

PITOT AND STATIC PRESSURE ERRORS IN STEADY LEVEL FLIGHT

1. NOTATION, UNITS, PRESSURE DEFINITIONS, CONSTANTS AND CONVERSION FACTORS

Numerical expressions are given in non-dimensional form so that correct results are obtained with any consistent set of units.

1.1 Notation and Units

		SI	British
a	speed of sound	m/s, kn	ft/s, kn
b	half-width of fuselage at pitot-probe station	m	ft
C_f	local skin friction coefficient		
C_p	pressure coefficient on fuselage, $\frac{p_{fus} - p_a}{\frac{1}{2}\gamma p_a M^2}$		
C_{cr}	Chapman-Rubesin viscosity coefficient		
c	half-height of fuselage at pitot-probe station	m	ft
d	diameter of static sensor port	m	ft
f	denotes functional relationship of type $f[\dots]$		
f_p	calibration factor for pitot probe, see Equation (4.1)		
f_{s_1}, f_{s_2}	boundary layer state factors, see Equation (5.7)		
l	length appropriate to boundary-layer growth at static sensor port station; used in defining Reynolds number	m	ft
M	Mach number, V/a		
M_{con}	Mach number outside boundary on conical surface at static sensor port station		
M_{local}	Mach number outside boundary layer at pitot-probe station		
M'	Mach number obtained after correcting for non-steady flight effects (based on p_p' and p_s , see Equations (6.1a) and (6.1b))		
p_a	ambient static pressure*	N/m ² , mb	lbf/ft ²
p_{con}	static pressure on conical surface at static sensor port station*	N/m ² , mb	lbf/ft ²

For footnotes see end of Notation.

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p_{fus}	static pressure on fuselage surface at static sensor port station*	N/m ² , mb	lbf/ft ²
p_{local}	static pressure on fuselage at pitot-probe station*	N/m ² , mb	lbf/ft ²
p_p	fully corrected value of pitot (absolute) pressure in pitot system in steady-level-flight conditions	N/m ² , mb	lbf/ft ²
p_p'	sensed pitot (absolute) pressure in steady-level-flight conditions (alternatively, value obtained after correction for any effects of non-steady flight, see Reference 22)	N/m ² , mb	lbf/ft ²
p_{p_i}	value of pitot pressure* registered (indicated) by transducer (note for steady level flight, $p_{p_i} = p_p'$)	N/m ² , mb	lbf/ft ²
$p_{p_{local}}$	sensed pitot (absolute) pressure for pitot probe within airframe flow field (used in Section 4 only)	N/m ² , mb	lbf/ft ²
p_s	sensed static (absolute) pressure in static system in steady-level-flight conditions	N/m ² , mb	lbf/ft ²
p_{s_i}	value of static pressure* registered (indicated) by transducer (note for steady level flight, $p_{s_i} = p_s$)	N/m ² , mb	lbf/ft ²
q_c'	impact pressure for steady-level-flight conditions ($q_c' = p_p' - p_s$)	N/m ² , mb	lbf/ft ²
Re	Reynolds number based on freestream conditions and length, l , appropriate to boundary layer growth at static sensor port station		
Re'/l	Reynolds number per unit length, using M' and p_s	1/m	1/ft
r	radius of static-probe body at static sensor port	m	ft
s	depth of static-sensor port	m	ft
T_a	ambient temperature	K	K
x	co-ordinate in x -direction, <i>i.e.</i> fuselage longitudinal datum or body axis (Sketch 1.1 shows positive directions)	m	ft
V	true airspeed [†] (resultant aircraft velocity with respect to air)	m/s, kn	ft/s, kn
V_i	indicated airspeed [†]	m/s, kn	ft/s, kn
v_{local}	velocity outside boundary layer of airflow [†] component parallel to surface of fuselage cross section at pitot-probe station (in absence of airframe interference, $v_{local} = -V \sin \alpha_{fus} \cos \beta$)	m/s, kn	ft/s, kn

For footnotes see end of Notation.

α	angle of attack (angle between projection of true airspeed vector on to aircraft plane of symmetry and angle of attack datum, see Sketch 1.1)	deg	deg
α_{fus}	local angle of attack of fuselage, allowing for effects of downwash and local changes in fuselage datum setting	deg	deg
α_p	local angle of attack of pitot or pitot-static probe	deg	deg
β	angle of sideslip (angle between true airspeed vector and its projection on to aircraft plane of symmetry), positive when starboard wing leads	deg	deg
β_{fus}	local angle of sideslip of fuselage	deg	deg
β_p	angle of sideslip of pitot probe	deg	deg
γ	ratio of specific heat capacities of air		
$\Delta C_{p\omega_{fus}}$	increment in pressure coefficient due to incidence ω_{fus} , $\frac{p_{fus} - [p_{fus}]_{\omega_{fus}=0}}{\frac{1}{2} \gamma p_a M^2}$		
Δp_a	correction for static-pressure error ($\Delta p_a = -\delta p_s = p_a - p_s$)	N/m ² , mb	lbf/ft ²
δ^*	displacement thickness of boundary layer at static sensor port	m	ft
δ_{con}	semi-vertex angle of conical surface in which static sensor ports are installed (probe or body)	deg	deg
δ_{fus}	angle of tangent to fuselage surface measured from x body axis in a plane containing that axis (semi-vertex angle for conical body)	deg	deg
δp	contribution to pressure error in a pressure system, ($\delta p_p = (p_p' - p_p)$ and $\delta p_s = (p_s - p_a)$)	N/m ² , mb	lbf/ft ²
ϵ	angle of downwash	deg	deg
ϵ_p	downwash angle at pitot probe	deg	deg
θ	inclination angle, i.e. pitch attitude of fuselage datum to horizontal plane, see Sketch 1.1	deg	deg
θ_{fus}	setting of fuselage longitudinal datum (x body axis at aircraft c.g.) relative to angle of attack datum, see Sketch 1.1	deg	deg
θ_p	pitot-pressure-probe setting angle measured relative to angle of attack datum in aircraft plane of symmetry	deg	deg

For footnotes see end of Notation.

λ	cross-flow velocity factor, see Appendix A		
$\Sigma(\delta p)$	summation of errors in a pressure system for a specified flight condition	N/m ² , mb	lbf/ft ²
ϕ	angle in plane of fuselage cross section between radial line from x body axis and aircraft plane of symmetry, $\phi = 0$ is at bottom centre line, see Sketch 1.2	deg	deg
ϕ_r	value of ϕ defining position of dividing streamline on fuselage (for $\beta = 0$, $\phi_r = 0$), see Sketch 1.2	deg	deg
χ_{mod}	modified viscous-interaction parameter, see Section 5.4		
ω_{fus}	angle of incident flow to fuselage longitudinal datum, measured in plane containing that datum, at point of intersection of fuselage and dividing streamline, see Sketches 1.1 and 1.2	deg	deg
ω_{local}	angle of incident flow relative to pitot probe mounted with its axis parallel to body datum (in absence of airframe interference, $\omega_{local} = \omega_{fus}$)	deg	deg
ω_p	resultant angle in incident flow at pitot-pressure probe	deg	deg
$\omega_{p_{crit}}$	critical angle of incident flow beyond which there is significant error in sensed pitot pressure	deg	deg
$ $	absolute value of enclosed parameter		

Superscript

'	denotes sensed value in steady level flight (alternatively, denotes value obtained after correction for any effects of non-steady flight, see Reference 22)
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Subscripts

$hole$	denotes static-pressure error due to port geometry
i	initial value of a parameter, usually a registered value, that is subject to corrections to arrive at a true value
lam	denotes laminar boundary-layer conditions
p	denotes pitot probe or pitot-pressure system
pe	denotes pressure error due to position of pitot probe
s	denotes static-pressure system
sf	denotes steady-level-flight conditions

For footnotes see end of Notation.

<i>turb</i>	denotes turbulent boundary-layer conditions
ω	denotes pressure error due to incident flow angle
<i>xmh</i>	denotes extreme conditions of Mach number or height
0	denotes conditions at sea-level in International Standard Atmosphere, ISA

* Note that these pressures are absolute.

† Note v_{local} is defined as airflow relative to static airframe, *i.e.* in contrast to V and V_i which are airframe velocities relative to air.

1.2 Definitions of Sensed and Indicated (Registered) Pressures

“Indicated” or “registered” values of pitot and static pressures are those provided by transducers (instruments) which have been corrected for any calibration or other inherent errors. Each transducer (instrument) responds to the sensed, or output, pressure of the pitot or static pressure system. In steady level flight there are no non-steady flight errors to allow for, so that the sensed pressures are identical to the indicated (registered) pressures. This distinction in pressure definitions is used for consistency with Item Nos 83029, 85011 and 85036 (References 21 to 23).

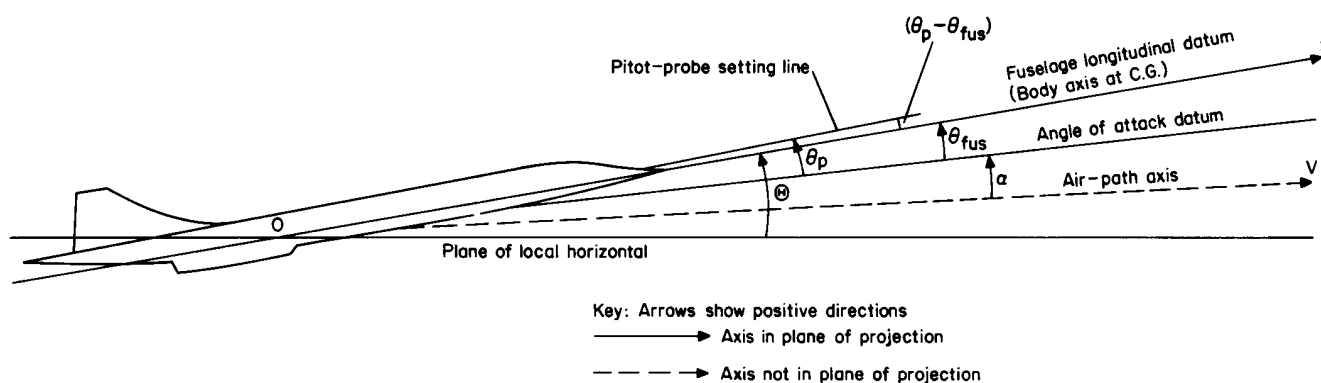
1.3 Constants and Conversion Factors

Constants

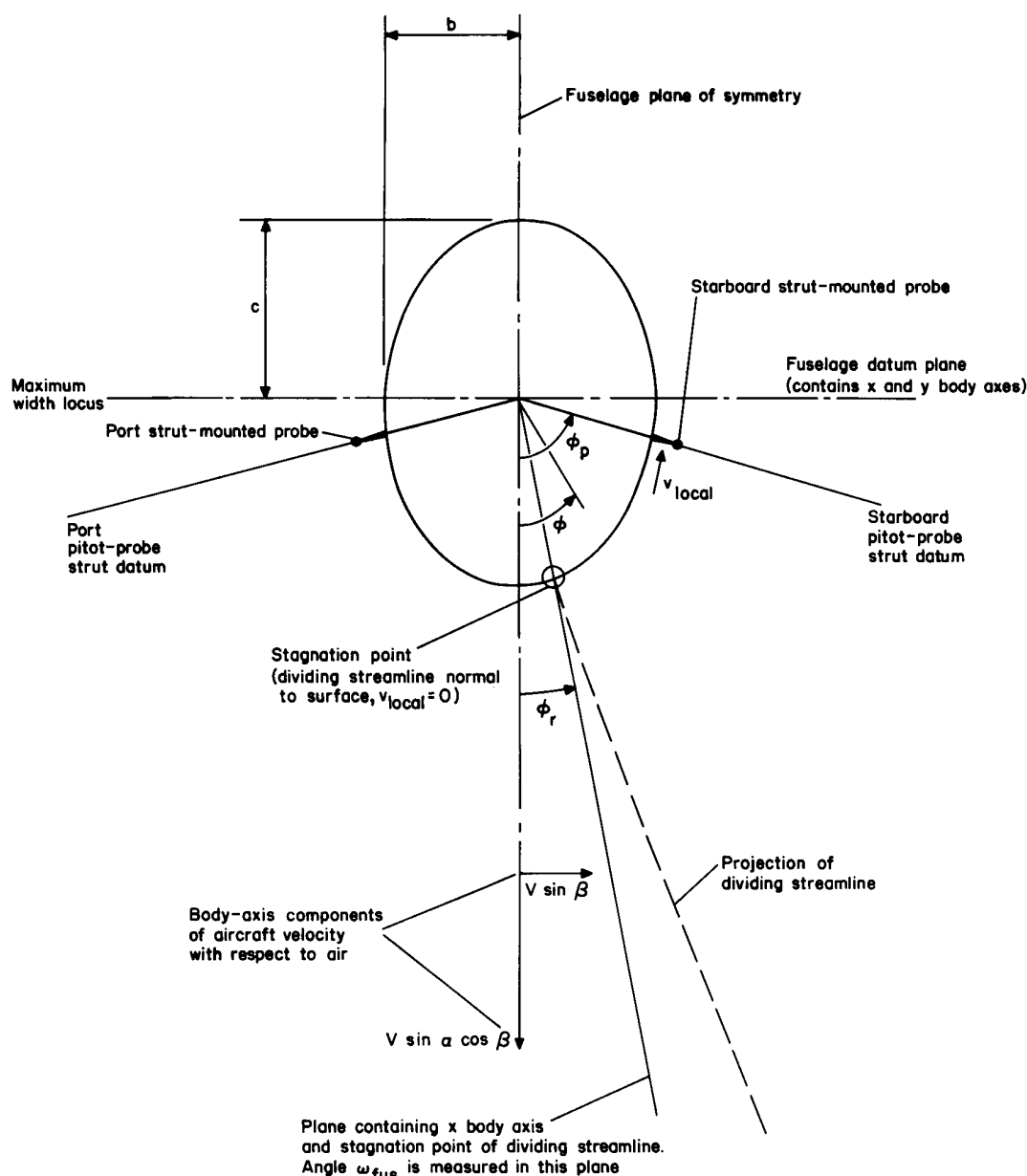
a_o	340.294 m/s 1116.45 ft/s 661.479 kn
P_{a0}	101 325 N/m ² , 1013.25 mb, 2116.22 lbf/ft ²
γ	1.4

Exact conversion factors used or implied

$$1 \text{ ft} = 0.3048 \text{ m}, \quad 1 \text{ n. mile} = 1852 \text{ m}, \quad 1 \text{ bar} = 10^5 \text{ N/m}^2$$



Sketch 1.1 Angle and axis definitions in aircraft plane of symmetry (unbanked flight)



Sketch 1.2 Angle definitions in plane of fuselage cross section (view looking forward)

2. INTRODUCTION

The air data system pressures sensed in steady level flight, *i.e.* pitot pressure, p_p' , and static pressure, p_s , are subject to errors. This Data Item considers, in turn, all likely contributions to these pressure errors and the implications of the various tests needed to determine the errors for steady-level-flight conditions. Examples are included of the magnitudes of the various contributions to error for typical installations and, where appropriate, estimation methods are given for particular effects. The Item is applicable for speeds up to $M \approx 2.0$, when total temperature exceeds 400 K. Beyond these limits, γ may be assumed constant no longer and further effects must be considered (see References 21 and 27).

For non-steady flight conditions, for example climb or descent, air-data-system pressures must first be corrected to derive equivalent steady-level-flight values. This should be done using the method of Item No. 85011 (Reference 22) to derive the non-steady errors themselves and the procedures of Item No. 83029 and/or No. 85036 (References 21 and 23).

Note, in particular, that Item No. 83029 deals with the overall process of allowing for all sources of errors in flight-analysis work and attention is drawn there to the importance of identifying and dealing in proper sequence with all significant errors in pressure sensing. The ultimate objective of this process is the derivation of true values of height, Mach number and calibrated airspeed.

Section 3 provides geometric definitions of axes and angles and reviews matters of general application to the Item.

Section 4 considers errors encountered by pitot-pressure sensors. These errors are usually small or negligible except,

- (i) in certain cases when aircraft angle of attack is not small and probe incidence angles may be large,
- (ii) at speeds above $M \approx 1.3$, for pitot probes mounted in positions other than at the nose, and where evidence suggests that aircraft flow-field effects may be significant.

Section 5 is concerned primarily with the static pressure error that is obtained for each aircraft (or aircraft type, as appropriate, to the analysis work) by in-flight calibrations. In many cases the main cause of static pressure error is aircraft flow-field interference. However, other considerations can be of importance and are also discussed, namely:

- (i) sensitivity of some static probes at supersonic speeds to Reynolds number and boundary-layer transition effects,
- (ii) effects of sensor orifice geometry on static pressure for both laminar and turbulent boundary layer conditions.

Section 6 summarises the errors dealt with in Sections 4 and 5 and indicates how they are combined and used in deriving true values of pitot and ambient pressures.

Section 8 gives an example problem involving both pitot and static pressure errors.

3. GEOMETRIC DEFINITIONS AND GENERAL MATTERS

3.1 Definitions of Angles and Axes

The angles and axes used in this Item are shown in Sketches 1.1 and 1.2.

The axes and setting lines shown in Sketch 1.1 are defined as follows:

- (i) **The air-path axis** is directed along the aircraft true airspeed vector, V , and so lies in the aircraft plane of symmetry only when sideslip angle, β , is zero.
- (ii) **The angle of attack datum** is defined in the aircraft plane of symmetry. It is taken here as the aircraft zero-lift line for the given configuration (flap setting, centre of gravity position, *etc*) and Mach number and, for some aircraft, may vary with height.
- (iii) **The fuselage longitudinal datum** is defined in the aircraft plane of symmetry and in this Item is identical with the aircraft "x" body axis. It is the datum to which pitch attitude angle, θ , is measured and is set at angle θ_{fus} to the angle of attack datum.

- (iv) The pitot-probe setting line is defined in the aircraft plane of symmetry and lies at angle θ_p to the angle of attack datum and hence at angle $(\theta_p - \theta_{fus})$ to the fuselage longitudinal datum.

Note that pitot probe setting angle, θ_p , may be affected by airframe aeroelastic properties and may therefore change under the influence of gravitational, aerodynamic and inertial forces (see Section 3.7 of Reference 15).

The axes and setting lines in Sketch 1.2 are defined as follows:

- (i) **the pitot-probe strut datum** is set at angle $\phi = \phi_p$, where ϕ is the angle, positive to starboard, measured from the bottom of the fuselage on the centre line ($-180 \leq \phi \leq 180$ degrees),
- (ii) **the fuselage maximum width locus** is shown lying in the fuselage datum plane (this is a usual, but not invariable practice).

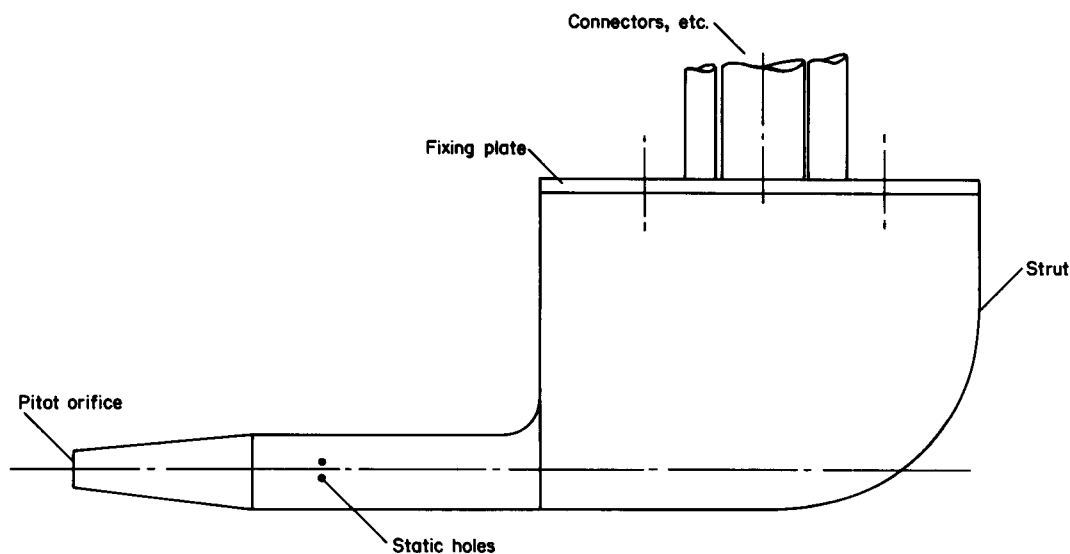
3.2 Pressure Sensors and their Positioning

These topics are dealt with briefly here; see Reference 16 for a more comprehensive discussion. For consideration of design tolerances and aerodynamic accuracy of pitot and static probes see, for example, Reference 2.

Sketches 3.1 and 3.2 show typical pitot-static probes although similar configurations may also be used to carry only pitot or static sensor ports.

3.2.1 Pitot-pressure sensors

A pitot-pressure sensor (or “pitot probe”, or “pitot tube”, or “total-pressure head”) is, in principle, a tube having its forward end open so that stagnation pressure of the airflow may be sensed. Provided that the tube is aligned approximately with the local airflow there is generally no error in sensing (but see Section 4). In practice, a pitot tube may be positioned almost anywhere relative to the airframe, provided it is outside any boundary layer or wake and provided it is not within a jet efflux or slipstream from a powerplant.



Sketch 3.1 Strut-mounted pitot-static probe

3.2.2 Static-pressure sensors

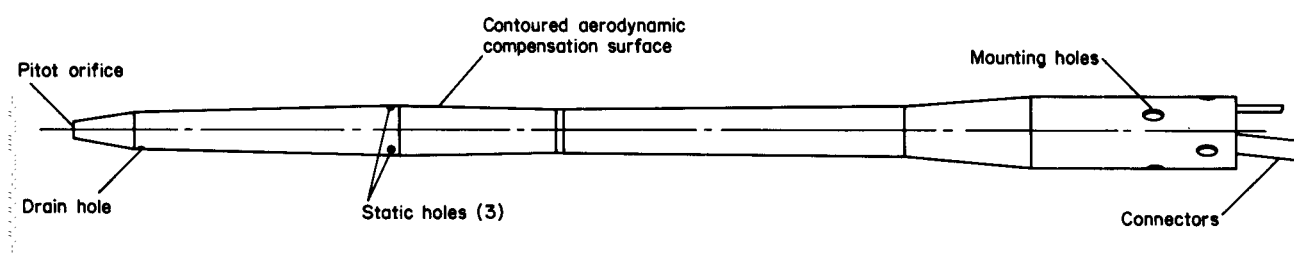
Static plate (static vent): A static pressure orifice is incorporated into a purpose-built plate, which is mounted on, or forms part of, the airframe surface. Static plates are usually restricted to the aircraft fuselage and are located where the static pressure is close to ambient pressure or where there is a small variation only of static pressure with changes in Mach number, incident flow angle and aircraft configuration.

Static probe: A static-pressure probe is usually combined with a pitot tube in the form of a pitot-static probe, see Sketches 3.1 and 3.2. The static ports are disposed around the probe circumference so as to minimise the effect of non-axial flow incidence. The probe surface may also be shaped, as indicated in Sketch 3.2, so that the pressure distribution arising from the shaping compensates for the aircraft pressure field (see Reference 16).

Typical locations for a pitot-static probe are:

- (i) boom-mounted forward of the nose of an aircraft,
- (ii) strut-mounted on the forebody of an aircraft,
- (iii) boom-mounted forward of a wing or of the leading-edge of a vertical tail of an aircraft.

Location (i) is favoured for flight-test work because flow-field interference at subsonic speeds is minimised and is absent altogether at supersonic speeds.



Sketch 3.2 Nose-boom-mounted compensated pitot-static probe

3.3 Leakage Standards for Pressure Systems

Any significant leak is normally unacceptable. A stringent standard for ground tests, taken from Reference 16, is as follows.

Pitot system: the rate of change of airspeed indication should be less than 1 knot per minute when the pressure in the pitot system is the maximum to be encountered by the aircraft.

Static system: the rate of change of altimeter reading should be less than 100 ft/min when the pressure in the static system is reduced to that corresponding to the maximum operating altitude of the aircraft.

4. PITOT-PRESSURE ERRORS

4.1 General Considerations

Pitot-pressure probes are relatively accurate as sensors of stagnation pressure* of a moving fluid. Errors occur, however, when the probe incidence angle, ω_p , relative to the local flow exceeds a critical value, $\omega_{p_{crit}}$. Also, at supersonic speeds, for a probe within the flow field of an aircraft, errors may arise from the position of the probe. Errors from these two sources may be determined by flight calibrations using, as a standard, a shielded pitot or a nose probe, respectively – see Reference 20.

The loss of pressure at supersonic speeds due to a normal shock at the probe entry is allowed for in such flight-test analysis methods as those of References 21 and 23.

4.2 Pitot-Pressure Error, $(\delta p_p)_\omega$, for Incidence Angles Greater than $\omega_{p_{crit}}$

Values of the error $(\delta p_p)_\omega$ and the angle $\omega_{p_{crit}}$ are very sensitive to probe geometry and are best obtained from probe manufacturers' data. An appreciation of these quantities may be obtained, however, from References 16 and 17, where $\omega_{p_{crit}}$ for normal configurations is seen to lie between 10 and 20 degrees, and where

$$\frac{(\delta p_p)_\omega}{p_a} = \frac{\gamma}{2} (M')^2 [\cos^2(\omega_p - \omega_{p_{crit}}) - 1] \times f_p. \quad (4.1)$$

In Equation (4.1) the calibration factor, f_p , is generally between† 2 and 7 and is not very sensitive to Mach number. As an example, if $\omega_{p_{crit}}$ is assumed to be 15 degrees and if $f_p = 2$, then the following non-dimensional errors may be computed, noting that M' is a function of p_p' and p_s (see Equations (6.1a) and (6.1b)).

ω_p deg	15	20	25	30	35
$\frac{(\delta p_p)_\omega}{\frac{\gamma}{2} p_a (M')^2}$	0	-0.015	-0.060	-0.134	-0.234

In general the angle of incidence, ω_p , is not equal to the aircraft angle of attack because of the probe setting angle, aircraft flow-field effects and airframe aeroelasticity.

A nose probe, *i.e.* one boom-mounted ahead of the aircraft nose, is least affected by the aircraft flow field. As interference can be a major contributor to angle of incidence, such probes may not be subject to the error $(\delta p_p)_\omega$.

Aircraft which have only one set of air-data instruments, for example some single-seat designs, may have a strut-mounted pitot probe on the aircraft forebody in the plane of symmetry. For this position the value of ω_p can be assumed equal to twice the angle of sideslip. For normal flight conditions, where the angle of sideslip is zero or small, the value of ω_p will not exceed $\omega_{p_{crit}}$.

* At supersonic speeds this includes the loss of pressure due to a normal shock at entry to the probe.

† Lower values can be found in unpublished data.

For cases where pitot probes are strut mounted on the **sides** of a fuselage forebody, large values of probe incidence may be encountered at moderate angles of attack. For example, for a typical strut-mounted probe at the maximum-width locus of a circular fuselage, the methods of this Item* give the following relationships between aircraft angle of attack, probe angle of incidence and pitot-pressure error.

Aircraft angle of attack, α deg	7.5	10	12.5	15
Probe angle of incidence*, ω_p deg	21.5	27	32.5	38
Pressure-error*, $\frac{(\delta p_p)_\omega}{\frac{1}{2} \gamma p_a M^2}$	-0.026	-0.086	-0.181	-0.305

4.3 Derivation of Pitot-Probe Incidence, ω_p

If there is reason to expect that the angle of incidence of airflow at the probe exceeds $\omega_{p_{crit}}$, it is necessary to estimate its value, unless special instrumentation is available to provide measurements. To estimate probe incidence requires a knowledge of probe location and setting angle together with the exchange rate, $d\varepsilon_p/d\alpha$, between the airframe-induced downwash angle at the probe and the aircraft angle of attack. In general, values of ε_p are best obtained from wind-tunnel measurements. Sections 4.3.1 and 4.3.2 give methods of estimating ω_p for probes mounted, respectively, ahead of the aircraft nose and on the fuselage forebody at or near the maximum-width locus.

4.3.1 Estimation of ω_p for nose probe mounted ahead of airframe

The general expression for ω_p is

$$\omega_p = \cos^{-1}[\cos\alpha_p \cos\beta_p]. \quad (4.2)$$

The probe angle of attack, α_p , measured in the aircraft plane of symmetry, is given by

$$\alpha_p = \alpha \left[1 - \frac{d\varepsilon_p}{d\alpha} \right] + \theta_p. \quad (4.3a)$$

For a nose probe mounted ahead of the airframe lifting surfaces, $d\varepsilon_p/d\alpha$ is negative at subsonic speeds. For supersonic Mach numbers such a probe is isolated from any airframe interference so that $d\varepsilon_p/d\alpha$ is zero and Equation (4.3a) simplifies to

$$\alpha_p = \alpha + \theta_p. \quad (4.3b)$$

In sideslip, the induced sidewash at the probe due to airframe interference is usually neglected to give

$$\beta_p \approx \beta. \quad (4.4)$$

* For this example, ω_p is evaluated using Equation (4.13) and assuming a downwash rate $(d\varepsilon_p/d\alpha) = -0.1$, angles $\theta_{fus} = 3$ deg, $\theta_p = 2$ deg and $\beta = 0$. The pressure error is evaluated using Equation (4.1) and assuming $\omega_{p_{crit}} = 15$ deg and $f_p = 2$.