Defence Science Journal, Vol. 52, No. 1, January 2002, pp. 65-71
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SHORT COMMUNICATION

Computation Curves for Air Data System

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ABSTRACT

Air data system of aircraft measures flow variables, primarily to monitor flight safety. The computational fluid dynamics approach to the problems for evaluating air data in a typical combat aircraft flow field is to find suitable sensor locations, to determine residual pressure correction and to compute local flow angularity at the proposed locations of sensors. The functional relationship between local flow angles and free-stream parameters being linear, it can be displayed as charts or nomograms.

Keywords: Flight safety, air data system, combat aircraft, mission critical aerodynamics, sensors, computation curves, flow angularity, local angle of attack, local side slip angle, position error, probe, vanes, pressure coefficient, Euler codes, computational fluid dynamics

1. INTRODUCTION

The function of an air data system (ADS) is to acquire mission critical aerodynamic quantities, such as static pressure, local angle of attack, local side slip angle, indicated air speed, pressure altitude, flight Mach number, static temperature and rate of climb. Air data is required for monitoring flight safety, stall warning, navigating the aircraft through complex manoeuvres, in-flight calibration and research. Figure 1 gives the block diagram of an ADS. Experimental measurement techniques of ADS have been reliable and procedures[1,2] proven for sensor instrumentation and calibration[3]. However, the choice of suitable location of sensors in the aircraft flow field has always posed problems, since the measurement is affected by shocks in the flow field, boundary layer growth, proximity of adjacent sensors or probes or sensor itself may obstruct engine air intake. In this paper, the procedure adopted for locating sensors is described and the computation curves for flow angularity over flight regime of a typical combat aircraft are presented. The computational fluid dynamics (CFD) approach to the problem of finding suitable sensor locations comprises two stages: (i) a baseline study of pressure distribution over the aircraft, and (ii) the position error correction at the proposed sensor locations to identify the optimum location. The ADS analysed here includes pitot-static probes, refueling probe and angle of attack vane, all stationed in the combat aircraft front fuselage as depicted in Fig. 2. The range of Mach numbers and free-stream angle of incidence for CFD flow field analysis are obtained from flight envelope diagram of aircraft. The flow properties in steady-level flight of aircraft is computed by two Euler codes: (i) AMES[4,5], and (ii) TDES[6]. The computation of geometrical flow angle–local flow angularity at the sensor location is of primary interest besides calculation of position error for the probe.

Angle of attack vane shown in Fig. 3 measures α_l directly and provides an early warning of onset of stalled condition caused by buffeting, pitch-down altitude change or wing drop. The α-sensor mountedon leading edge or near-lifting surface by

Revised 19 March 2001

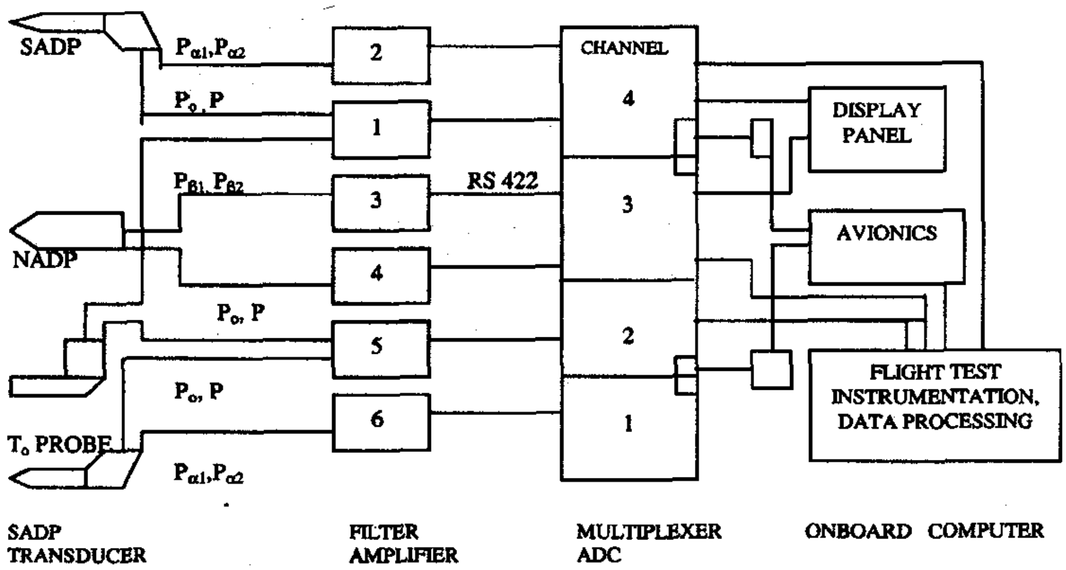


Figure 1. Data acquisition system of air data sensors

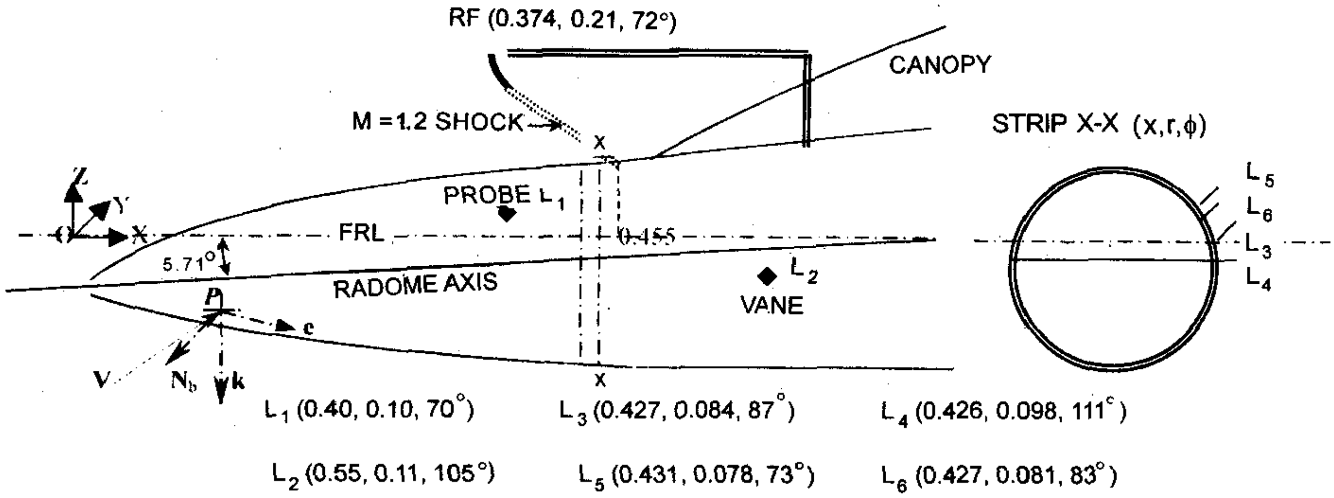


Figure 2. Schematics of front fuselage with sensor locations

upwash, and β-sensor is affected by sidewash at these locations. Using INS wind-corrected air speeds referenced to aircraft body axes, upwash and sidewash corrections may be applied to flow angles as calibration corrections.

The pitot-static probes shown in Fig. 4 are usually located ahead of wing tip, ahead of vertical stabiliser tip, at the side of the fuselage side-mounted air data probe (SADP) as in Fig. 2 and in the nose section nose-mounted air data probe (NADP). The pitot-static tube measures both total pressure (P_o) and static pressure (P), their difference ($P_o - P$) is proportional to air speed, and static pressure is proportional to altitude. Mach number is obtained from air speed and altitude as $M \propto (P_o - P)/P$.

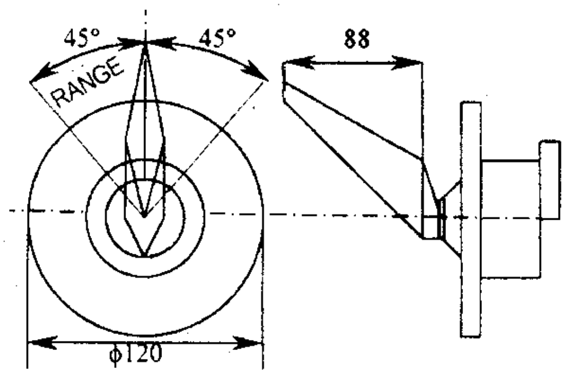


Figure 3. Angle of attack vane

2. LOCATION & POSITION ERROR OF PROBE

In actual computation employing CFD codes, static pressure is evaluated as primitive flow variable by the solution vector. Figure 5 shows the contours of zero static surface pressure coefficient, C_{p_0}, at M = 0.95 and M = 1.6 and angle of attack (α^0) range. The regions indicated by arrows, where C_{p_0} contour lines cluster may be identified as locations for pressure measurement. Location of probe in and around these regions makes it less prone to errors because the pressure distribution is close to free-stream value and independent of angle of attack so that the presence of aircraft is compensated to a large extent. Figure 6 shows the variation of C_p with angle of attack and Mach number at L_6 pitot probe location. The influence of Mach number on measurement accuracy is significant at supersonic Mach numbers only. It is observed that the C_p values for the free-flight Mach number range lie within ± 0.1. Alternatively, one may follow the procedure outlined by Wuest[1] in

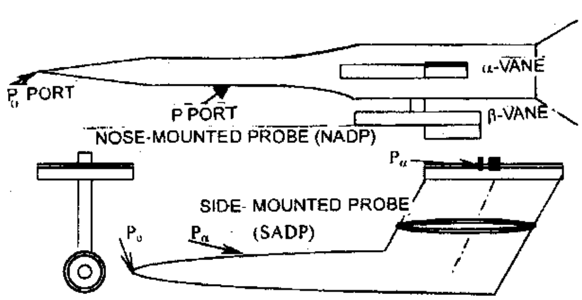


Figure 4. Pitot probes

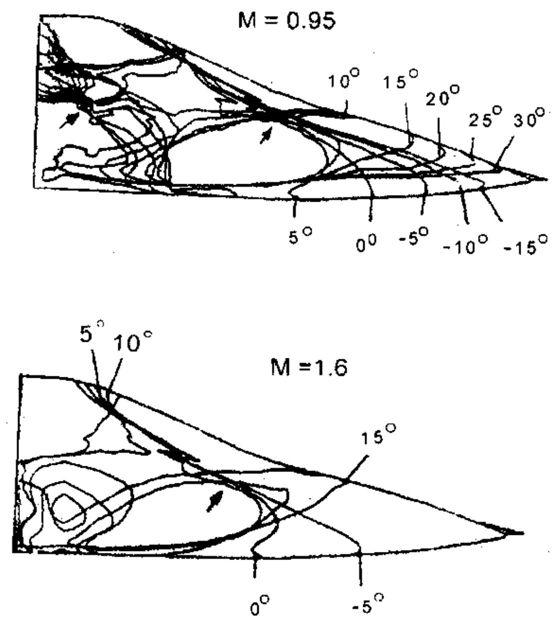


Figure 5. C_{p_0} contour lines for angle of attack (α^0) range at M = 0.95 and M = 1.6.

which zero static pressure error distribution points along fuselage reference line are marked as suitable locations for pressure ports. But C_p distribution study being the first step is not the only criterion, and other factors as already mentioned must be considered before fixing the sensor locations.

The positioning of probe in the aeroplane flow field gives rise to position error which must be compensated by calibration. Position error, defined as

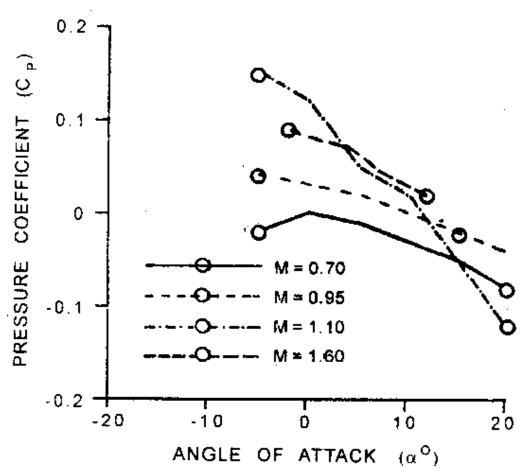
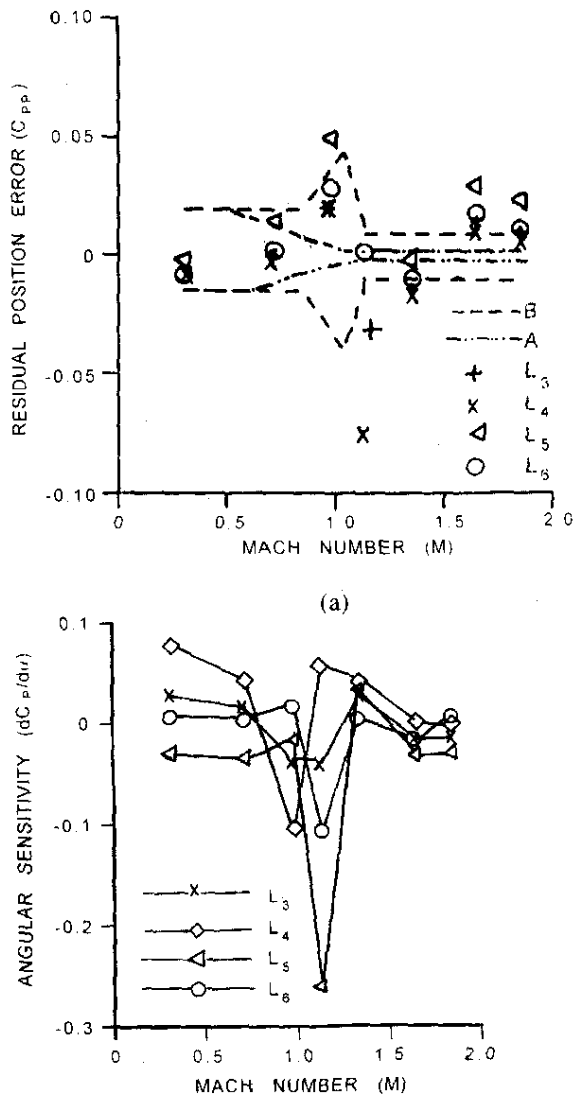


Figure 6. Effect of angle of attack (α^0) on pressure distribution at L_6 probe location.

the difference between locally measured static pressure (P_m) and the ambient static pressure (P_{in}) is influenced by true angle of attack (α^0), air speed and configuration. Position error coefficient, $C_{pp} = (P_c - P_m)/q = (P_{in} - P_m)/q_c$, where P_c is the computed static pressure. It is customary to report C_{pp} as the ratio of impact pressure(q_c) rather than dynamic pressure $q(= 0.5\rho V^2)$. In a study carried out by Wuest, $q_c = 1.5q$ for M>1.3. After selecting suitable pitot-probe locations, position error correction is determined as described below.

The ruled region X-X in Fig. 2 indicates the four proposed mounting locations, L_3, L_4, L_5 and L_6 of pitot-static probe. Pitot probe used for evaluation of position error is aerodynamically compensated by comparison with aerodynamic standards and it conforms to quality assurance specifications prescribed in MIL-P-832053. The residual static pressure error coefficient evaluated from CFD computed static pressure and the wind tunnel measured ambient static pressure data of probe for 1g flight Mach number range are plotted in Fig. 7. It also shows the sensitivity of probe for the angle of attack range at the four proposed locations. The envelope of tolerance for position error coefficient as specified in MIL-P-26292C for clean configuration and full weight range is bounded by curves A and B. During in-flight measurement, residual static pressure correction is applied to C_{pp} values that lie within this envelope through air data computer. In Fig. 7, residual error of L_6 is within permissible limits at all Mach numbers and the maximum deviation of pressure error is the least. The residual error and maximum deviation of pressure error of other probes increase in the order L_4, L_3 and L_5 except close to Mach number unity, where C_{pp} of L_4 is greater than that of L_3. The angular sensitivity of probe at L_3 varies gradually even at Mach number unity as evident from Fig. 7. L_6 and L_4 exhibit almost same degree of variation in residual errors with angle of attack (α^0) at Mach number unity but to a greater extent than L_3. Although high sensitivity will improve accuracy, it does affect the sensor response adversely. But location L_4 is unlikely to be affected by flow separation because it is located at the vertical tangent plane or maximum half-breadth of lobe. The probe at location L_5 is the worst candidate because of the largest residual static pressure errors and abrupt change in its sensitivity. If residual error is the predominant factor in selection of probe location, then L_6 should be acceptable as the best choice.



(a)

(b)

Figure 7. (a) Residual position error of probes, and (b) angular sensitivity of probes.

The refuelling probe mounted on aircraft front fuselage is shown in Fig. 2. The influence of this probe on pitot-probe locations was investigated because of its proximity to the pitot probe. Using

Euler code, the standing normal shock in front of the refueling probe tip was captured for supersonic Mach numbers. The point of impingement of the shock and its subsequent reflection from the front fuselage with the resultant pressure rise is computed as part of flow field solution. As can be seen in Fig. 2, the impingement of shock on fuselage at Mach number 1.2 is just behind the location of the pitot probes.

3. COMPUTATION CURVES

In the study of motion of aerospace vehicles, two orientation angles systems are commonly used: Classical Euler angles which become singular when inclination angle is zero or line of nodes vanishes. To obviate this difficulty, the second orientation angles system is defined as pitch, roll and yaw angles orientation system in aircraft dynamics. Various definitions of flow angles based on these coordinate systems are found in the literature. True angle of attack (α^{o}) is defined as the difference between the pitch attitude angle and the flight path climb angle of aircraft. The α is the most important flow angle in the study of dynamic performance (stall) and stability derivative characteristic of aircraft longitudinal dynamics. Angle of side slip (β) is an important parameter in the lateral dynamics of aircraft (fin loads). The formula for computing local angle of attack, α_l and local side slip angle, β_l in aircraft axes reference frame are given by $\alpha_l = \tan^{-1}(w/u)$ and $\beta_l = \sin^{-1}(v/V)$. These angles are defined[6] exactly in the same way as free-stream angles[6]. However, at the body surface as at point P in Fig. 2, flow angularity (α_l') may be defined by a single angle as the angle between incident velocity vector V and the unit tangent vector e ($=N_b \times k$) formed at the intersection of the tangent and horizontal planes i.e. $\alpha_l' = \cos^{-1}\{(e\cdot V)/|e\cdot V|\}$. The cartesian velocity components u, v and w computed by Euler codes are substituted in the above formula to obtain the local flow angles at the sensor locations.

The variation of local flow angularity with free-stream parameters at pitot probe L_6 and vane L_2 locations are plotted in Fig. 8. The Mach number independent of local flow angles at probe location as seen in Fig. 8 suggests that flow angularity depends

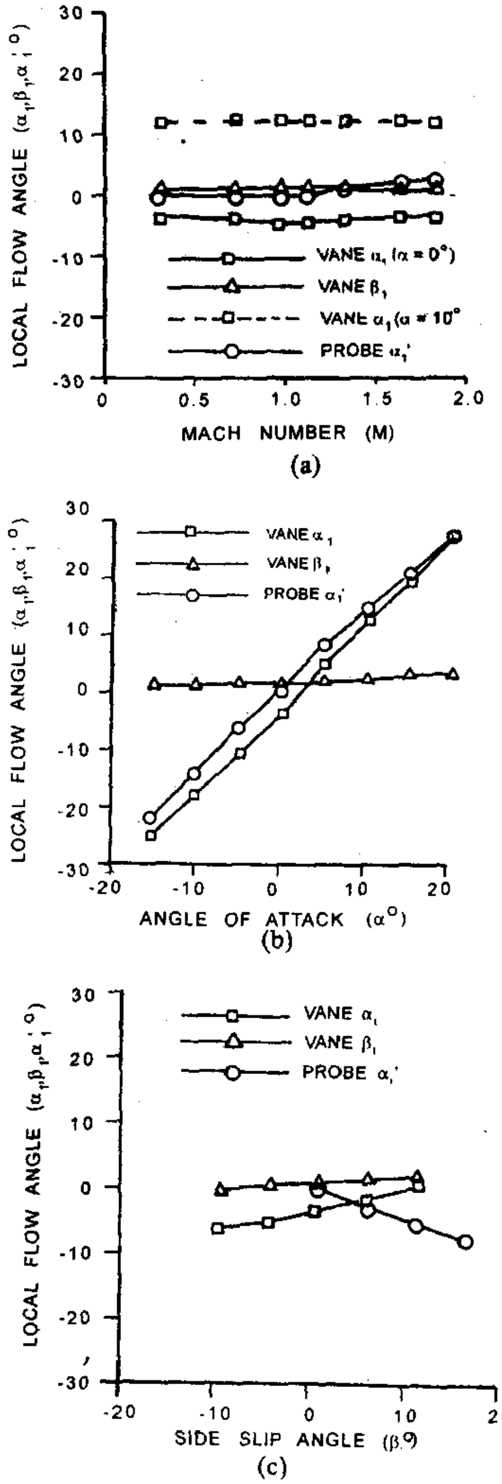


Figure 8. Variation of local angle of attack (α_l), local side slip angle (β_l), and flow angularity, (α_l') with free-stream (a) Mach Number (M), (b) angle of attack (α^{o}), (c) side slip angle (β^{o}).

solely on aircraft geometry in isenthalpic flow of calorically perfect gas. Moreover, the straight line graphs permit one to plot a set of nomograms with free-stream α or β as parameters. The local angle of attack α_l at L_6 probe is more sensitive to side slip angle β and its inverse relation as opposed to direct relation for vane is due to change in curvature and formation of oblique shock in the wind shield region. On the other hand, as β varies, the local side slip angle β_l remains constant and nearly zero at vane location, which therefore identifies L_2 as the appropriate location for α-vane. These inferences are further exemplified by nomograms with side slip angle (β) and Mach number (M) as parameters at probe and vane locations. It can be seen in Fig. 9 that the effect of side slip or cross flow is conspicuous at the probe location only and the influence of Mach number in Fig. 10 is insignificant even at M = 1.6. This method of computing local flow angles[4] indicates an excellent agreement with experimental data.

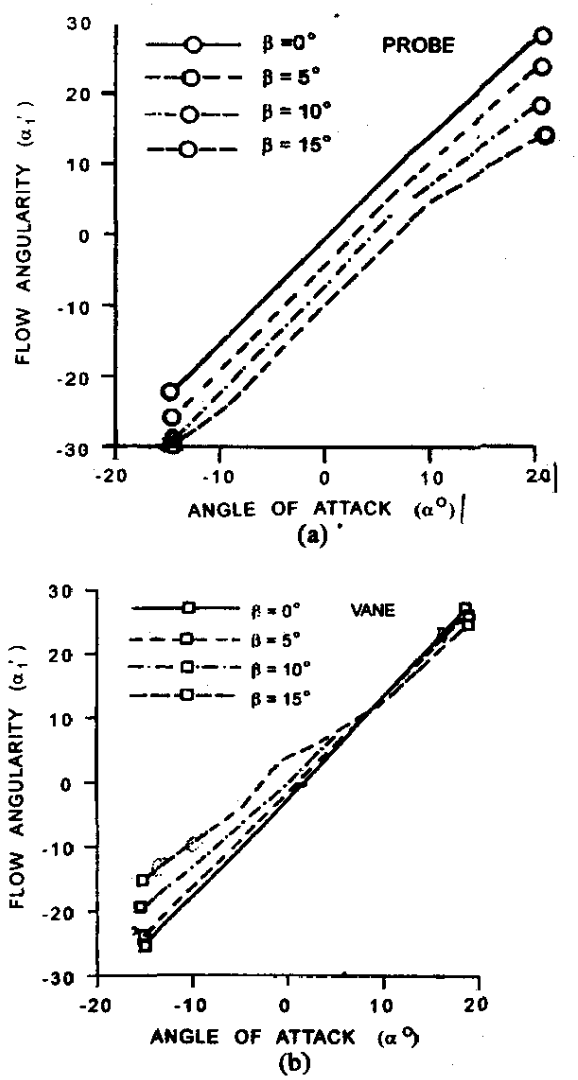


Figure 9. Flow angularity at (a) L_6 probe location, and (b) L_2 vane location.

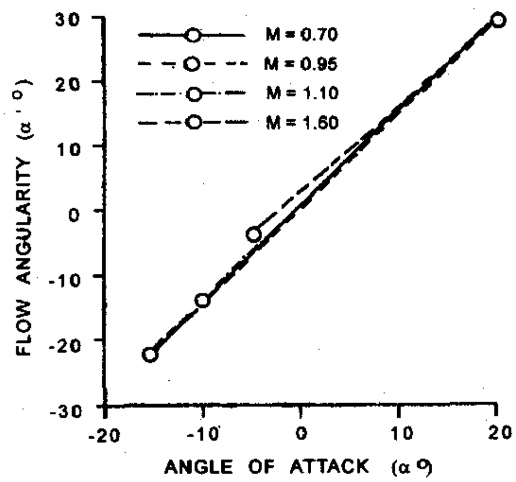


Figure 10. Influence of Mach number at L_6 probe location.

4. CONCLUSIONS

The CFD Euler codes have been used to generate combat aircraft air data for the best sensor locations and probe calibrations. Since the turnaround time is less than an hour, pilot studies could be conducted for several proposed locations with little computational effort. The linear variation of flow angles with free-stream parameters may be displayed as charts or nomographs. By CFD flow simulation, the position error of pitot probes can be minimised with consequent improvement in accuracy. Since analysis is performed for 1g straight and level flight conditions, care should be exercised in extrapolation of air data and appropriate corrections to the formula must be applied to cover the entire flight envelop.

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