JOURNAL OF AIRCRAFT
Vol. 43, No. 2, March–April 2006

Air Data Computation in Fly-by-Wire Flight-Control Systems

Fabio Cervia*
Teleavio S. r. l.—Finmeccanica Company, I-16153 Genoa, Italy
and
Eugenio Denti,† Roberto Galatolo,‡ and Francesco Schettini§
University of Pisa, I-56122 Pisa, Italy

The aim of air data systems is the determination of flight parameters (such as pressure altitude, Mach number, angles of attack and sideslip) from measurements of local pressures and of local flow angles on wings or fuselage provided by a proper set of sensors. The active and integrated use of flight parameters in a full-authority fly-by-wire flight-control system imposes redundant system architecture to achieve an adequate level of reliability and safety. In this paper a methodology for air data computation is proposed that allows the flight parameters to be evaluated on the basis of data measured by four multifunction air data probes. It takes into account the effects of the modification of aircraft configuration during flight, as well as the effects of aircraft maneuver. Finally, it includes dedicated algorithms for the management of redundancy, which are able to detect possible system failures and to provide consolidated outputs. The methodology has been implemented in the Matlab/Simulink environment and a preliminary comparison of the results with flight test data showed satisfactory performance.

Nomenclature

a = asymptotic speed of sound
$C_{p_{\mathrm{front}\,i}}$ = frontal pressure coefficient of the ith probe
$C_{p_{\mathrm{slot}\,i}}$ = slot pressure coefficient of the ith probe
Config = aircraft configuration parameter
$\boldsymbol{d} = (X_s, 0, 0)$ = distance between the section of installation of the probes and the center of mass of the aircraft
f_{front} = characteristic function of the stand alone probe for the frontal pressure
f_i = flow angle function of the ith probe
f_{Li} = local pressure function
$f_{M\,\mathrm{LE}}$ = compensation function of Mach number for δ_{LE}
$f_{M\,\mathrm{TE}}$ = compensation function of Mach number for δ_{TE}
$f_{P\,\mathrm{LE}}$ = compensation function of static pressure for δ_{LE}
$f_{P\,\mathrm{TE}}$ = compensation function of static pressure for δ_{TE}
f_{slot} = characteristic function of the stand alone probe for the slot pressure
M_{Li} = local Mach number at the location point of the ith probe
M_∞ = asymptotic Mach number
$\bar{M}_\infty$ = consolidated Mach number
$\hat{M}_\infty$ = Mach number compensated for configuration effects
$\tilde{M}$ = Mach number calculated in the previous step
$P_{\mathrm{front}\,i}$ = frontal pressure measured by the ith probe
$P_{\mathrm{slot}\,i}$ = slot pressure measured by the ith probe
P_{sa} = asymptotic static pressure
$\bar{P}_{sa}$ = consolidated static pressure
$\hat{P}_{sa}$ = static pressure compensated for configuration effects
U_s = component of V_s along the X axis of the body-fixed reference frame
V_{cg} = airspeed at the center of mass
V_s = airspeed at the section of installation of the probes
x_i, y_i, z_i = position of the ith probe (body-fixed reference frame)
α = angle of attack
$\bar{\alpha}$ = consolidated angle of attack
β = angle of sideslip
$\bar{\beta}$ = consolidated angle of sideslip
γ = specific heat ratio of air
δ_{LE} = deflection of the wing leading edge surface
δ_{TE} = deflection of the wing trailing edge surface
λ_i = local flow angle of the ith probe
$\hat{\lambda}_i$ = local flow angle compensated for roll rate effects
$\boldsymbol{\Omega}(P, Q, R)$ = angular velocity (roll rate P, pitch rate Q, yaw rate R)

I. Introduction

AIR data systems consist of all the elements that allow static pressure, Mach number, and angles of attack and sideslip to be evaluated on the basis of local airflow measurements provided by external air data probes. The evaluation of such flight parameters is performed by dedicated computation functions, implemented either in the flight-control computers (FCCs) or in specific processing units. The functional failure analysis for modern fly-by-wire flight-control systems, together with the need to satisfy safety requirements,[1,2] impose, at design level, adequate redundancy of the components, as well as definition of robust logic for failure management.

The air data system studied in this paper is that designed for the new jet trainer Aermacchi M-346, based on pseudo-quadruplex redundancy, which employs four self-aligning air data probes named integrated multi-function probes (IMFP)[3] symmetrically installed on the fuselage, two starboard and two port (Fig. 1). On the basis of this architecture and the designed air data algorithm, it should be possible to operate within safety requirements and without appreciable losses of performance and functionality, even in the presence of more than one failure (fail operative—fail safe).

Received 24 February 2005; revision received 13 July 2005; accepted for publication 27 August 2005.

*Aerospace Systems Engineer; fabio.cervia@seleniacomms.com.
†Associate Professor of Flight Dynamics, Department of Aerospace Engineering; e.denti@ing.unipi.it.
‡Associate Professor of Aerospace Systems, Department of Aerospace Engineering; r.galatolo@ing.unipi.it.
§Ph.D. Student, Department of Aerospace Engineering; f.schettini@ing.unipi.it.

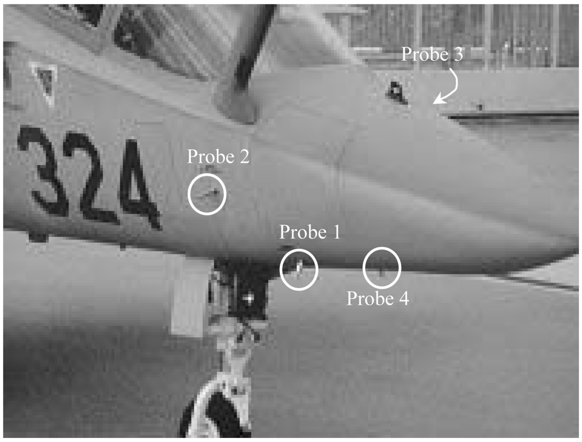

Fig. 1 Probe installation on Aermacchi M346.

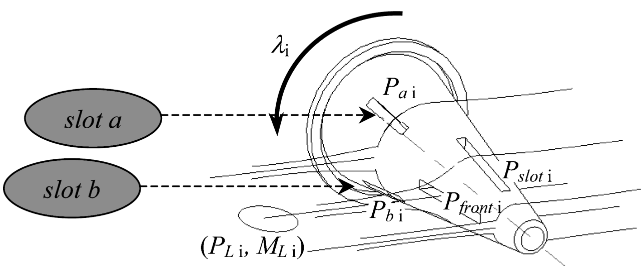

Fig. 2 Local flow conditions and probe measurements.

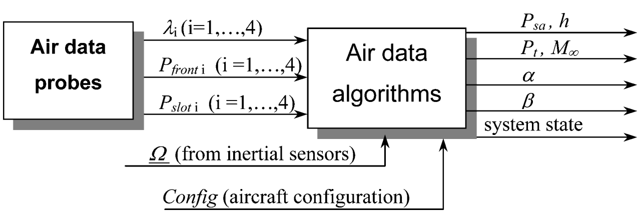

Fig. 3 Inputs and outputs of the computation algorithms.

The shape of the probes is a truncated cone with the axis normal to the surface of the fuselage. Each probe has five pressure slots, distributed at equal interspaces on an angle of 180 deg (Fig. 2). Two of the five slots (referred to as "*a*" and "*b*" in Fig. 2) allow the probe to be aligned according to the direction of the local flow (null-seeking probe[3,4]) by means of a vane mechanism that rotates the probe until the pressures at the two slots are equal. The other three slots are devoted to local airflow pressure measurements.

Each probe provides three outputs: the local flow angle λ_i measured by a rotary transducer (where subscript $i = 1, \ldots, 4$ refers to the probe number), the frontal pressure $P_{\mathrm{front}\,i}$ ("like total" pressure) provided by the frontal slot aligned with the local flow direction, and the slot pressure $P_{\mathrm{slot}\,i}$ ("like static" pressure). The last is obtained as the average of the pressures measured by the two slots at 90 deg from the local flow direction.

The computation algorithm of the air data system has to solve the problem illustrated in Fig. 3. The flight parameters must be determined on the basis of the 12 signals provided by the four probes (four local flow angles and eight local pressures), ensuring correct redundancy management by identifying possible failures and by providing an adequate system reconfiguration. In addition, the algorithm has to manage situations in which one or more probes do not provide reliable measurements because they are in the wake of the fuselage. Finally, the algorithm has to take into account (Fig. 3) both aircraft maneuver and configuration effects (landing gear extraction, position of the flaps, etc). Actually, the local flow conditions in the point of installation of the ith probe depend not only on the attitude and on the airspeed of the aircraft, but also on the aircraft configuration and on its angular velocity.

II. Problem Definition

Disregarding the effects of unsteady aerodynamics (which will be examined during flight tests), the following dependencies can be assumed:

$$\lambda_i = f_i(\alpha, \beta, M_\infty, \mathbf{\Omega}, \mathrm{Config}) \tag{1}$$

$$P_{\mathrm{front}\,i} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 \cdot C_{p_{\mathrm{front}\,i}}(\alpha, \beta, M_\infty, \mathbf{\Omega}, \mathrm{Config})\right] \tag{2}$$

$$P_{\mathrm{slot}\,i} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 \cdot C_{p_{\mathrm{slot}\,i}}(\alpha, \beta, M_\infty, \mathbf{\Omega}, \mathrm{Config})\right] \tag{3}$$

If the functions f_i, $C_{p_{\mathrm{front}\,i}}$, and $C_{p_{\mathrm{slot}\,i}}$ are known, the model given by Eqs. (1), (2), and (3) provides the correlation between the measurements of the probes and the parameters α, β, P_{sa}, M_∞, $\mathbf{\Omega}$, and Config. The parameter Config includes all the variables that differ from those defining the motion of the aircraft with respect to air, that is, moving surface positions, landing gear position, external store condition, and throttle setting. The last is directly related to the airflow through the engine and influences the flowfield around the aircraft. The problem to solve during flight (Fig. 3) is the inverse of the model (1), (2), and (3), that is, to determine the angles of attack and sideslip (α, β), the static pressure (P_{sa}), and the Mach number (M_∞). The unknowns of the problem are therefore four and the model provides 12 equations, 3 for each of the probes. To get the solution of the problem it is necessary to use at least 4 out of the 12 equations. In this way, it is possible to define more subsystems, which provide more solutions. Theoretically these solutions are coincident; in practice they are affected by errors, due to the accuracy of the probes and the approximations introduced by the computation algorithm. Besides, the algorithm can provide completely discordant solutions when some probes are in failure. Actually, the comparison between the different solutions is used to detect the failures (by means of proper monitoring algorithms) and to consolidate acceptable solutions (by means of proper voting algorithms) in order to provide one value only for each computed parameter and to reconfigure the system in case of recognized failures.

III. Aerodynamic Field Under Stationary Conditions

Before the algorithms are described, the methodology used for the characterization of the aerodynamic field around the aircraft is illustrated. The available methodologies to establish the f_i, $C_{p_{\mathrm{front}\,i}}$, and $C_{p_{\mathrm{slot}\,i}}$ functions that appear in Eqs. (1), (2), and (3) are essentially three: numerical codes, wind tunnel tests, and flight tests. The first two are used in a preliminary development of the algorithms, whereas the database coming from the flight tests is used for the calibration of the algorithms. In the present paper, such functions have been obtained using data from wind tunnel tests and some computational fluid dynamics analyses.

These tests have been performed on a model of the M346 in the whole operative range of angles of attack, sideslip, and Mach number and for different configurations of the aircraft. The tests are related to conditions of rectilinear motion ($\mathbf{\Omega} = 0$). The effects of $\mathbf{\Omega}$ are introduced by means of an approach that will be described further on. During the wind-tunnel tests, the functions f_i in (1) were calculated by direct measurements of the local flow angles at the points where the probes are located on the aircraft. The functions $C_{p_{\mathrm{front}\,i}}$ and $C_{p_{\mathrm{slot}\,i}}$ that appear in Eqs. (2) and (3) have been determined by combining the measures of the aerodynamic field around the aircraft model at the probe locations with the calibration curves of the stand alone probe. This approach disregards part of the effects of interference between the probes and fuselage.

The flow conditions at the location of the generic ith probe are identified by local pressure P_{Li} and local Mach number M_{Li}. Under stationary conditions,

$$P_{Li} = P_{sa} \cdot f_{Li}(\alpha, \beta, M_\infty, \mathrm{Config}) \tag{4}$$

$$M_{Li} = g_{Li}(\alpha, \beta, M_\infty, \mathrm{Config}) \tag{5}$$

The stand alone probe characteristics are[3]

$$P_{\mathrm{front}\,i}/P_s = f_{\mathrm{front}}(M); \qquad P_{\mathrm{slot}\,i}/P_s = f_{\mathrm{slot}}(M) \tag{6}$$

where P_s and M are the asymptotic conditions of the flow around the isolated probe. Setting for the generic probe $P_s = P_{Li}$ and $M = M_{Li}$ (Fig. 2) and using Eq. (4),

$$P_{\mathrm{front}\,i}/P_{sa} = (P_{\mathrm{front}\,i}/P_{Li})(P_{Li}/P_{sa}) = f_{\mathrm{front}}(M_{Li}) \cdot f_{Li}(\alpha, \beta, M_\infty, \text{Config})$$

$$P_{\mathrm{slot}\,i}/P_{sa} = (P_{\mathrm{slot}\,i}/P_{Li})(P_{Li}/P_{sa}) = f_{\mathrm{slot}}(M_{Li}) \cdot f_{Li}(\alpha, \beta, M_\infty, \text{Config}) \tag{7}$$

Considering Eq. (5), (7) can be easily put in the form (2) and (3). In conclusion, the measurements in the wind tunnel of the local conditions of flow P_{Li}/P_{sa} and M_{Li} and the knowledge of Eqs. (6) allow the functions $C_{p_{\mathrm{front}\,i}}$ and $C_{p_{\mathrm{slot}\,i}}$ that appear in (2) and (3) to be reconstructed under the condition $\mathbf{\Omega} = 0$.

IV. Computation Algorithm

In this section we describe the algorithm developed to solve the air data computation problem defined in Sec. II. In the first part, we refer to a condition of rectilinear motion and fixed aircraft configuration (with aerodynamic control surfaces frozen, landing gear retracted, absence of external stores, and not taking into account the airflow through the engine).

The effects of maneuver and aircraft configuration will be accounted for by the alternative approaches described in Secs. IV.C and IV.D, respectively. For this reason we neglect the $\mathbf{\Omega}$ and Config parameters and the model (1), (2), and (3) reduces to the following:

$$\lambda_i = f_i(\alpha, \beta, M_\infty) \tag{8}$$

$$P_{\mathrm{front}\,i} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 C_{p_{\mathrm{front}\,i}}(\alpha, \beta, M_\infty)\right] \tag{9}$$

$$P_{\mathrm{slot}\,i} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 C_{p_{\mathrm{slot}\,i}}(\alpha, \beta, M_\infty)\right] \tag{10}$$

where functions f_i, $C_{p_{\mathrm{front}\,i}}$, and $C_{p_{\mathrm{slot}\,i}}$ have been determined as illustrated in Sec. III.

As said in Sec. II, the problem to be solved has four unknowns (α, β, P_{sa}, and M_∞) and 12 equations are available. These equations are related to the 12 measurements provided by the four probes. A possible combination of such equations is the following:

$$\lambda_j = f_j(\alpha, \beta, M_\infty)$$

$$\lambda_k = f_k(\alpha, \beta, M_\infty)$$

$$P_{\mathrm{front}\,h} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 C_{p_{\mathrm{front}\,h}}(\alpha, \beta, M_\infty)\right]$$

$$P_{\mathrm{slot}\,h} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 C_{p_{\mathrm{slot}\,h}}(\alpha, \beta, M_\infty)\right] \tag{11}$$

where the first two equations are related to the angles measured by two generic probes (jth and kth probe), whereas the last two equations are related to the pressures measured by any probe (hth probe), which can be different from the probes used for the first two equations. In principle, it is possible to obtain 24 different systems of type (11) (four values of $h \times$ six couples j, k, with $j \neq k$).

Equations (11) are closely connected because angle measurements are dependent on the Mach number and pressure measurements are functions of the angles of attack and sideslip. To solve system (11) an iterative method is thus needed. However, iterative methods are not suitable for embedded software, because they can lead to convergence problems.

For this reason we propose a different approach, which is based on the assumption that the evolution of the Mach number is much slower than the variation of the angles of attack and sideslip. This makes it possible to assume that the Mach number that appears in functions f_j and f_k can be approximated with its value at the previous computation step ($\tilde{M}$). Such an assumption makes it possible to separate the first two equations of system (11) from the last two. The first two equations can be then used to determine the angles of attack and sideslip (as explained in Sec. IV.A), whereas the last two equations provide (see Sec. IV.B) the P_{sa} value and the updated value of M_∞.

A. Determination of Angles of Attack and Sideslip

On the hypothesis that the Mach number is known, the first two equations of system (11) can be written in the form of the following $\Re^2$ to $\Re^2$ function:

$$\begin{Bmatrix} \lambda_j \\ \lambda_k \end{Bmatrix} = \underline{f}_{jk}(\alpha, \beta, \tilde{M}) \tag{12}$$

The angles of attack and sideslip can be estimated by means of the determination of the inverse function:

$$\begin{Bmatrix} \alpha \\ \beta \end{Bmatrix} = \underline{g}_{jk}(\lambda_j, \lambda_k, \tilde{M}) \tag{13}$$

where $\underline{g}_{jk} = \underline{f}_{jk}^{-1}$. Because six different couples (λ_j, λ_k) are available, six functions of the type (13) can be determined, which give six solutions (α, β). Comparing these solutions, it is possible to identify the failure of any probe and to obtain a single consolidated solution (α, β). It is noticeable that the failure of a probe produces the loss of three couples (λ_j, λ_k); nevertheless the monitoring can be applied to the residual three, allowing a possible second failure to be recognized. However, in the case of failure of two probes it is not possible to know which probe led to the second failure. As a consequence, a solution (α, β) cannot be determined and the system cannot be monitored any more.

It is worth noting that the inverse of function (12) exists if $\underline{f}_{jk}$ is injective, that is, if there is a biunique correlation between the points of the two sets: (α, β) and (λ_j, λ_k). During flight, it is possible that a generic couple (λ_j, λ_k) goes out of its injective domain and so it cannot be used until it goes back within it.

B. Determination of Static Pressure and Mach Number

The last two equations of system (11) can be now written in the form

$$P_{\mathrm{front}\,h} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 C_{p_{\mathrm{front}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty)\right]$$

$$P_{\mathrm{slot}\,h} = P_{sa}\left[1 + (\gamma/2)M_\infty^2 C_{p_{\mathrm{slot}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty)\right] \tag{14}$$

where $\bar{\alpha}$ and $\bar{\beta}$ are the consolidated values of the angles of attack and sideslip, evaluated as explained in the previous section.

Solving for the static pressure and the square of the Mach number,

$$P_{sa} = P_{\mathrm{slot}\,h} \times \frac{C_{p_{\mathrm{front}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty) - (P_{\mathrm{front}\,h}/P_{\mathrm{slot}\,h})C_{p_{\mathrm{slot}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty)}{C_{p_{\mathrm{front}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty) - C_{p_{\mathrm{slot}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty)} \tag{15}$$

$$M_\infty^2 = \frac{2}{\gamma} \times \frac{(P_{\mathrm{front}\,h}/P_{\mathrm{slot}\,h}) - 1}{C_{p_{\mathrm{front}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty) - (P_{\mathrm{front}\,h}/P_{\mathrm{slot}\,h})C_{p_{\mathrm{slot}\,h}}(\bar{\alpha}, \bar{\beta}, M_\infty)} \tag{16}$$

Equation (16) is an implicit equation of the type $X = g(X)$, where $X = M_\infty$, and it can be solved iteratively by writing it in the form $X_{i+1} = g(X_i)$ and by choosing, as the first element of the succession, the consolidated value of the Mach number at the previous FCCs time step.

A sufficient condition for the convergence of the succession to a solution is

$$\left|\frac{\mathrm{d}\,g(X)}{\mathrm{d}X}\right| < 1 \tag{17}$$

which has to be satisfied in a neighborhood of the solution itself. A wide-ranging analysis, based on the data available for the considered aircraft, outlined as function (16) satisfies condition (17) in the whole operative range of α, β, and M_∞. Also, simulations showed that it converges quickly.

Because the FCC's frame is "faster" than the aircraft dynamics, the evolution of the Mach number is very slow if compared to the

FCC's time scale. As a consequence, the second element of the succession is always very close to the theoretical solution and it can be considered a good approximation of the solution itself. Extensive simulations, over the entire Mach range, showed the correctness of such an assumption and the good performance of the approach.

In conclusion, by approximating the Mach number that appears on functions $C_{p_{\mathrm{front}\,h}}$ and $C_{p_{\mathrm{slot}\,h}}$ with its value at the previous computation step ($\tilde{M}$), Eqs. (15) and (16) give a satisfactory approximation of the Mach number at the current time step, as well as the current value of P_{sa}, without using any iterative method.

Concerning the monitoring, the application of Eqs. (15) and (16) for the four probes provides four different solutions (P_{sa}, M_∞). Comparing such solutions, it is possible to identify the failure of a probe and to obtain a consolidated pair of values $(\bar{P}_{sa}, \bar{M}_\infty)$.

Monitoring is still possible if two probes are in failure. In the case of failure of three probes, the third failure is recognizable. However, it is not possible to know which probe led to this failure. As a consequence, a solution cannot be determined and the system cannot be monitored any more.

It is worth noting that the procedure to determine $(\bar{P}_{sa}, \bar{M}_\infty)$ needs a previous determination of consolidated values of angles of attack and sideslip $(\bar{\alpha}, \bar{\beta})$. In the case of loss of such information, due to failures in the measurement of the local flow angles, it is still possible to determine $(\bar{P}_{sa}, \bar{M}_\infty)$ if alternative procedures, based for example on measurements from inertial sensors, are implemented in order to estimate α and β.

C. Maneuver Effects

In principle, the aircraft's angular motion ($\boldsymbol{\Omega}$) induces a variation in the IMFP measurements. In this paper, we assume that the pitch rate Q and the yaw rate R do not affect the probe measurements. However, they induce a difference between the angles of attack and sideslip relative to the center of mass of the aircraft and those relative to the installation section of the probes. To obtain the values relative to the aircraft's center of mass, the following relationship is used, which relates the airspeed at the center of mass to the airspeed at the installation section of the probes,

$$\boldsymbol{V}_{cg} = \boldsymbol{V}_s - \boldsymbol{\Omega}^* \wedge \boldsymbol{d} \tag{18}$$

where $\boldsymbol{\Omega}^* = (0, Q, R)$ is the aircraft angular speed due to Q and R, and the airspeed at the installation section of the probes $\boldsymbol{V}_s$ is given by

$$\boldsymbol{V}_s = \bar{M}_\infty a \cdot \begin{Bmatrix} \cos\bar{\alpha}\cos\bar{\beta} \\ \sin\bar{\beta} \\ \sin\bar{\alpha}\cos\bar{\beta} \end{Bmatrix} \tag{19}$$

Equations (18) and (19) allow the angles of attack and sideslip at the center of mass of the aircraft to be computed. A similar approach can be found in Ref. 5.

Concerning the effects of the roll component (P) of the angular velocity on the probes measurements, the local flow angles are strongly affected by this variable. As a first step, we propose the following correcting formula based on simple kinematic considerations:

$$\tan(\hat{\lambda}_i - \lambda_i) = C_i \cdot P\sqrt{y_i^2 + z_i^2}\Big/(U_s + Qz_i - Ry_i) \tag{20}$$

where C_i is a corrective coefficient to be tuned during flight tests.

D. Configuration Effects

The local flowfield at the probes location depends on the configuration parameter, Config. Dedicated wind-tunnel tests, carried out to evaluate such effects, showed a minor influence of throttle, rudder, ailerons, and horizontal tail, whereas the effects of the deflections of the trailing edge and leading edge flaps $(\delta_{\mathrm{LE}}, \delta_{\mathrm{TE}})$ are quite important.

On the basis of such results, the configuration effects have been accounted for by adding them directly to the values of P_{sa} and M_∞ obtained as explained in Sec. IV.B, as follows:

$$\hat{P}_{sa} = P_{sa} \cdot [1 + f_{P\,\mathrm{TE}}(\alpha, \beta, \delta_{\mathrm{TE}}) + f_{P\,\mathrm{LE}}(\alpha, \delta_{\mathrm{LE}}, M_\infty)] \tag{21}$$

$$\hat{M}_\infty = M_\infty \cdot [1 + f_{M\,\mathrm{TE}}(\alpha, \beta, \delta_{\mathrm{TE}}) + f_{M\,\mathrm{LE}}(\alpha, \delta_{\mathrm{LE}}, M_\infty)] \tag{22}$$

It is worth noting that functions $f_{P\,\mathrm{TE}}$, $f_{P\,\mathrm{LE}}$, $f_{M\,\mathrm{TE}}$ and $f_{M\,\mathrm{LE}}$, depend on the specific probe being considered. For this reason, corrections (21) and (22) are applied to the values of P_{sa} and M_∞ before the execution of monitoring and voting processes.

The algorithms for the compensations of the effects of aircraft configuration on the angles of attack and sideslip are still under evaluation. However, all compensating algorithms will be critically reviewed on the basis of flight-test results.

E. General Organization of Air Data Computation

The algorithm is characterized by two sequential computation processes. With reference to Fig. 4, the first process computes six couples of angles of attack and sideslip, by means of Eq. (13), using the local flow angles measured by the IMFP probes and the consolidated Mach number of the previous step as inputs. The six couples are then forwarded to the monitoring and voting block, which identifies possible failures and provides consolidated values for both angle of attack and sideslip. The second process calculates four couples of static pressures and Mach numbers, by means of Eqs. (15) and (16), using the following inputs: the pressures measured by the IMFP probes, the consolidated Mach number of the previous step, and the consolidated angles of attack and sideslip coming from the first process. In this case, as well, a monitoring and voting block provides a consolidated value of Mach number, corresponding to the current step, and a consolidated value of static pressure. Before the voting and monitoring phase, Mach number and static pressure are compensated for surface deflections δ_{LE} and δ_{TE}.

Concerning the maneuver effects, the same figure shows the two corrections mentioned in Sec. IV.C: the first acts directly on the local flow angles measured by the probes (roll rate effects); the second evaluates the angles of attack and sideslip relative to the aircraft's center of mass (pitch and yaw rate effects).

V. Data Compression

Functions g_{jk}, $C_{p_{\mathrm{front}\,h}}$, and $C_{p_{\mathrm{slot}\,h}}$, which appear in Eqs. (13), (15), and (16), have to be stored in the FCC memory. This is a challenging problem due to the large number of data associated with them. Actually, for each Mach number it is necessary to store 20 functions of two variables (12 functions g_{jk}, 4 functions $C_{p_{\mathrm{front}\,h}}$, and 4 functions $C_{p_{\mathrm{slot}\,h}}$). If such functions are stored in the form of look-up tables, in order to guarantee an adequate definition of the functions themselves in the whole flight envelope, we need to store at least 10^3 real numbers for each look-up table. Assuming approximately 10 Mach stations, we have to store at least $20 \times 10 \times 10^3$ real numbers.

To overcome this problem, the look-up tables have been approximated by means of the following third-degree polynomial functions:

$$\begin{aligned}\alpha = g_{jk_\alpha}(\lambda_j, \lambda_k) &= a_0 + a_1\lambda_j + a_2\lambda_k + a_3\lambda_j^2 + a_4\lambda_j\lambda_k \\ &\quad + a_5\lambda_k^2 + a_6\lambda_j^3 + a_7\lambda_j^2\lambda_k + a_8\lambda_j\lambda_k^2 + a_9\lambda_k^3\end{aligned} \tag{23}$$

$$\begin{aligned}\beta = g_{jk_\beta}(\lambda_j, \lambda_k) &= b_0 + b_1\lambda_j + b_2\lambda_k + b_3\lambda_j^2 + b_4\lambda_j\lambda_k \\ &\quad + b_5\lambda_k^2 + b_6\lambda_j^3 + b_7\lambda_j^2\lambda_k + b_8\lambda_j\lambda_k^2 + b_9\lambda_k^3\end{aligned} \tag{24}$$

$$\begin{aligned}C_{p_{\mathrm{front}\,h}}(\alpha, \beta) &= c_0 + c_1\alpha + c_2\beta + c_3\alpha^2 + c_4\alpha\beta \\ &\quad + c_5\beta^2 + c_6\alpha^3 + c_7\alpha^2\beta + c_8\alpha\beta^2 + c_9\beta^3\end{aligned} \tag{25}$$

$$\begin{aligned}C_{p_{\mathrm{slot}\,h}}(\alpha, \beta) &= d_0 + d_1\alpha + d_2\beta + d_3\alpha^2 + d_4\alpha\beta \\ &\quad + d_5\beta^2 + d_6\alpha^3 + d_7\alpha^2\beta + d_8\alpha\beta^2 + d_9\beta^3\end{aligned} \tag{26}$$

where the polynomial coefficients have been determined by a least-squares technique at fixed values of the Mach number. The results

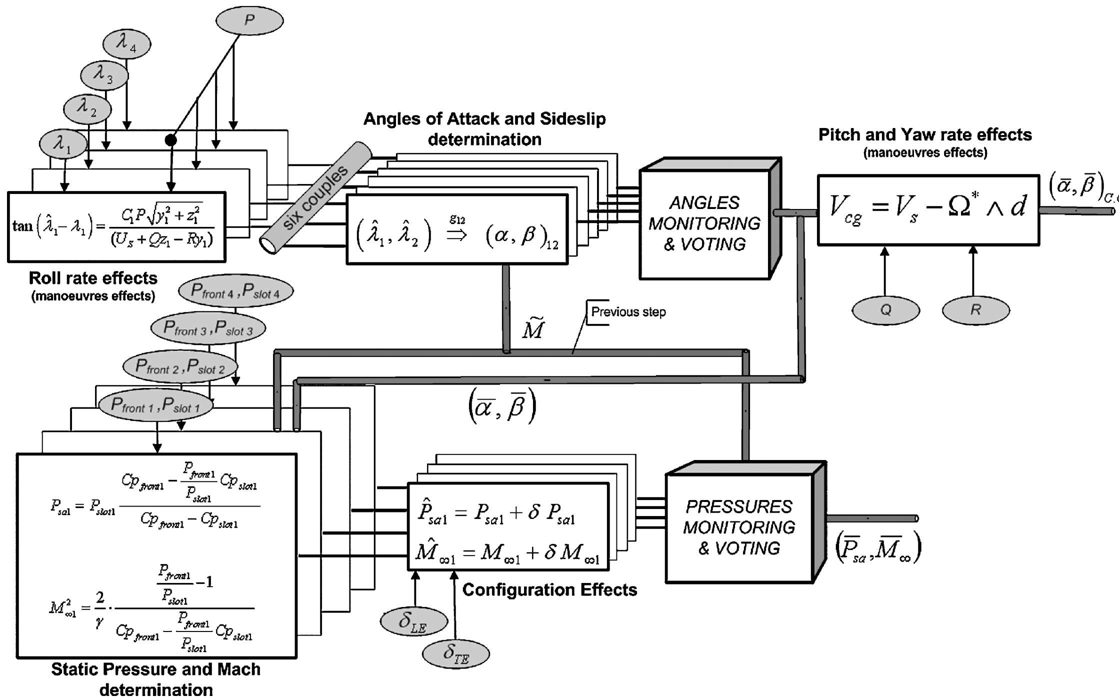

Fig. 4 Flow diagram of the computation algorithm.

Fig. 5 Nose boom used during flight tests of Aermacchi M346.

given by the polynomials above are then interpolated in order to take into account the actual Mach number.

Such an approach leads to dramatic data compression because each polynomial is defined by 10 coefficients, with a reduction of two orders of magnitude in the number of data to be stored in the FCC's memory.

The same approach has been used for the functions that appear in Eqs. (21) and (22), which have been approximated as follows:

$$f_{P\,\mathrm{LE}} = e_{10} + e_{11}\alpha + e_{12}\delta_{\mathrm{LE}} + e_{13}\alpha^2 + e_{14}\alpha\delta_{\mathrm{LE}} + e_{15}\delta_{\mathrm{LE}}^2 \tag{27}$$

$$f_{M\,\mathrm{LE}} = e_{20} + e_{21}\alpha + e_{22}\delta_{\mathrm{LE}} + e_{23}\alpha^2 + e_{24}\alpha\delta_{\mathrm{LE}} + e_{25}\delta_{\mathrm{LE}}^2 \tag{28}$$

$$f_{P\,\mathrm{TE}} = e_{30} + e_{31}\alpha + e_{32}\beta + e_{33}\alpha^2 + e_{34}\alpha\beta + e_{35}\beta^2 \tag{29}$$

$$f_{M\,\mathrm{TE}} = e_{40} + e_{41}\alpha + e_{42}\beta + e_{43}\alpha^2 + e_{44}\alpha\beta + e_{45}\beta^2 \tag{30}$$

As in the previous case, the polynomial coefficients that appear in Eqs. (27) and (28) have been determined at fixed Mach numbers and the results are interpolated to take into account the actual value of the Mach number itself. The polynomial coefficients in Eqs. (29) and (30) are assumed to be independent of the Mach number, but they depend on δ_{TE}, which can assume a limited number of different values.

VI. Validation of the Procedure and First Results

The air data computation procedure has been implemented in the Matlab/Simulink environment and extensively tested in order to assess its performance. For this purpose the procedure has been interfaced with a flight simulator that includes a model of the IMFP probes. The simulator takes into account a number of minor phenomena that are not considered in the procedure, namely, the effects of all moving surfaces of the aircraft, the effects of landing gear, the dynamics of sensors, etc. In addition, the flight simulator uses the full look-up tables coming from wind-tunnel tests, without any approximation.

This procedure gives good results in a large part of the flight envelope. The main challenge is to obtain polynomial functions that

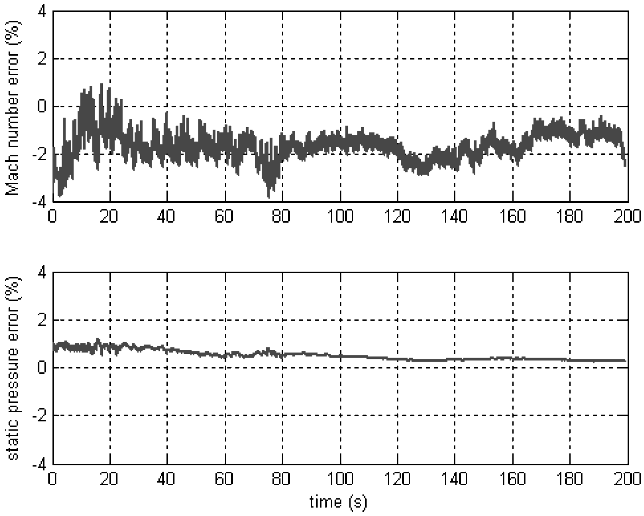

Fig. 6 Errors in Mach number and static pressure.

approximate the look-up tables with small errors in the entire flight envelope.

The next step will be the calibration of the procedure, that is, the tuning of the polynomial coefficients that appear in the equations from (23) to (30) on the basis of flight test results. During flight tests a nose boom (Fig. 5) provides measures of total pressure and static pressure, together with the angles of attack and sideslip that are used for the calibration.

Analysis of data coming from flight tests started recently. As an example, Fig. 6 reports the errors in Mach number and static pressure provided by the procedure within a flight test. During this portion of flight the angle of attack, the Mach number, and the altitude varied within the ranges 2–14 deg, 0.25–0.4, and 4000–4600 m, respectively. The variation of the angle of sideslip was very small, as well as that of the load factor.

It can be observed that the errors deriving from the preliminary validation of the procedure are quite small (within a few percent) both for Mach number and for static pressure.

It is worth noting that such results were obtained using polynomial coefficients that approximate the look-up tables coming from wind-tunnel tests. It is the authors' opinion that the current small errors will further diminish when such coefficients are tuned on flight-test data.

VII. Conclusions

An air data computation procedure has been developed that estimates flight parameters (angles of attack and sideslip, Mach number, and static pressure), taking into account the effects of aircraft maneuvers as well as the variations of aircraft configuration.

The procedure is fault-tolerant because it includes monitoring algorithms able to identify possible failures of the air data probes. In addition, it needs a limited number of data to be stored on the FCCs, thanks to data compression achieved by replacing the look-up tables of the aerodynamic database with least-squares polynomial functions.

A preliminary comparison of the results with flight-test data achieved satisfactory performance in spite of the fact that the procedure is still using polynomial functions obtained by interpolating data coming from wind-tunnel tests. A further increment of accuracy level might be expected when the coefficients of such functions are tuned on flight-test data.

Acknowledgments

The computation algorithm presented in this paper was developed at the Department of Aerospace Engineering of the University of Pisa in collaboration with the societies Teleavio and Aermacchi, within the framework of the program for the development of the flight control system of the new jet trainer Aermacchi M346.

References

[1]Collinson, R. P. G., "Fly-by-Wire Flight Control," *Computing and Control Engineering Journal*, Vol. 10, Aug. 1999, pp. 141–152.

[2]McLean, D., "Aircraft Flight Control System," *The Aeronautical Journal*, Vol. 103, March 1999, pp. 159–165.

[3]Menzies, M. A., "Integrated Air Data Sensors," *The Aeronautical Journal*, Vol. 105, April 2001, pp. 223–229.

[4]Lawford, J. A., and Nippress, K. R., "Calibration of Air-Data Systems and Flow Direction Sensors," AGARDograph 300 Flight Test Techniques Series, Vol. 1, 1988.

[5]Webster, F., and Smith, T. D., "Flying Qualities Flight Testing of Digital Flight Control Systems," RTO AGARDograph 300 Flight Test Techniques Series, Vol. 21, 2001.