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SMART FAULT-TOLERANT AIR-DATA SENSOR FOR AIRCRAFT FLOW ANGLES MEASUREMENT

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Abstract

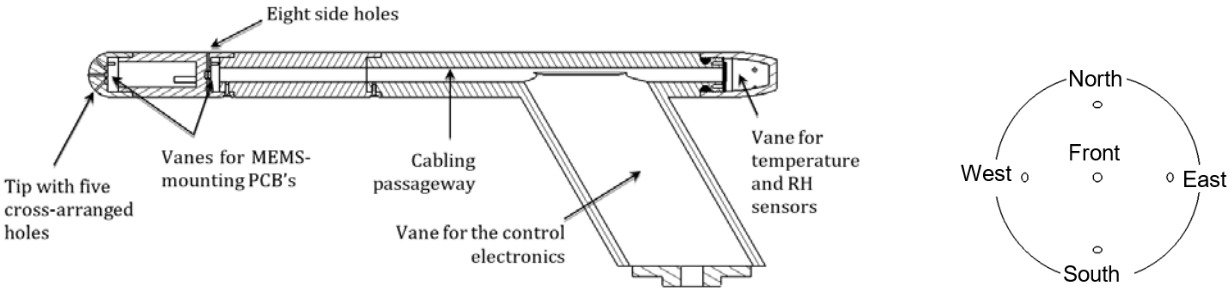
This paper deals with the development of a smart multi-hole probe for aircraft air data sensing. The system aims at the calculation of static and total pressures, the angle-of-attack and the angle-of-sideslip starting from the elaboration of the pressure measurements on holes. The probe is characterized by fault-tolerant capabilities with respect to the loss of pressure data, and it is developed as an embedded system including MEMS sensors and a control electronics for multiple reconstructions of flow measurements. The basic idea for the reconstruction algorithm is that, for typical aircraft envelopes, flow angles are small (<15° for both attack and sideslip), and the shape of the pressure field around the stagnation point of a hemispherical body is essentially independent from the flow angles. Thus, once characterised the flow at the aircraft installation for zero angles of attack and sideslip, the reconstruction can be performed by minimising the errors between the five pressure measurements on the probe tip and the predictions of a set of models imposing different locations of the stagnation point. The geometry of the probe is designed and validated by CFD simulations, with the basic objective of enabling the algorithm to reconstruct the flow angles even in case of a pressure data loss. The work describes the initial phases of the system development, from the conceptual phase, up to the manufacturing of a first prototype used for the wind tunnel tests.

1 Introduction

A digital fully-integrated multifunction probe for air data sensing play a key role for the application of the fly-by-wire technologies in the modern flight control system. Actually, accurate measurements of airspeed and flow angles allow to implement essential flight control functions, such as the stall protection, the envelope protection, and the aircraft control laws reconfiguration.

In this context, this work aims at the following objectives:

- to design an innovative multi-function air data probe with integrated electronics, which will be capable, starting from the elaboration of pressure and temperature measurements on holes, to reconstruct:
    - static pressure
    - total pressure
    - total air temperature
    - flow angles, i.e. Angle-of-Attack (AoA) and Angle-of-Sideslip (AoS)
- to develop innovative reconstruction algorithms, for increasing the outputs' accuracy;
- to develop health-monitoring algorithms, capable to detect and isolate the critical faults (e.g. hole occlusions, pressure sensor faults), and to assure fault-tolerant operation;
- to use novel technologies and materials for the probe manufacturing (3D printing), aiming to reduce size.



(a) (b)

Fig. 1. Multi-function air data probe: (a) longitudinal section; (b) tip holes definition.

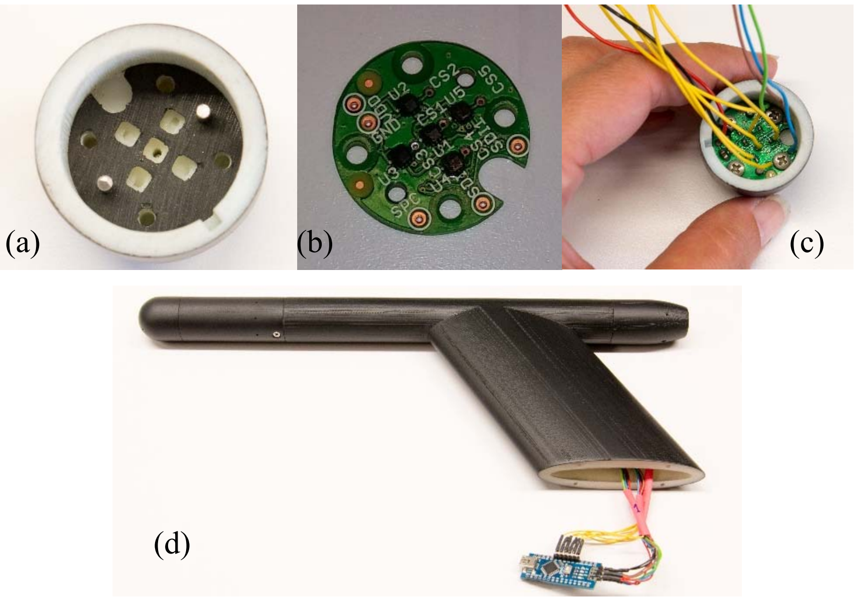


Fig. 2. Multi-function air data probe: (a) probe tip with seal; (b) PCB with MEMS sensors; (c) cabled tip; (d) complete assembly of the prototype.

2 System Description

The proposed multi-function air data system is essentially composed of (Fig. 1.a):

- a multi-hole probe, with five cross-arranged holes on the probe head (assumed to be aligned with the aircraft longitudinal axis) and a set of eight circumferential holes on the probe side;
- a sensors' system composed of MEMS pressure transducers at the probe holes, thermistors and Relative Humidity (RH) sensors at the probe bottom vane, and a triaxle accelerometer, used to compensate for probe displacements due to airframe flexibility;
- a Multi-Function Probe Control Unit (MFPCU), which
  - regulates the electrical power input for the system components
  - acquires the sensors' measurements
  - implements health-monitoring algorithms
  - implements the reconstruction algorithms for providing values of Static Pressure (SP), Total Pressure (TP), Total Air Temperature (TAT), AoA and AoS.

The basic idea underlying the system architecture definition is that the air entering the probe holes must be directly led to the sensors, in order to remove long pipes that increase the probe weight. This led to the need of small channels in the body of the probe tip, which should also house the sensors' unit. The MEMS sensors, chosen to minimise size and weight, are equipped with integrated temperature sensor for thermal compensation of the pressure measurement.

Five MEMS sensors measure the pressures at the probe head holes, i.e. (Fig. 1.b):

- "North" pressure (P_{North})
- "South" pressure (P_{South})
- "West" pressure (P_{West})
- "East" pressure (P_{East})
- "Front" pressure (P_{Front})

while other two sensors are used to acquire the Uncorrected Static Pressure (USP), i.e. the pressure an inner chamber where the air entering at eight circumferential holes located on the probe side is merged.

The multi-function probe is characterized by an integrated architecture with sensing and electronic units inside the probe body, to optimize the design in terms of size and weight, Fig. 2.

3 Multi-function probe design

3.1 Probe modules

The structural parts manufacturing has been obtained by 3D printing technique, with ABS powder as basic material. The probe is composed of four main modules (Fig. 3):

- *Tip*, housing the five pressure transducers to sense the pressure at the tip holes
- *Static*, housing two pressure transducers, each one devoted to sense the pressure of a stagnation chamber linked to the eight circumferential holes
- *Support*, housing the PCB powering the system components and implementing the reconstruction and health-monitoring algorithms;
- *Bottom*, housing the thermistors and RH sensors to sense the outside temperature and the humidity via circumferential holes.

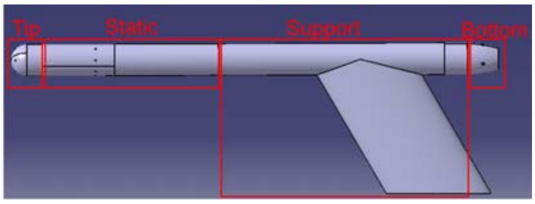


Fig. 3. Probe modules.

The tip module allows to install the pressure transducers as close as possible to the tip holes to eliminate connecting tubes and to enhance the sensors accuracy. Each hole is connected with a dedicated channel carved in the probe body, which terminates on transducer side with a little chamber for creating the required "dead volume". The pressure transducers will be welded on a specific PCB) and a seal will avoid pressure losses that could cause asymmetric behaviours, Fig. 2.a-c.

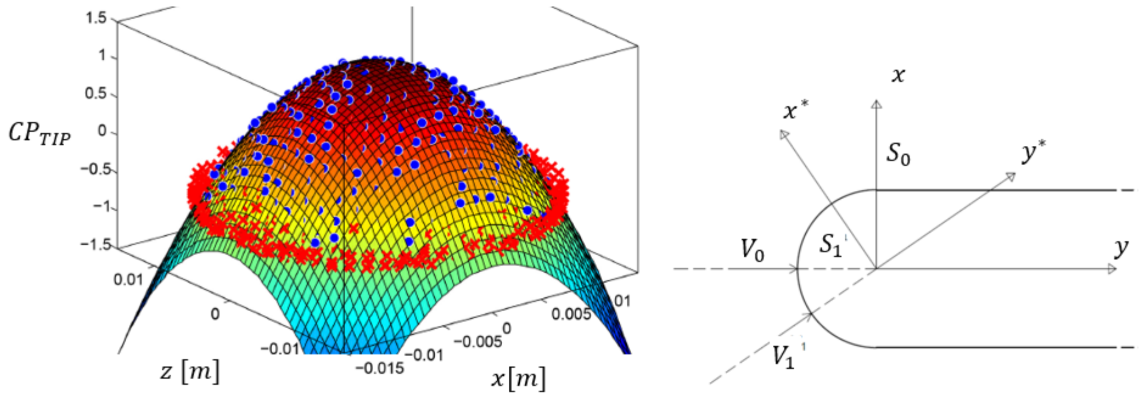
3.2 Aerodynamic design

The aerodynamic design of the probe has been strongly coupled with the reconstruction and health-monitoring functions development, by shaping the probe modules in order to obtain:

- low sensitivity of the tip pressure field around the stagnation point with respect to airflow direction (Fig. 4, Fig. 5 and Fig. 6);
- low sensitivity of the static pressure value at the measuring points with respect to airflow directions and speed;
- low sensitivity of the Outside Air Temperature (OAT) at the measuring points with respect to airflow directions and speed;
- minimum drag for the support module.

(a) (b)

Fig. 4. Examples of probe tip shapes:
(a) hemispherical; (b) spherical.



(a) (b)

Fig. 5. CFD analysis: (a) hemispherical tip; (b) tip reference frame.

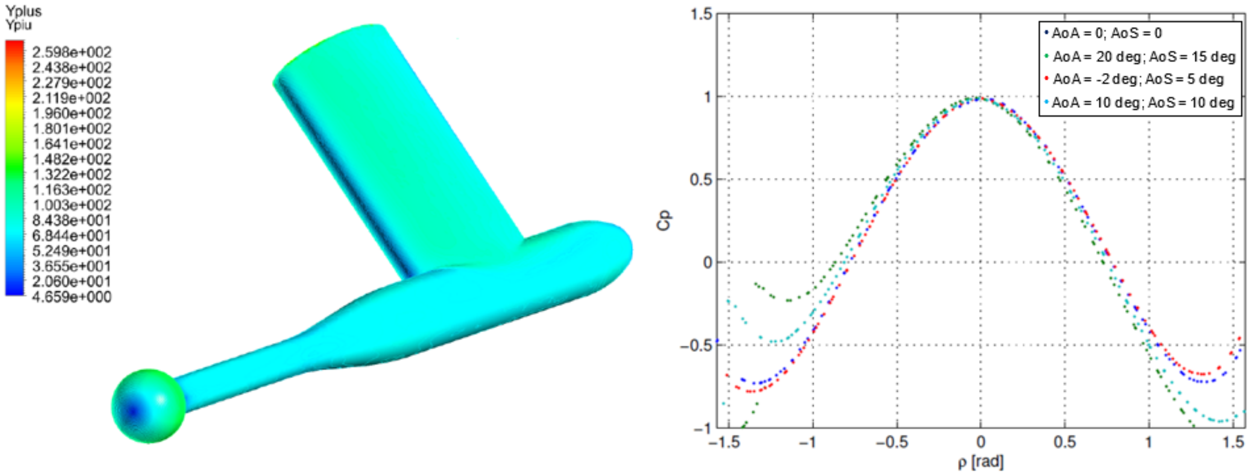


Fig. 6. CFD analysis: (a) spherical tip; (b) tip surface pressure for different AoA and AoS.

4 Algorithms' design

4.1 Reconstruction algorithm

The conventional approach to the air data reconstruction is based on the use of polynomial calibration functions, which receive as inputs the pressure measurements and directly provide as outputs the flow angles [1][2][3][4][5][6]. Alternative approaches with neural networks have also provided good results [10], but airworthiness certification concerns discourage the use of these techniques. The use of polynomial calibration functions, though convenient in terms of computational resources, requires an extensive calibration activity [7][8][9], in which the complete range of the airflow angles must be tested, with strong impact on development costs.

The proposed approach starts from the basic idea that, for small values of AoA and AoS (i.e. the typical working ranges for aircrafts), the pressure field around the stagnation point of a hemispherical or spherical probe tip is essentially independent from the flow angles (Fig. 6.b). Thus, the reconstruction can be performed by using an unique 2D calibration function ($\boldsymbol{C_{P\,tip}}$), referred to the pressure field at zero airflow angles.

The calibration function ($\boldsymbol{C_{P\,tip}}$, Eq. (1)) provides the tip pressure coefficient as a function of the tip surface coordinates defined around the stagnation point (Fig. 5).

$$C_{P\,tip}(x,z) = c_0 + c_{10}\,x + c_{01}\,z + c_{20}\,x^2 + \cdots + c_{02}\,z^2 + c_{30}\,x^3 + c_{03}\,z^3 \qquad (1)$$

The reconstruction is based on an iterative loop, in which, at each step, guess values of AoA and AoS are imposed, and the errors between the tip holes' pressures and the calibration function predictions are calculated. The iteration ends when the pressure errors are minimised.

In particular, the flow angles reconstruction receives as inputs the estimated values of Static Pressure (SP) and Total Pressure (TP), derived from a conventional polynomial technique, Eqs (2)-(3)

$$C_{P\,SP} = c_{s0} + c_{s1}\frac{P_{North} - P_{South}}{P_{centre} - USP} + \cdots + c_{s2}\frac{P_{West} - P_{East}}{P_{centre} - USP} \tag{2}$$

$$C_{P\,TP} = c_{T0} + c_{T1}\frac{P_{North} - P_{South}}{P_{centre} - USP} + \cdots + c_{T2}\frac{P_{West} - P_{East}}{P_{centre} - USP} \tag{3}$$

where c_{S0}, c_{S1}, c_{S2}, c_{T0}, c_{T1} and c_{T2} are polynomial coefficients (depending on Mach number), while $C_{P\,SP}$ and $C_{P\,TP}$ are the pressure coefficients of the static pressure and total pressure, defined in Eqs. (4)-(5).

$$C_{P\,SP} = \frac{USP - SP}{P_{centre} - USP} \tag{4}$$

$$C_{P\,TP} = \frac{P_{centre} - SP}{P_{centre} - USP} \tag{5}$$

Thus, once known:

- the coordinates of the five holes in the tip reference system x_m, y_m, z_m (where m = *North*, *South*, *Front*, etc.);
- the pressure coefficients at holes $C_{P\,m}$

$$C_{P\,m} = \frac{P_m - SP}{TP - SP} \tag{6}$$

- the polynomial coefficients $(c_{0}, c_{10}, c_{20}, \dots)$ of the $C_{P\,tip}$ function referred to zero airflow angles;

the reconstruction algorithm evaluates the angles AoA and AoS for which the coordinate transformation of the tip reference system implies the minimisation of the pressure errors with respect to the CP_{TIP} function.

Finally, the algorithm also evaluates the TAT by elaborating the OAT measurement from the thermistor in the bottom module vane together with the estimation of the dynamic pressure derived by TP and SP.

4.2 Health-monitoring algorithm

A specific health-monitoring algorithm has been developed for each output of the multi-function probe.

Concerning the SP value, considering that the static pressure is characterised by a very slow dynamics, a cross-lane monitoring technique is applied with four measurements: the two MEMS sensors outputs at current step and their values at previous step. A similar concept is also applied to the OAT measurement, by using the two thermistors and RH sensors in the stagnation chamber of the bottom module.

A different approach has been used for the tip pressure measurements. Since the iterative loop for the reconstruction of AoA and AoS can be performed with three only tip holes' measurements, different flow angles estimations, obtained with different sets of measurements, can be compared for health-monitoring purposes. By considering all the combinations of three measurements, ten sets are obtained and ten couples of AoA and AoS are available, Table 1.

	Elaborated measurements				
Reconstruction set ID	**Front**	**North**	**South**	**West**	**East**
AoA$_1$, AoS$_1$		■	■	■	
AoA$_2$, AoS$_2$		■	■		■
AoA$_3$, AoS$_3$	■	■	■		
AoA$_4$, AoS$_4$	■	■			■
AoA$_5$, AoS$_5$	■	■		■	
AoA$_6$, AoS$_6$		■		■	■
AoA$_7$, AoS$_7$			■	■	■
AoA$_8$, AoS$_8$	■		■	■	
AoA$_9$, AoS$_9$	■		■		■
AoA$_{10}$, AoS$_{10}$	■			■	■

Table 1. AoA and AoS reconstructions with groups of three tip holes' measurements

When the system is completely operative (no fault), the algorithm defines five groups, each one composed of four couples (AoA, AoS) that exclude a specific tip hole measurement, Table 2. For example, the group "NorthFault" is composed of all the four couples (AoA, AoS) that can be obtained without using the pressure measurement of the hole "North".

Reconstruction group	**Reconstruction sets ID**
NorthFault	(AoA_7, AoS_7), (AoA_8, AoS_8), (AoA_9, AoS_9), (AoA_{10}, AoS_{10})
SouthFault	(AoA_4, AoS_4), (AoA_5, AoS_5), (AoA_6, AoS_6), (AoA_{10}, AoS_{10})
WestFault	(AoA_2, AoS_2), (AoA_3, AoS_3), (AoA_4, AoS_4), (AoA_9, AoS_9)
EastFault	(AoA_1, AoS_1), (AoA_3, AoS_3), (AoA_5, AoS_5), (AoA_8, AoS_8)
FrontFault	(AoA_1, AoS_1), (AoA_2, AoS_2), (AoA_6, AoS_6), (AoA_7, AoS_7)

Table 2. Reconstruction groups definition

Once defined the reconstruction groups, the algorithm performs two monitoring functions in parallel: one acting on AoA, and the other on AoS. Each of the two monitoring function operates as follows:

- the four AoA (AoS) values of each group are set in increasing order;
- the differences between the two extreme values and the mean one is calculated;
- if both differences are lower than a fixed threshold, no pressure fault is detected in the group, otherwise pressure fault is detected in the group;
- the fault isolation is then performed by identifying the only reconstruction group in which no fault is detected

For example, if a fault is related to the measurement of the "North" tip hole, the fault causes a threshold crossover in all groups except the one named "NorthFault", because this is the only group for which the reconstruction is performed without the "North" tip hole (Table 1 and Table 2).

Conclusions

A digital fully-integrated multi-function probe for air data sensing has been developed in the work. The probe design is based on an innovative multi-hole architecture in which the air entering the probe holes is directly led to a PCB with MEMS sensors by means of short channels obtained in the body of the probe itself via 3D printing manufacturing. Innovative reconstruction and health-monitoring algorithms have been developed for increasing accuracy and assuring fault-tolerant operations. The proposed health-monitoring strategy is capable of detecting and isolating a pressure fault (sensor fault, hole occlusion, etc.), by operating multiple reconstructions of the flow angles values on subsets of measurements. The probe design has been carried out with an interdisciplinary approach, by harmonizing aerodynamic concerns, the acquisition/elaboration data issues, and the structural manufacturing. A first probe prototype has been manufactured to verify the capabilities and the performances of the system, and low-speed wind tunnel tests are planned to verify the potentialities of the proposed solutions.

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