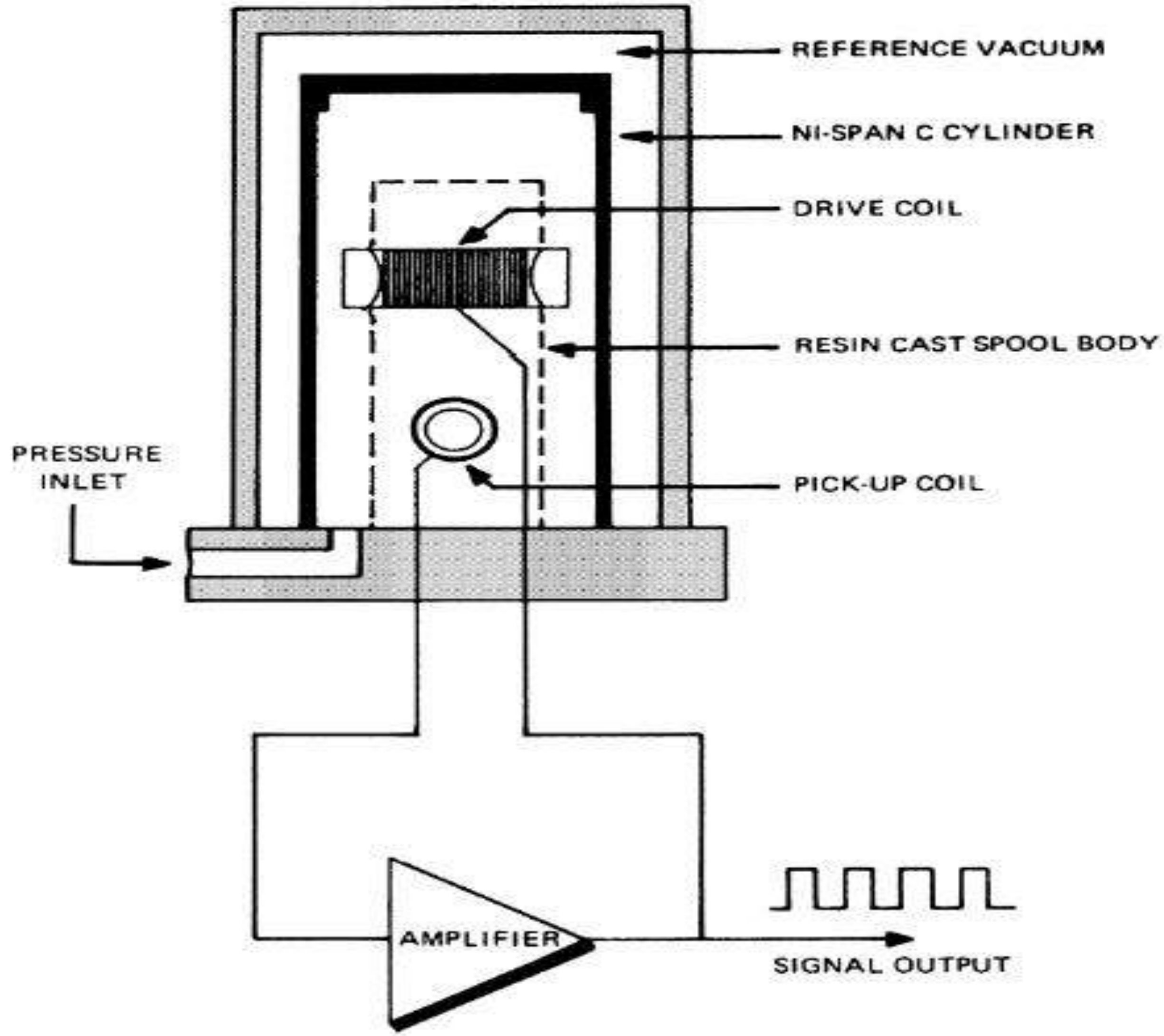
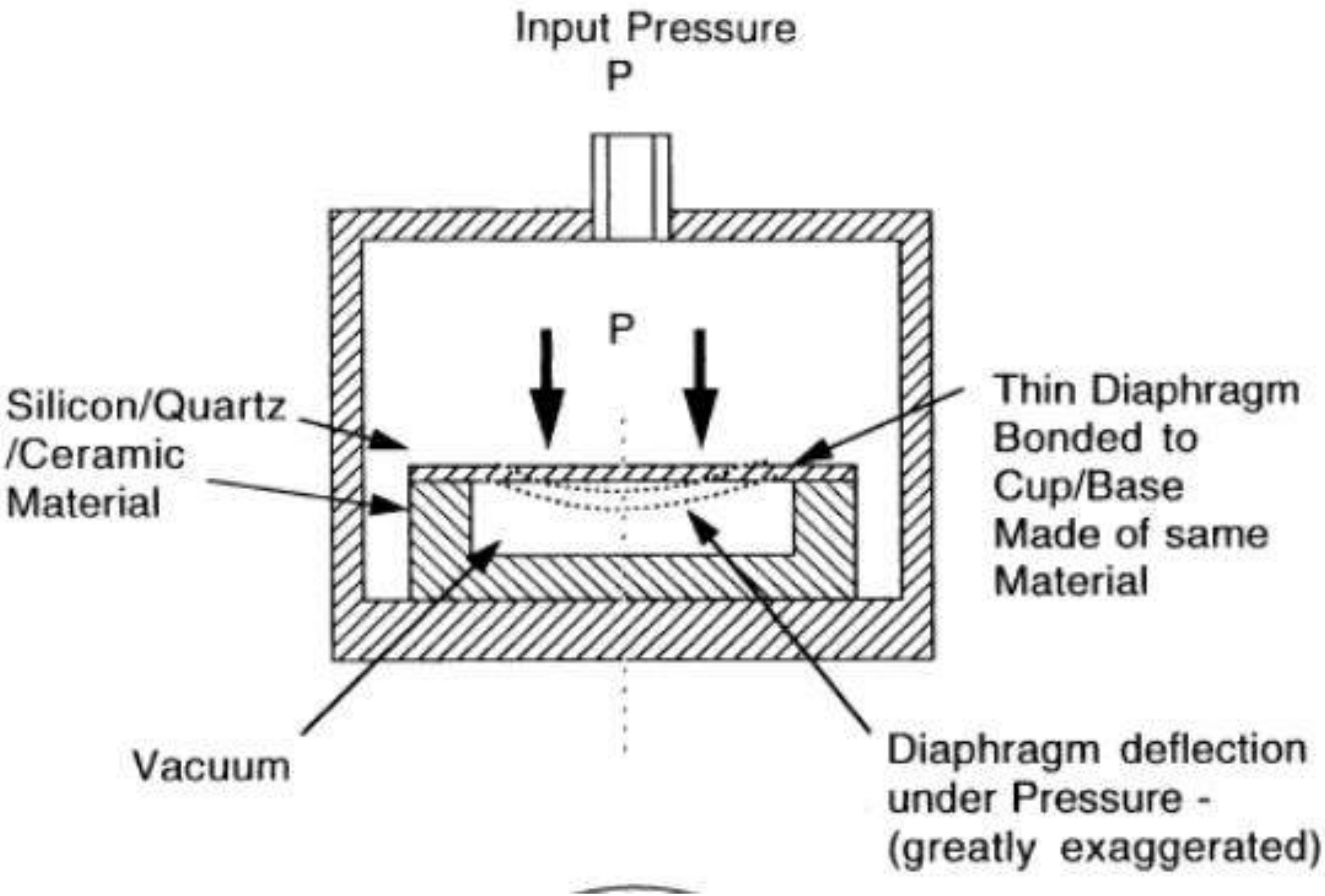


Fig. 7.10 Vibrating pressure sensor schematic (by courtesy of Schlumberger Industries).

(b) *Solid state capsule pressure sensors*

This type of pressure sensor consists essentially of a capsule with a relatively thin diaphragm which deflects under the input pressure. They are fabricated from materials such as silicon, quartz, fused silica, or special ceramics. Figure 7.12 illustrates the basic construction. These materials exhibit virtually 'perfect mechanical properties' with negligible hysteresis and very stable and highly linear stress/strain characteristics. The modulus of elasticity variation with temperature is very stable and can be readily compensated by measuring the sensor temperature.



Input Pressure
P
P
Silicon/Quartz
/Ceramic
Material
Thin Diaphragm
Bonded to
Cup/Base
Made of same
Material
Vacuum
Diaphragm deflection
under Pressure -
(greatly exaggerated)

The deflection of the solid state capsule under pressure is typically only 25 to 50 μm full scale, or less. The techniques which have been adopted to measure this very small deflection are briefly described below.

(i) *Integral strain gauges*. Piezo-resistive networks (or bridges) are ion implanted at the edge of a thin silicon diaphragm. Application of pressure causes the diaphragm to deflect thereby deforming the crystal lattice structure of the silicon which in turn causes the resistance of the piezo-resistive elements to change. The piezo-resistive elements are connected in a Wheatstone's bridge configuration as shown in Figure 7.13 with two opposite resistive elements of the bridge located radially and the other two located tangentially on the diaphragm. The applied input pressure causes the resistance of the radial elements to decrease and the tangential elements to increase, or vice versa, depending whether the pressure is increasing or decreasing and so unbalances the Wheatstone's bridge. The output of the bridge is proportional to both pressure and temperature as the modulus of elasticity of silicon is temperature dependent. A temperature sensitive resistive element is therefore incorporated into the diaphragm to measure the temperature so that the temperature dependent errors can be corrected in the subsequent processing of the sensor output.

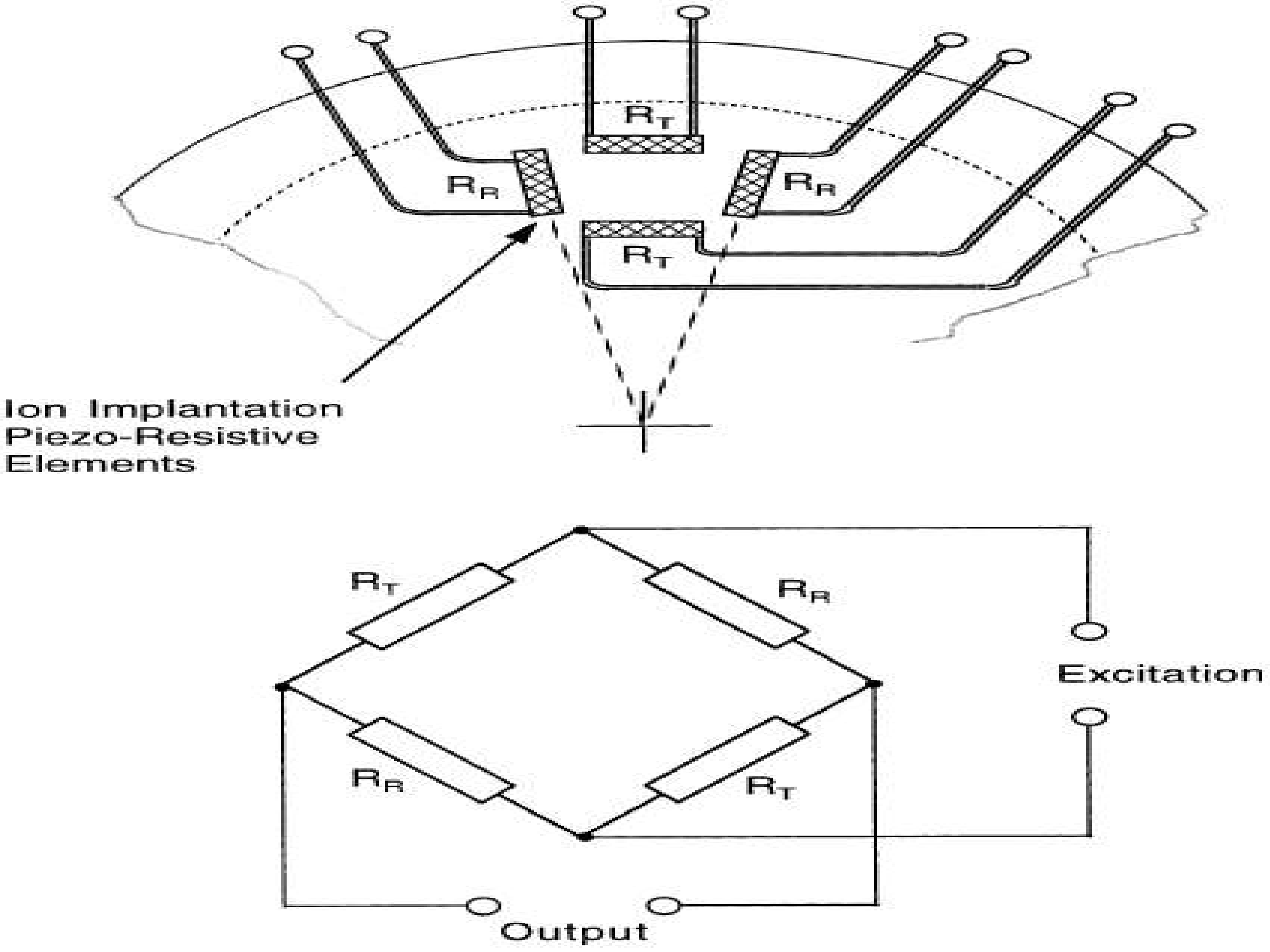


Fig. 7.13 Strain gauge configuration.

(ii) *Capacitive pick off*. An alternative technique is to deposit a metallic film on an area at the centre of the diaphragm to form a capacitive element (or 'pick-off') whose capacitance changes as the diaphragm deflects under pressure. This forms part of a capacitance bridge network. Figure 7.14 shows the device construction. A correctly designed capacitive pick off bridge combination can have extremely high resolution and can detect the incredibly small changes in capacitance resulting from minute deflections of the diaphragm. (It is noteworthy that the highest resolution yet

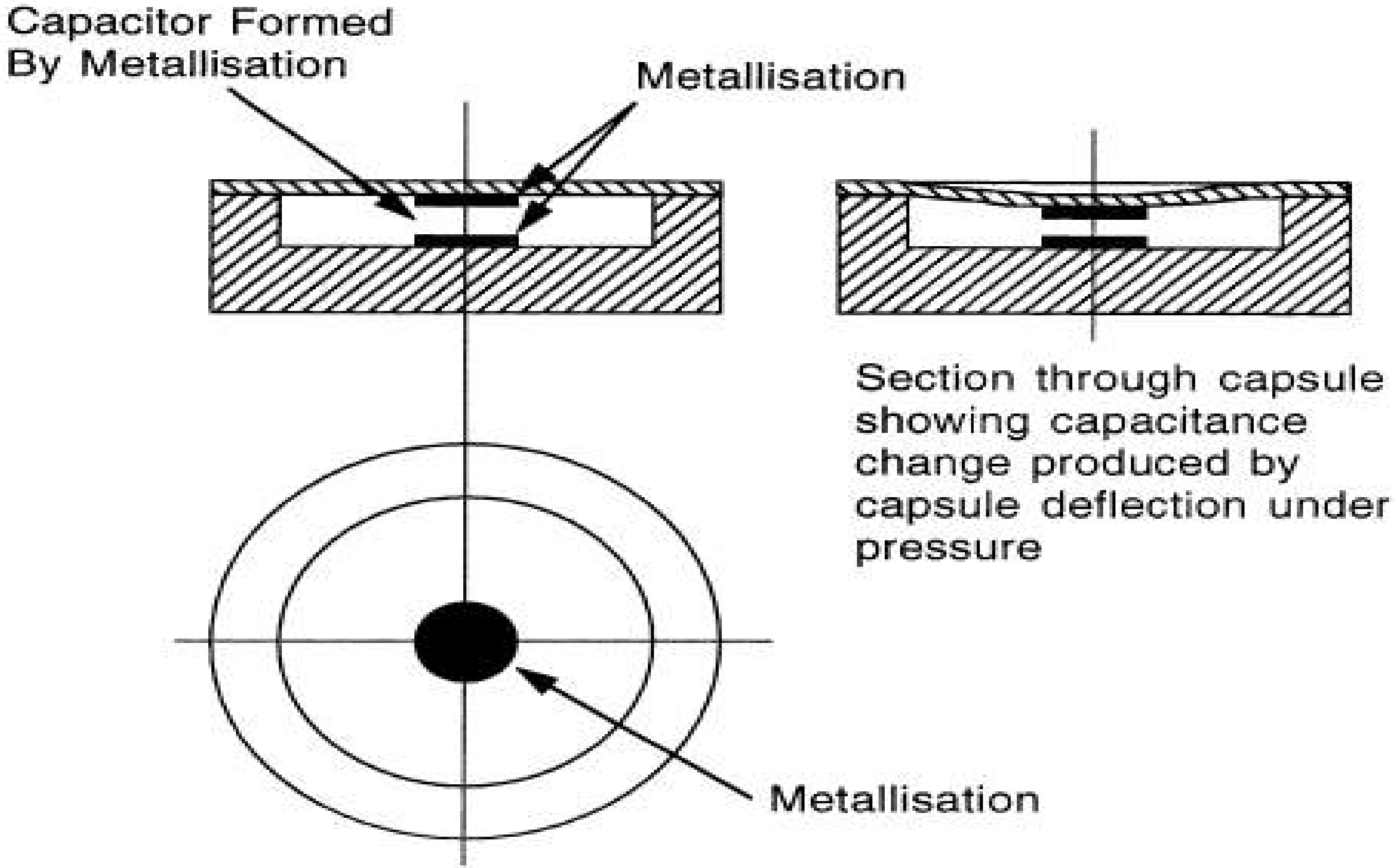


Fig. 7.14 Capacitance pick-off.

THANK YOU