Escola Politècnica Superior de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

TREBALL DE FI DE CARRERA

TÍTOL DEL TFC: Design of an enhanced air data sensor for a Very Light Aircraft

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

AUTOR: Oriol Castro Arnau, Anna Folch Codera

DIRECTOR: Cesare Cardani

DATA: 26 de febrer de 2009

Title: Design of an enhanced air data sensor for a Very Light Aircraft

Author: Oriol Castro Arnau, Anna Folch Codera

Director: Cesare Cardani

Date: February, 26th 2009

Overview

This project is the following part of a previous thesis about the design, development and implementation of a data acquisition system: "Development of an Integrated Flight Test Instrumentation System for Ultra Light Machines" called *Mnemosine* by Alberto Rolando.

Participating in the improvement of the part *Urania.* Once the new design was decided and the implementation was done, the calibration of the new Pitot – boom has become a critical part where the pressure sensors, temperature sensor and the Pitot tube has been analyzed and tested in a wind tunnel.

In this document the pre-documentation for the experimental test, the results and conclusions including the elaboration of a program in Matlab in order to calculate those important magnitudes and to show in an easier way all the results is presented.

ÍNDEX

INTRODUCTION... 1

CHAPTER 1. STUDY ABOUT THE PREVIOUS PROJECTS 2

1.1. Development of an Integrated Flight Test Instrumentation System for Ultra Light Machines” 2

1.2. “Progettazione e realizzazione di un sistema d'aquisizione dati aria per prove di volo” 4

CHAPTER 2. MEASURING THE VARIABLES: THE SENSORS...................... 7

2.1. The Pressure 7

2.2. The Temperature.. 8

2.3. Angles of incidence alpha and beta 9

CHAPTER 3. ERRORS AND CONDITIONS IN THE ACQUISITION SYSTEM11

3.1 The Pressure 11
3.1.1 Total Pressure 12
3.1.2 Static Pressure 12

3.2 The Temperature.. 13

3.3 Angles of incidence alpha and beta 13

CHAPTER 4. THE CALIBRATION 15

4.1 The Pressure 15
4.1.1 Pressure Sensor Calibration... 16

4.2 The Temperature.. 18

4.3 The angles of incidence alpha and beta 18
4.3.1 Manual Calibration.. 18
4.3.2 Laser Calibration 19
4.3.3 Calibration in de wind tunnel 20

CHAPTER 5. SYSTEM CALIBRATION PROCESS 22

5.1 Previous analysis of the wind tunnel tests.. 22
5.1.1 Pito boom's characteristics and configuration 22
5.1.2 Results Estimation.. 24

5.2 Calibration test summary and results 29
5.2.1 Test description 29
5.2.2 Taking the values 31

5.2.3 Results 32

5.3 Estimation of the pressure sensor error 34
5.3.1 Converter A/D 34

5.4 Analysis about Pitot error impact above ADS information 36
5.4.1 Calculation 36
5.4.2 The Program 38
5.4.3 The results 50

5.5 Non accuracy due to refer the pitot errors to qc 52

FINAL CONCLUSIONS 55

PERSONAL EVALUATION 56

BIBLIOGRAPHY 57

INDEX OF TABLES

CHAPTER 1. STUDY ABOUT THE PREVIOUS PROJECTS 2

Table 1.1 Data of old Pd sensor. 2

Table1.2 Data of old Ps sensor. 3

Table 1.3 Data of old T sensor. 3

Table1.4 Data of old potentiometer. 3

Table 1.5 Data of the new static pressure sensor. 5

Table 1.6 Data of the new dynamic pressure sensor. 5

Table 1.7 Data of the new temperature sensor 5

CHAPTER 4. THE CALIBRATION 15

Table 4.8 Results of the Ps calibration. 17

Table 4.9 Results of the Pd calibration. 17

Table 4.10 Results of the alpha calibration. 20

Table 4.11 Results of the beta calibration. 21

CHAPTER 5. SYSTEM CALIBRATION PROCESS 22

Table 5.12 Data calibration pitot-boom. 32

INDEX OF FIGURES

CHAPTER 1. STUDY ABOUT THE PREVIOUS PROJECTS 2

Fig. 1. 1 Appearance of the old probe 4

Fig. 1.2 FTB 00092 AX 4 [measures in inchs] 6

CHAPTER 2. MEASURING THE VARIABLES: THE SENSORS 7

Fig. 2.3 Scheme of a pitot tube. 7

Fig. 2.4 Detail of our pitot extracted from the datasheet of the probe. 8

Fig. 2.5 Scheme of temperature sensor operation 9

Fig. 2.6 Temperature's sensor Fitting-out circuit 9

Fig. 2.7 Sketch of the installation and operation of the vans to measure AOA i SSA 10

Fig. 2.8 Intern scheme of the potentiometer. 10

CHAPTER 4. THE CALIBRATION 15

Fig. 4.9 Image of the ADTS utilized. 16

Fig. 4.10 The angle reference for the manual calibration. 19

Fig. 4.11 Scheme of the laser vane test. 20

CHAPTER 5. SYSTEM CALIBRATION PROCESS 22

Fig. 5.12 Scheme of the pitot tube. 22

Fig. 5.13 Our Pitot tube entrance design 23

Fig. 5.14 Standard Pitot tube entrance design 23

Fig. 5.15 Ps Error respect qc as an M function 24

Fig. 5.16 Ps Error respect qc as an alpha/beta function 24

Fig. 5.17 Pitot total pressure tuve 25

Fig. 5.18 E-6 pitot total pressure tube 26

Fig. 5.19 Results of the test with E-6 pitot tube 26

Fig. 5.20 Different results of the Static pressure error when the tube is lineup 27

Fig. 5.21 General picture of the wind tunnel and detail of the probe chamber with the boom installed. 30

Fig. 5.22 Images of the anchoring system of the probe inside the wind tunnel. 30

Fig. 5.23 Image of the electronic of the system 31

Fig. 5.24 Correction of the dynamic pressure respect angle alpha. 33

Fig. 5.25 Correction of the dynamic pressure respect angle beta 33

Fig. 5.26 Correction – alpha and beta – for Red = 37000... 34

Fig. 5.27 Zero error graph. 35

Fig. 5.28 Full Scale error graph.. 36

Fig. 5.29 Main menu 46

Fig. 5.30 Data menu.. 46

Fig. 5.31 Ways to introduce the values 47

Fig. 5.32 Error message.. 47

Fig. 5.33 Graph options 48

Fig. 5.34 Graph.. 48

Fig. 5.35 Saved files 49

Fig. 5.36 Final graph.. 49

Fig. 5.37 Error of altitude in function of V and alpha – beta 50

Fig. 5.38 Error of velocity in function of V and alpha – beta.. 51

Fig.5.39 Error of Mach number in function of V and alpha – beta...................................... 52

INTRODUCTION

We can define this project as the following part from one previous project which it has as aim to improve one part from the PhD project done by the professor Alberto Rolando: “Development of an Integrated Flight Test Instrumentation System for Ultra Light Machines”.

The main motivation of this project is that a system like this still does not exist in the aeronautic market. The systems which the big manufacturers provide us are extremely heavy and expensive, for this reason it is not suitable for this kind of aircraft which everyday has more supporters and the small manufacturers cannot cope with all the work. Consequently the main aim was to create a system adaptable to the different VLA models, easy to use and modify with low costs.

The final result is the system called *Mnemosine.* From all the *Mnemosine* subsystems, our project is going to analyze the one called *Urania.*

Once all the system *Mnemosine* was done and the tests started, they quickly realized the low accuracy of the data acquisition system. The probe's construction, as its installation and the sensors used did not show a good precision in the results. For that reason a new project about a re-design, improvement and replacement of the *Urania* system started.

Together with two Italian students who are doing their laurea's project, we are going to do the most important tasks: a description about the sensor's errors, its calibration, preparation and realization of a test in the wind tunnel and an analysis about the possible effects of the pressure errors through the parameters Altitude, Speed and Mach number.

First of all we have studied the previously projects to learn what are about, in which point of development they are, in order to know what is the goal of our project. After that we need to know the behavior of the different sensors, how each part of the probe works, what errors we need to bear it in mind, how we can calibrate each one and how we are going to do the test in the wind tunnel. Once we have done the test, we are going to create a Matlab program in order to analyze the results. And finally there are the conclusions.

CHAPTER 1. STUDY ABOUT THE PREVIOUS PROJECTS

1.1. *Development of an Integrated Flight Test Instrumentation System for Ultra Light Machines”*

On April 2008 this project was handed in the University Politecnico di Milano. Its aim is creating a flight test system adapted to the civil aircraft known as Ultra Light Machines (ULM) or nowadays Very Light Aircrafts (VLA).

The final result is the system called *Mnemosine.* It is a modular system which contains different independent subsystems connected by communication buses joined to a central unit. In order to satisfy the simplicity of the system, the operations done during the flight are minimum; the system saves all the data from every subsystem indicating the time. Consequently all the data processing can be done later in a personal computer.

From all the *Mnemosine* subsystems, our project is going to analyze the one called *Urania.*

Urania is the Air Data System from the project *Mnemosine*. It is made up of the following transducers: a dynamic pressure sensor MPXV-5004-G from Freescale Semiconductor, a static pressure sensor MPX51000 from the same manufacturer, a temperature sensor AD22100 and finally two potentiometers SP2801 from Novotechnik responsible for measuring the angles of incidence *alpha* and *beta*. Next we can observe few summary tables showing us the most important sensor's variables:

Table 1.1 Data of old Pd sensor.

Range	da 0 a 3,92 KPa
Maximum pressure	16 KPa
Temperature range	-30°C to +65°C
Sensitivity	10 V/KPa
Accuracy	±1,5 %FS

Table1.2 Data of old Ps sensor.

Range	da 15 a 115 KPa
Maximum pressure	400 KPa
Operating temperature	0 +85
Sensitivity	45 mV/KPa
Accuracy	±2,5 %FS
Response time	1 ms

Table 1.3 Data of old T sensor.

Range	-50°C to +150°C
Sensitivity	22.5 mV/K
Accuracy	±2 %FS
Linearity	±1 %FS

Table1.4 Data of old potentiometer.

Torque	0.2 N·cm
Weight	32 g
Electrical resistance	5 Ω
Repeteability	¡0,001 %
Linearity	±0,3 %FS

In order to pick up and read both pressures they use a rudimentary Pitot Tube in the shape of L, and in order to measure both angles they decided to use two metallic sheets in the shape of triangle which lines up with the airflow. Once the different sensors and all the previous elements are joined, the final appearance of the probe from Air Data System is:

Fig. 1. 1 Appearance of the old probe

This probe is welded in the end of a metallic bar long enough to avoid the presence of the wing in the magnitude's values. The other extreme is fixed under the wing of the test aircraft, it is the model P92 ECHO-80 made by the company Capua-based Construzioni Aeronautiche Tecnam S.r.l and it is property of the Aerospace department of the university.

Once all the system *Mnemosine* was done and the tests started, they quickly realized the low accuracy of the data acquisition system. The probe's construction, as its installation and the sensors used did not show a good precision in the results. For that reason a new project about a re-design, improvement and replacement of the *Urania* system started.

1.2. “Progettazione e realizzazione di un sistema d’aquisizione dati aria per prove di volo”

The process to create a new system includes different stages: first stage is a study about the prerequisites, second stage is a choice and selection about the new sensors, third one is the installation of all the elements and the final stage is an explanation of the new data's evaluation process.

A consequence of this re-design is the selection of new sensors as well as a new system to assembly and fixes the probe. The new sensors are HCA0611ARH8 for the static pressure, HCLA0050EU for the dynamic pressure, E22011 from Rosemount Inc. for the temperature and finally two potentiometers to calculate the angles of incidence. The new summary tables are:

Table 1.5 Data of the new static pressure sensor.

Fondo scala	$60 \div 110$KPa
Pressione massima	3000 KPa
Compensazione termica	0^{o}C $\div 85^{o}$C
Accuratezza	± 1.0%FS
Convertitore A/D	15 bit
Ritardo	2 ms

Table 1.6 Data of the new dynamic pressure sensor.

Fondo scala	$0 \div 5$ KPa
Pressione massima	75 KPa
Compensazione termica	-25^{o}C $\div 85^{o}$C
Errore di linearità	± 0.25%FS
Convertitore A/D	12 bit
Ritardo	0.5 ms

Table 1.7 Data of the new temperature sensor.

Fondo scala	$-62 \div +85$ ^{o}C
Quota operativa	$0 \div 15250$ m
Fattore correttivo η	≤ 0.002
Costante di tempo τ	$10 \div 50$ s
Autoriscaldamento	$0.03 \div 0.08$ ^{o}C/mW

The new sensors introduce an improvement but also the way that the sensors integrate into each other. Thanks to Alenia Aermacchi the project has relied on a commercial Flight Test Boom to implement their sensors, specifically it is the model FTB 00092 AX 4 from Rosemount inc. And its structure is:

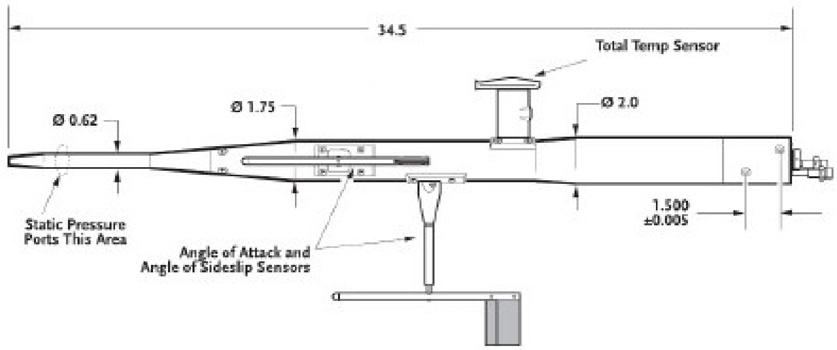

Fig. 1.2 FTB 00092 AX 4 [measures in inchs]

Therefore this project ends with the construction of the new air data system, a study about the behavior of the news sensors and the data's processing done. However, it is not an ended project, because there is not a sensor's calibration, the characterization of the individual errors and integration errors as well as a flight test.

CHAPTER 2. MEASURING THE VARIABLES: The sensors

The probe of our ADS has all the different sensors to measure 4 concrete parameters. Through the system will elaborate in the post processing all the other important air values. This processing has to be done as accurate, correct and reliable as possible. Next we are going to explain how we can measure the parameters.

2.1. The Pressure

Possibly the pressure is the most critical parameter because from both pressures we can calculate the flight speed and also very important, the altitude. For that reason the system which measures the pressure has to be accurate, correct and reliable.

From the beginning of the aeronautic science, collecting information about the aircraft and its environment has been the soul of this battle, and the pressure is not an exception. During all these years the tool used to measure it has nearly not been altered, it is the Pitot Tube, a simple system but in which has been done a lot of test due to the complex behavior of the airflow.

Fig. 2.3 Scheme of a pitot tube.

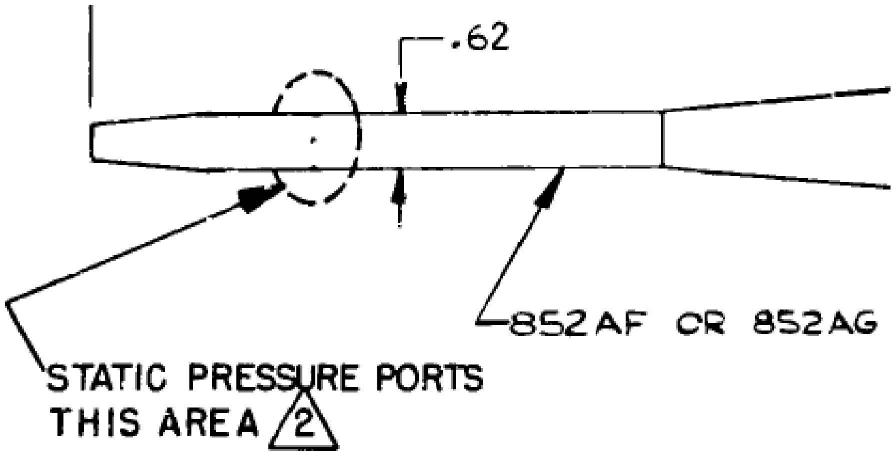

Fig. 2.4 Detail of our pitot extracted from the datasheet of the probe.

In our system there is a pitot tube as the one in the sketch situated in the probe's extreme and two pressure sensors. There is a main overture which if it is line up with the airflow provides us the total pressure and through another small side overtures situated in a distance from the end of the pitot tube provides us the static pressure. Next chapter we are going to explain deeply about the design of the pitot tube, the location of the overtures and how it affects in its behavior. As we have said before, we have a pressure static sensor which we will connect into the static ports and a differential sensor which provides us the dynamic pressure and we will connect it in the static and total pressure ports. These sensors work using the distortion of a piezoelectric membrane due to the effect of the pressure variations, this distortion is noticed and converted in a output tension value equivalent at the input pressure.

2.2. The Temperature

The temperature value is also important and there are some ways to measure it. In our case we are going to use a temperature sensor used in aircrafts and helicopters that its number Mach is not higher than 0.6. It is going to be situated in the back part of the boom, where there are going to be the electronics of the system, containing the sensible element and the fitting-out circuit.

The sensitive element is a RTD: Resistance Temperature Detector, it is a resistance which changes its value depending on the environment temperature. The resistance used is known as Pt 500, because the material used is platinum and has a $R0 = 500\ \Omega$. The sketch of its internal operation and design is below:

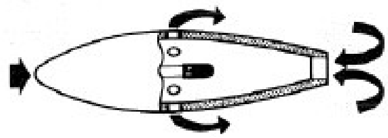

Fig. 2.5 Scheme of temperature sensor operation.

As we can observe the sensor is closed by an aerodynamic design, it contains two side overtures which create a low pressure area with the airflow circulation. This fact and the overture in the back makes that an airflow enters inside in the opposite sense of the aircraft speed. Consequently the optimum conditions of the RTD measurement are created. The sensors only show us a resistance's variation, for this reason we need to develop an electric circuit which creates it into a tension variation. This is the function of the fitting-out circuits. The most traditional one is the resistance bridge simple or complex, but in our case the 4 wire voltometric method was chosen:

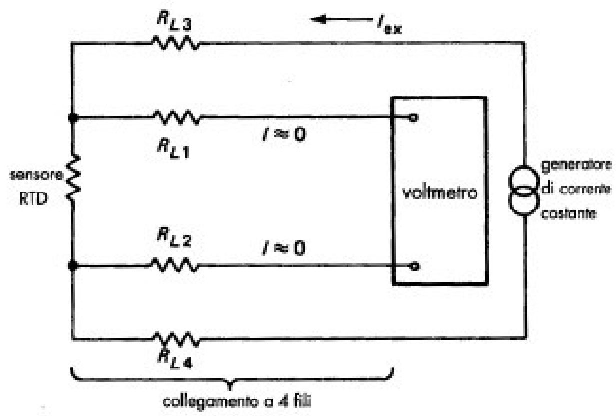

Fig. 2.6 Temperature's sensor Fitting-out circuit

2.3. Angles of incidence *alpha* and *beta*

The last parameter measured by the system is the angle of incidence, specifically it is the AOA: Angle of Attack and of SSA: Side Slip Angle. The operation is simple, the probe has installed two vanes with 90 degrees between them, the first one in one side and the other one in the lower part.
Once the probe is inside the airflow these two sheets are aerodynamically and dynamically stable and both are going to lie up with the airflow.

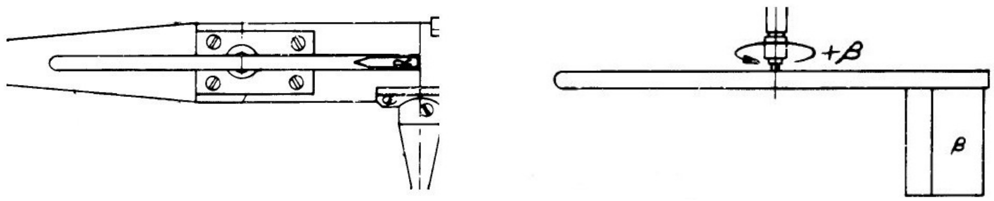

Fig. 2.7 Sketch of the installation and operation of the vans to measure AOA i SSA

If the relative position of the probe is not 0 degrees, this angle applied into the vans is going to be transmitted to the potentiometer.

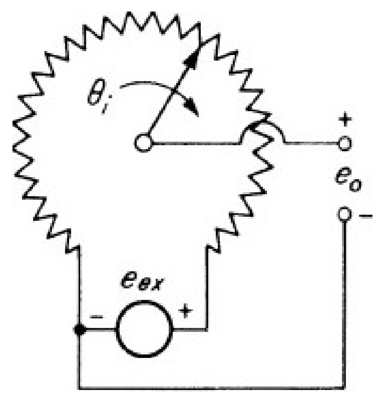

Fig. 2.8 Intern scheme of the potentiometer.

CHAPTER 3. ERRORS AND CONDITIONS IN THE ACQUISITION SYSTEM

When we work with sensor systems, we try to read a physic magnitude and transform it into something that we can manage and quantify. The most traditional method consists of transforming the physical measure into tension in order to work electronically and to convert the signal that we obtain into a digital data. Along all these transformations we can find errors which makes the measured value and the real value different. For this reason the sensor system has to be studied in detail to minimize all the errors.

According to the document NASA Reference Publication 1046 the main errors that we can find in the air data sensor system are:

- Total and static pressure errors of the pitot-static installation and the temperature error of the temperature probe.
- Errors due to time lag in the transmission of the pressures.
- Errors relating to the operation of the instrument mechanism.

We have three different sources where we have to concentrate our attention in order to reduce into the minimum all the errors. The last point are the errors introduced by the mechanism from our system. The main problem is the nonlinearity of the physic magnitudes and the conversion analogical – digital. In our system these errors has already been counted and the electronics has been chosen and installed to delete or correct the errors.

Also we should analyze the errors from the element sensor, if it does not interpret the correct result or it does not answer as specifically as the manufacturer has anticipated. We can consider it already correct because one of the previous tasks has been the calibration of every sensor separately.

3.1 The Pressure

Previously we have seen that we have two important sources of errors in the pressure measurement. We are going to study the different possible causes to determine which errors we need to be careful of. For this reason we use the document NASA Reference Publication 1046 as a guide and the information about the system from the projects in the 1.1 and 1.2.

First of all we discuss the topic of lag of time. This problem appears only in the pressure measurement and it is caused by the distance between the sensor and where the air is captured, and this causes a variation of the pressure. We

can divide it into two different errors, the first one represents an acoustic problem and the second one a problem about the variation of the pressure.
The acoustic error is not considerable because the distance between the sensor and the pitot is short, this fact do not let the pressure waves alter drastically from one point to the other. The problem about the pressure is bigger than the last one but we are using an electric pressure sensor which works with a small volume and this error normally is not considered.

One error that we can not underestimate and its correction is an important aim of this project is the installation error. Using the same method as in the reference document we are going to analyze the errors due to the design, configuration and installation of the pitot tube. We are going to calculate separately the error in the total pressure and in the static pressure, also the errors when the tube is line up with the airflow and when we have a variation in the angle.

3.1.1 Total Pressure

We consider the error when the tube lines up with the airflow and inclined:

- Line up: If we want to install correctly the pitot tube, it must be enough far from the aerodynamic surfaces which can disrupt the airflow, for example the wings or the engines and gas exits. If this is the case the pressure measure would be correct. An analysis about the distance about the tube location respect the attack wing side in order to delete the disruptions of the airflow has been done. The results of this study determined that in a chord and a half in front the wing these effects would not be a problem. After this study the boom which connects the probe with the aircraft was built.
- Inclined: in this case an inevitable error is introduced. Its magnitude depends on the design of the pitot tube entrance, for example if the entrance is symmetric, the errors will be the same if the tube is inclined positively or negatively. In order to determine its value, we have to do a test in the wind tunnel.

3.1.2 Static Pressure

There are different methods to measure the static pressure in an aircraft, in our case, as we know; we use some static pressure ports located around the tube. The presence of the tube which alters the airflow interfering in the measurement is the cause of this error. For this reason the error is created by the pressure distributions along the tube when it is lined up and the pressure distributions around the tube when it is inclined.

- Line up: the error in this condition is done by the pressure distribution which is created in the tube, in the distance of one diameter from the entrance there is a negative pressure which increases until becoming a free pressure in five diameters from the beginning. We need to verify the distance where the static pressure ports are in the correct location. Our case is a commercial probe so the manufacturer has already counted all these aspects during the design.

- Inclined: the error is produced by the variation of the pressure distribution around the tube. For example, if we have an angle alpha inclined positively, the pressure above both sides of the tube will not be the same. This fact and the circular distribution of the different static pressure ports introduce an error. In order to quantify it we need to do a real test, for example using a wind tunnel.

Also we can find errors introduced for the design used for example in the distribution of the ports, its size, etc. As we have said in the total pressure case, the manufacturer has already considered it.

3.2 The Temperature

In this case the most important problems are from the sensor and not from its installation. First of all using a sensor with a cover to protect it, let us delete problems as the water evaporation, the formation of ice when it works in temperatures below zero degrees or the effect of the solar radiations.

All the effects that could be a source of errors have been analyzed and shown by the manufacturer and we can determine if these effects are a problem or not. The sensor's performance, when the speed increases as well as the Mach number, is one of these sources. Analyzing the manufacturer's graphs and knowing our range of Mach (0.05 – 0.25), we can see that the performance in the worst case would be 99.8 %. Another important thing is the sensor's answer with temperature variations, how the sensor answer when there is a hard change. Analyzing the information provided by the manufacturer we determine that in the worst case, the answer would be between 10” and 50”. In our conditions we do not have any high change of temperature. Finally the last parameter is the self warming-up which is created by an electric flow through the sensor making the temperature of the resistance increase. Doing an estimated calculation we obtain that in the worst case it would not be higher than 0.1 ºC/mW.

3.3 Angles of incidence alpha and beta

The main source of errors is the system which transmits the inclination. This was studied with the last system because the boom which connected the wing with the probe was only a metallic tube. When they did the flight tests, they detected vibrations and movements which caused the incidence values was not correct. This fact was one of the main important items in the re-design of the system. In the end of this project, the flight test has not done yet, so we do not know the final result.

The only source of errors could be the potentiometer if we don't apply a correct calibration. This part is analyzed in the next point.

CHAPTER 4. THE CALIBRATION

According to wikipedia the definition of calibration is:

Calibration is the validation of specific measurement techniques and equipment. At the simplest level, calibration is a comparison between measurements of known magnitude or correctness made or set with one device and another measurement made in as similar a way as possible with a second device.

As we have analyzed before, there are some error sources which could be a problem, for this reason we need to do a calibration process. In this process we determinate the magnitude of these possible errors and we explain the necessary correction.

From the beginning we have explained the most important calculations will be done after the flight test, so all the error sources will be corrected inside the program code which executes this processing. It makes easier the work because we do not need to correct nearly anything of the system which will be fixed in the aircraft.

4.1 The Pressure

The calibration process of the pressure measurement we can divide it in two stages. The first one is the calibration of the pressure sensors and the second one is the calibration of the pitot tube.

In the first stage, as it has already been explored previously, we obtain with an experimental method, the sensor's behavior. We need to know if the sensors operation and answer is the same as the manufacturer says. This process introduces the sensors in a device where we can manipulate and know the input pressure while the sensors are showing us the value.

Once we have done it, we can start the second stage of the calibration, it consists to analyze the answer of all the pressure system under certain conditions. There are some errors that can appear while we are measuring the total pressure and static pressure using the pitot tube. In order to quantify these errors we are going to do a test in the wind tunnel, in the points 5.1 and 5.2 there is the preparation and the summary of this test. The reasons of realizing the test using a wind tunnel are:

- Environment controlled
- Possibility of measuring different speeds using a stable way.
- Easy to prepare and execute.
- Letting us realize modifications in the test while it is running.
- Costs and time minimum.

- The university has an adequate wind tunnel

As an extra process for the calibration it would be better to do a test during a flight. Install all the system in an aircraft; it can be P92 or another one. However, this test has not been planned so it is not included in this project.

4.1.1 Pressure Sensor Calibration

The calibration process has not been applied only to the sensors, also all the electronics and the converter A/D has been calibrated. For that reason in the test, the input was a pressure and the output was counts from the converter. The calibration has been possible thanks for Alenia- Aermacchi de Varese who has let us to use one of their systems which simulates the pressure conditions that we would have in a specifically altitude depending on the model (ISA or another).We can use this system for the dynamic pressure sensor and the static pressure sensor, in the case of the dynamic pressure we would choose the parameter qc as the difference between a variable total pressure and a fixed static pressure. This system is called ADTS: Air Data Test System, it is the model DRUCK ADTS 405. In order to consider correct the values from this system, its precision has to be three times more than the precision from the system to calibrate. The test was basically static; it means that all the values were taken once the system was stabilized.

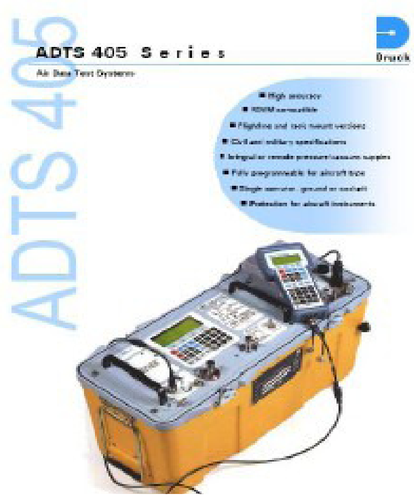

Fig. 4.9 Image of the ADTS utilized.

In the beginning of the test it is necessary to record the parameters which could influence the values as environment pressure, temperature or relative humidity. The characteristics of both tests are:

- Static Pressure: the test consists in simulating an increase of altitude from zero to the operative limit of the P-92. For this reason every time that the altitude increased the pressure changed. Taking the output values in counts for every “bloc”. Once we arrived to the maximum altitude, we proceed doing the same in the opposite sense.

- Dynamic Pressure: this process is similar, but this time we simulated a variation of the speed from zero to the limit of P-92 located around the 250 km/h. Once we arrived to the maximum value, a reduction of the speed started. Both stages has been done each N km/h.

The analysis of the results and its presentation in order to know the behavior of the sensors, a Matlab program was done. The following tables show us the results of the tests.

Table 4.8 Results of the Ps calibration.

FS_counts	2^{15}
FS_press	1100 mbar
r	1
S	54.5185 counts/mbar
D	- 31017 counts
Equation Calibration	$Counts = 54.5185*PS - 31017$
Equation Finale	$PS = 0.0183*counts + 568.9225$

Table 4.9 Results of the Pd calibration.

FS_counts	2^{12}
FS_press	50 mbar
r	1
S	547.4044 counts/mbar
D	1422.8 counts
Equation Calibration	$Counts = 547.4044*PD + 1422.8$
Equation Finale	$PD = 0.0018*counts - 2.6904$

The different values are:

- FS_counts: is the sensor full span in counts of the converter.
- FS_press: is the same as before but using mbar.
- r: index of regression.
- S: slope of the calibration.

- D: value of the zero in the calibration.
- Equations: the two equations used in calibration, the first with an input in counts and the second in pressure.

Analyzing the results we know that they are similar to the results of the old sensors, and the system is nearly linear so the errors are small. With the numeric results of the test we can say that the new system has a higher quality than the previous one.

4.2 The Temperature

The temperature sensor calibration is easier than the pressure sensor. As we have explained before the errors only can be introduced by the sensor element. For that reason the calibration only needs to introduce the sensor inside a controlled environment and taking all the values from the sensor and from the reference sensors. Once we have enough values we compare both data in order to obtain a regression about the sensor's behavior. This process is going to let us know if there is a point where its behavior is not correct.

4.3 The angles of incidence *alpha* and *beta*

This calibration process does not have any similarity with the previous ones. The main reason is that we do not have any documentation about the behavior of the potentiometer and the aerodynamic surface. We do not know the relationship between the angle and the output value of the potentiometer. For this reason we have to do a test, in order to evaluate the behavior of both potentiometers and calculate its answer. We have done three suggestions:

- Manual Calibration: it was done few months ago and the results were not good.
- Laser Calibration: it has not been done yet. According to the preliminary calculations, the results would be better than the previous system.
- Calibration of the wind tunnel: we did it while the calibration of the pitot tube was done. The results have been good. This test isn't a replacement of the previous test, it is a way to obtain extra information about the behavior of the vane.

Next we explain how every method works and which the results are.

4.3.1 Manual Calibration

This calibration is a simple method which consists to put the vans manually in an angle. In order to use this method we need to establish a reference as the sketch below. Once the angle has been established, we read the output of the potentiometer and we do the same different times. The most important problem is the low accuracy, first of all lining up the vane with the angle, second the low stability when it has been established. For that reason in the end the results were very different from the real ones.

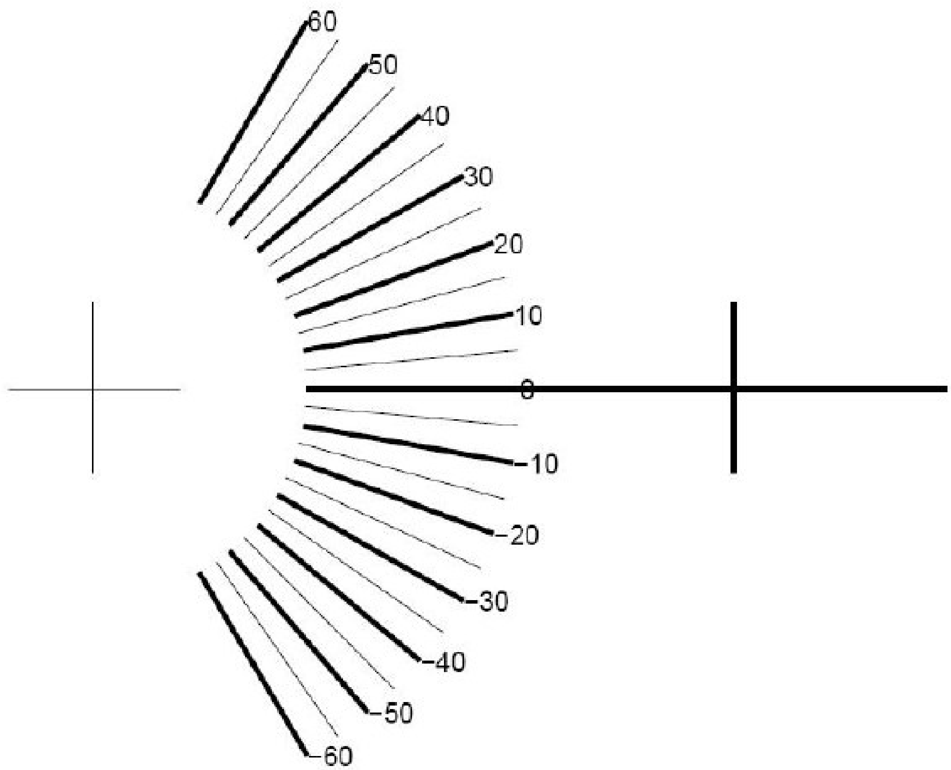

Fig. 4.10 The angle reference for the manual calibration.

4.3.2 Laser Calibration

The main aim of this method is the improvement of the previous results. The idea is simple, consisting in install a laser in the vane that we are calibrating.
We need to be sure that the probe is correctly fixed, and the vane normal respects the floor. Once we have done this we fix a mirror in the wall where we project the laser, we have to reflex the laser in the mirror and it returns in the same direction through the wing. When it has been achieved we can determine that the wind is perpendicular to the surface, and we can continue with the test.
In this second stage we have to apply a certain angle to the vane, so the laser leaves the zero established and moves into right or left. When the angle is achieved, we register the output of the potentiometer and take the position of the laser. We can determine the angle that we were applying using trigonometry and the distance between the zero and the wall.

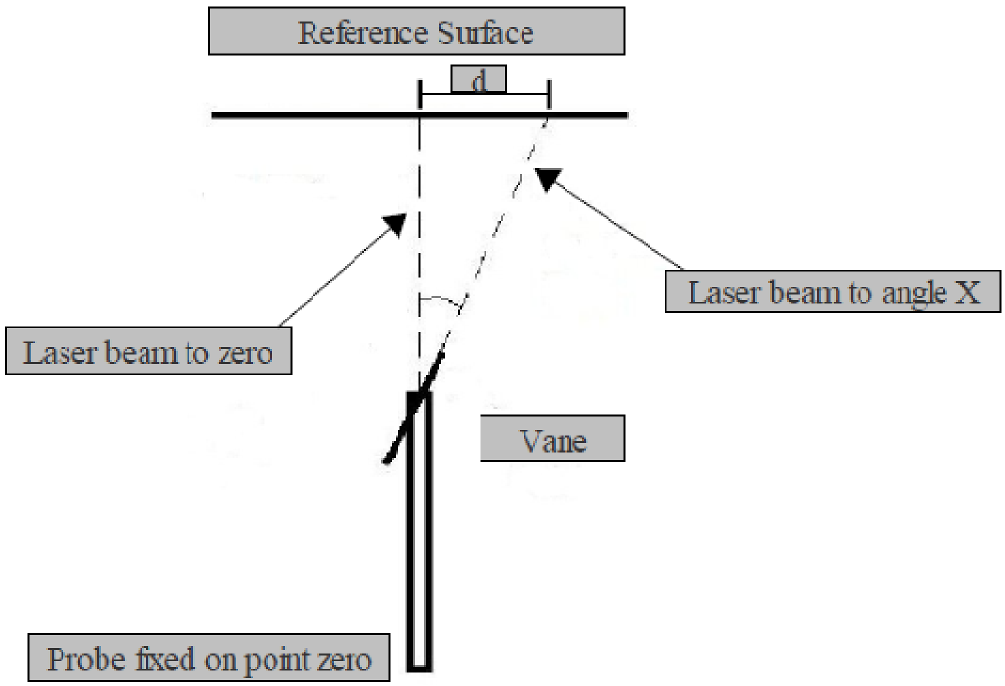

Fig. 4.11 Scheme of the laser vane test.

4.3.3 Calibration in de wind tunnel

This method uses the test about the calibration of the pitot tube in order to obtain the values of the potentiometers. As we have explained in the point 2.1 to calibrate the pitot tube we need to take values in different incidence angles while we are doing it, we also analyze the potentiometers. Using this method we have angles more accurate and stable than the first method explained and we could have a view of the aerodynamic behavior of the entire system. The steps are the same that in the pressure calibration because we do it at the same time. After processing the data the results are:

Table 4.10 Results of the alpha calibration.

FS_counts	2^{10}
FS_ang	25º
r	0.9997
S	11.72 counts/degº
D	268.57 counts
Equation calibration	$Counts = 11.72*alpha + 268.57$
Equation Finale	$Alpha = 0.0853*counts - 22.8971$

Table 4.11 Results of the beta calibration.

FS_counts	2^{10}
FS_ang	20º
r	0.9975
S	- 11.4256 counts/degº
D	442.5556 counts
Equation calibration	*Counts* = - 11.4256**beta* + 442.5556
Equation Finale	*Beta* = - 0.0875**counts* + 38.7338

Comparing the new results with the results from the previous system we can say that the new one has a better quality but we really cannot compare both results because we have not done the same tests. In the new system the angle alpha is measured with accuracy about 0.85º, a correct value, instead the angle beta has accuracy about 1.91º.

CHAPTER 5. SYSTEM CALIBRATION PROCESS

5.1 Previous analysis of the wind tunnel tests

First of all we are going to study the results that we can find during our calibration's test in a wind tunnel. We can achieve it using results from other tests which have been done before. Knowing the pitot tube's main characteristics we are going to search similar tests, analyze them and extract estimated results.

The tubes used are not the same model and the speed conditions are different, but we can find a first view about our future results.

5.1.1 Pito boom's characteristics and configuration

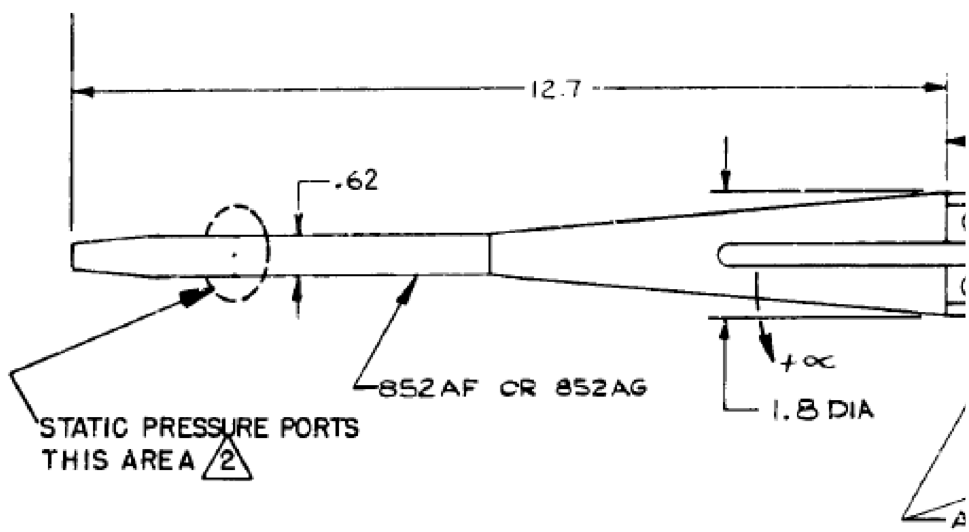

Fig. 5.12 Scheme of the pitot tube.

The diameter which appears in our datasheet is 0.62 inches, the scale used is ½ and the inch's value is 2.54 cm. Consequently our diameter is 3.1496cm.

If we use as a reference the 12.7 inches where the pitot's tube ends, we can know the static pressure ports are located in 12.7/2 = 6.35 and 6.35/2=3.175, about 2.8 inches from the tub's beginning, that means it is situated in 14.224 cm.

The static pressure ports are in 4.5 times D.

We know that there are 4 static pressure ports, but we don't have any information about the angles. The design of our pitot's beginning is showed in the datasheet.

The pitot's tube is a revolution solid which is symmetric in X and Y axis, we can establish it is a pitot's tube model f or g.

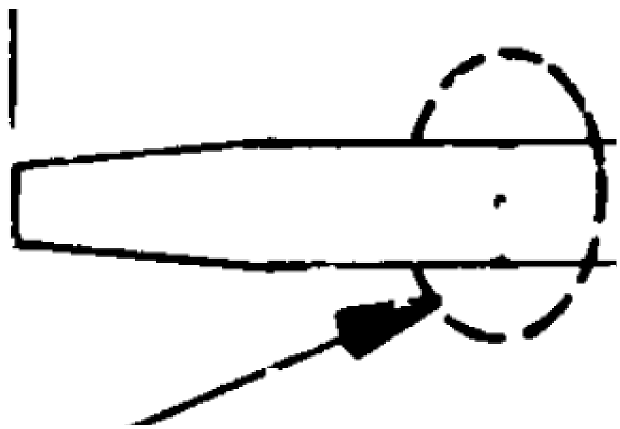

Fig. 5.13 Our Pitot tube entrance design

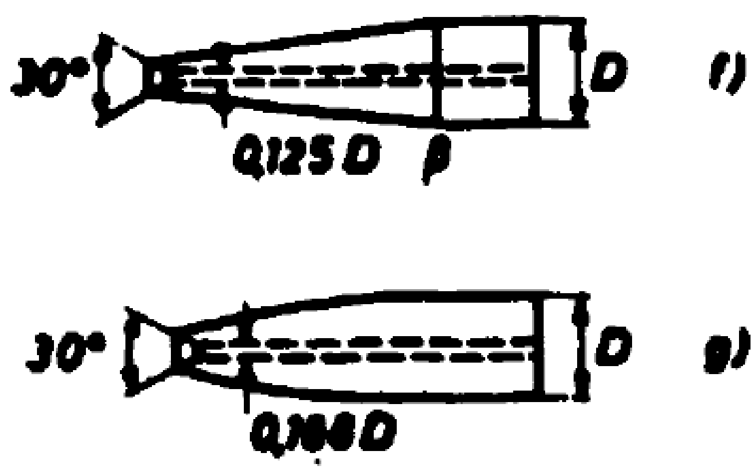

Fig. 5.14 Standard Pitot tube entrance design

We haven't found tests with our pitot boom's model (852 AF – AG) we assume as an estimated result the tests done with the model 855E to calculate the static pressure error respect the speed and alpha-beta.

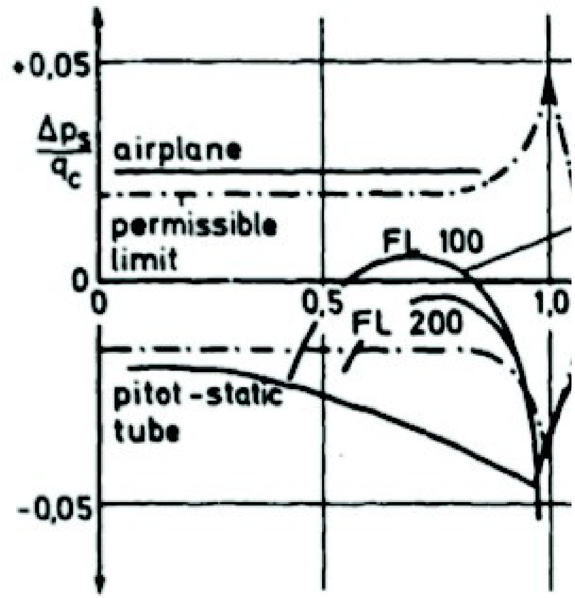

Fig. 5.15 Ps Error respect qc as an M function

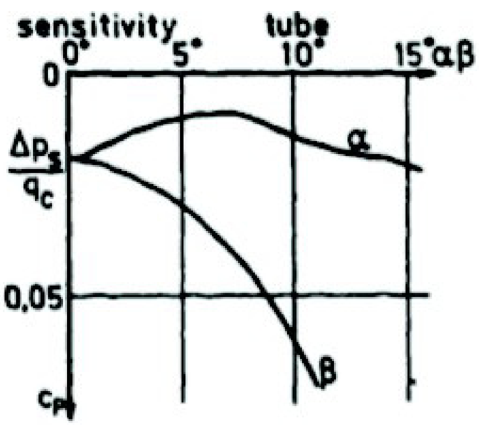

Fig. 5.16 Ps Error respect qc as an alpha/beta function

5.1.2 Results Estimation

5.1.2.1 Total Pressure – Pitot Tube line up

When the pitot tube is not inclined to the airflow, the result is the real static pressure's measure. In our case we should do the test several times with different speeds to verify that the Mach's influence is minimum (the pressure's measures should not change when the speed increases).

SUGGESTION 1: From speed 0 increasing about 20-25 km/h the airflow speed each time. Being carefully if this increase is valid when we calculate the static pressure measures that we perform at the same time.

NOTE: Knowing that probably we can regulate and control the airflow speed in the wind tunnel, we can know exactly it values which is not the case with the Mach number measures. We need to use the Mach number to calibrate and analyze the results. We should know test's room temperature and everything necessary which let us make a correct conversion. In the case we use an instrument which gives us a feedback in the Mach number inside the test's room, this should not be a problem.

SUGGESTION 2: After all we have said before and thinking about the result's representation, we should increase from M=0,0.02 to M=0.2 o 0.3 (The maximum speed and Mach number are limited for the wind tunnel configuration).

5.1.2.2 Total Pressure – Pitot Tube inclined

In order to see the effect of alpha's variation respect Pt error, we are going to use a test done in a pitot tube with an entrance model E-6, which it is the most similar that we have found in our case and as an orientative analysis is going to be useful.

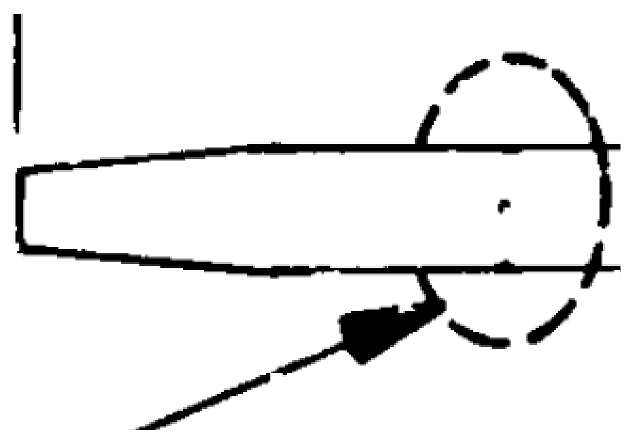

Fig. 5.17 Pitot total pressure tuve

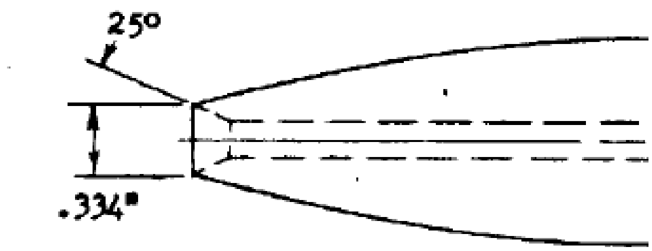

Fig. 5.18 E-6 pitot total pressure tube

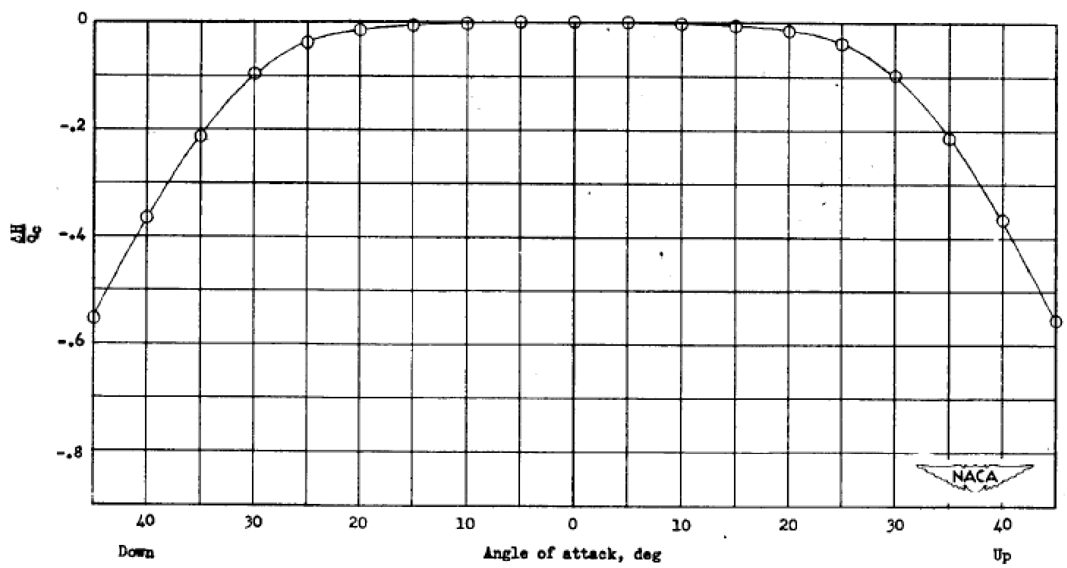

Fig. 5.19 Results of the test with E-6 pitot tube

As we can observe in the previous graph, we have an area between +/- 15° (also we can consider +/- 20°) where the error is nearly 0. From here on, it has a progressive increase, we must remember the maximum error we can accept is 1% from qc, this value is equal a 0.01 in the axis Y in this graph.

SUGGESTION: An advisable data's distribution would be the ones used in this study. Take values every 5 grades, as positive as negative because our pitot tube is symmetric. We are considering linear this graph between each 5 grades.

We will not introduce any important variation if we take as right the result that we have used as a sample, we do not have enough information to anticipate the results considering the Mach number's influence when we change the angle of attack. On the other hand all the tests done consider this influence only from M = 0.2 (taking our maximum speed using ISA we obtain a Mach number maximum = 0.2).

5.1.2.3 Static Pressure

First of all we should say that Ps error values are taken referred to qc, because in our speed's rang it entails nearly linear. For that reason applying the necessary correction is easier.

The main problem if we use this method is that we are applying a correction in an error which is referenced to a value that during the flight it already contains errors, because we obtain this value through the difference between Pt and Ps.

SUGGESTION: A possible solution can be: introduce a resourceful calculation inside the algorithm in the air data system which it takes care of apply all the corrections. Using this method with a number of cycles not established yet we can reduce the effects of the error. We should determine the operations we need to use in these cycles and study how many cycles are necessary.

5.1.2.4 Static Pressure – Pitot Tube line up

In order to reduce the number of tests necessaries to calibrate the Pitot tube we use a mix calibration. That is, while we are writing the results down to calibrate Pt error we also do it to calibrate Ps error. Referring to the pitot tube line up, where we have a Ps error due to the tube's presence, we use the same intervals.

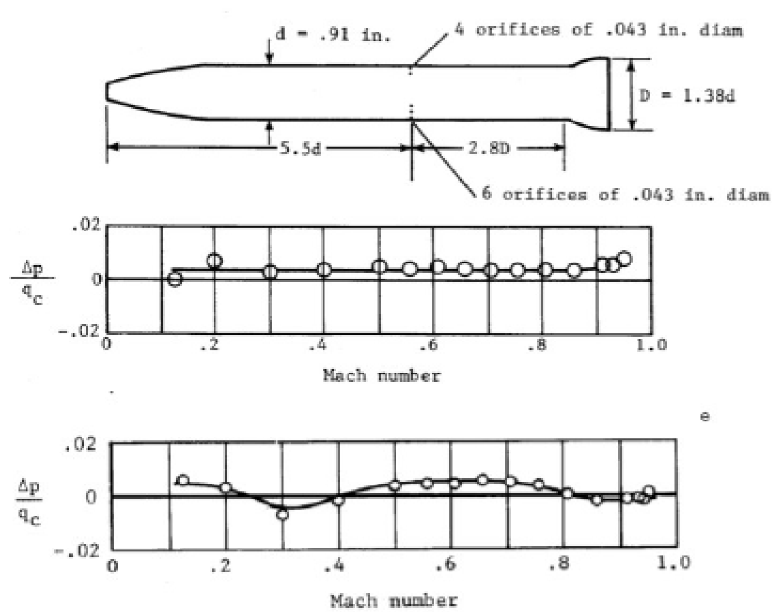

Fig. 5.20 Different results of the Static pressure error when the tube is lineup

Therefore we should analyze if the speed intervals (Mach's variation) that we have determined in the case of total pressure values with the tube line up are useful now. We can establish that our pitot tube is similar to the one in the previous graph, we know it is not the same tube for that reason we use a less favorable case.

First we can observe that in both cases the variations and values starts to M=0.1. In our environment the Mach number cannot be bigger than 0.3. Consequently we are interested in a small margin. The intervals we have chosen are from 0.0 to 0.2/0.3 (depending on the wind tunnel capacity) each 0.02. We can establish that the number of samples is adequate.

SUGGESTION: We can use the same intervals we have already chosen, so we initiate the test with M = 0.0 and it is going to increase in 0.02 each time until the maximum tunnel wind speed is achieved.

NOTE: The same as in the previous case we need to know if we can measure the Mach number directly from our test room or if we only can know the airflow speed.

5.1.2.5 Static Pressure – Tube inclined

We haven't found any example or project that we can use to determine an estimation about the expected results in the case of static pressure error in front of alpha-beta variation. So we need to do a test without any idea about the results that we are going to obtain. We can only say that surely the 5 grades variation from pressure total test will not be valid, for that reason this test is going to be independent and subsequent from the other ones.

In order to execute a satisfactory regression about the error's behavior, a prudent interval could be taking values every 2 grades. Being carefully about possible influence in the variation of the Reynolds number. One way we can use to determine this influence could be doing tests in different speeds while we keep a fix angle. In short the test would be done of a constant speed, always inside the limits we set, and changing the angles as positive as negative. A thing that we can anticipate thanks to all the documentation is that the error's behavior is different for positive angles and negative angles, it is the same for alpha and beta. As we have already mentioned in few angles we are going to change the speed as below as above the test speed.

SUGGESTION:

- alpha – constant speed. From angle 0, increasing 3-5 grades (depending on the system sensitivity) until achieve 25 grades. In some points measuring of different speeds. The same process for negative angles, knowing that the increase can be bigger.
- beta – From angle 0, increasing 5 grades until achieve 20 grades. Same interval for angles in the right and left from the axis. To some angles taking values using different speeds.

5.2 Calibration test summary and results

The aim of this part is to be the summary of the tests of the pressure system calibration and the alpha-beta values from our air data system. This test has been done Thursday 12 of February 2009 in the aerodynamic laboratory, inside the aeronautic department facilities in the University of Politecnico di Milano. Specifically it was done in one of the wind tunnels belonging to the University, during the morning with the presence of the engineers responsible for the wind tunnel and also the presence of the professor Alberto Rolando, tutor of this project.

5.2.1 Test description

As we have said before the calibration test was done in a wind tunnel. Some of its characteristics are:

- Design: atmospheric tunnel with closed cycle.
- Maximum Speed: ~ 70 m/s.
- Capacity to control the difference between the outside pressure and inside pressure.
- The sensors in the wind tunnel let us know: Pabs, Pd i Temperature.
- The wind tunnel needs a while to arrive and stabilize the test conditions requested. The control system shows us when these conditions have been achieved.

Every tunnel parameter is administrated from the control system situated outside the room because the noise in high speeds is considerable. In order to avoid problems the control and analysis of the sensor system's data are going to do it separately. The data acquisition system can store all the information in files *.dat. It is a text file in ASCII that permits to have the chance to do every kind of analysis because of its simplicity.

Fig. 5.21 General picture of the wind tunnel and detail of the probe chamber with the boom installed.

In order to fulfill the requests of the test, a special system was built to fix the probe. This system is fixed in the platform under the test area, outside the tunnel, and it permits us modify the different angles with which the probe interact with the air flow. Every time that we need to modify the angles we have to stop the test. This system excels in its low cost and simplicity, on the other hand it is slow and it makes our test be longer. If the calibration needs to take values in a lot of speeds and angles, this system is unfeasible.

Fig. 5.22 Images of the anchoring system of the probe inside the wind tunnel.

The way that the probe takes every data is the same as later will be done inside the plane, using the same electronic systems. So we have a circuit which fits out the signal for every sensor, after this there is a digital data processing in order to send through the bus CAFFE and finally a computer receives the data and shows us it. Being important emphasize that the data which comes from the probe is not registered automatically unless once the test conditions have been stabilized we need to make a note of the value that the system indicates. These values are not fixed, it changes quickly, it is due to the outline conditions. For that reason the person who makes notes of the values has to do an approximation that it has not to be the most certain.

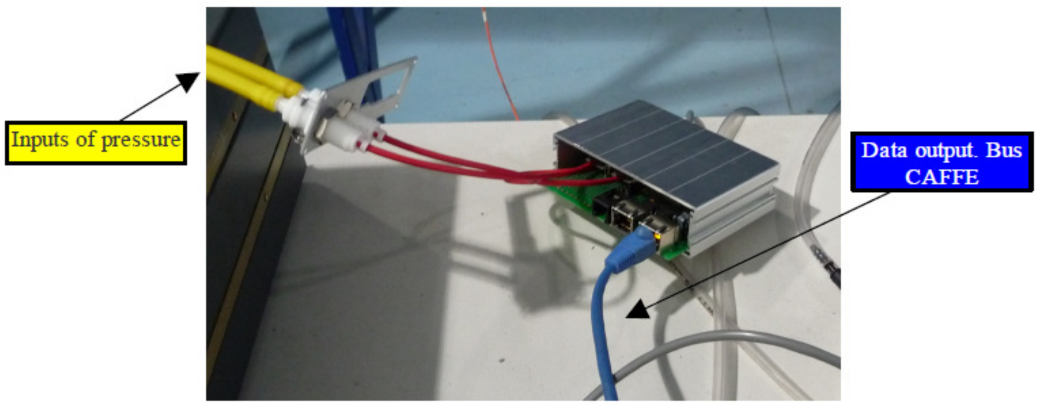

Fig. 5.23 Image of the electronic of the system

5.2.2 Taking the values

The test followed the procedures suggested in the previous part, in order to have enough values to do the post analysis and error's characterization. As we have said previously the process became longer when we introduced more angles and speeds. For that reason before initiating it we decided to reduce the number of tests depending on the following criterion:

- In a combination of angles alpha and beta we make the test with three different speeds. 15m/s, 35 m/s and 55 m/s these values involve measuring around the minimum inside the P-92, the maximum and a third one between its.
- Intervals for the angle alpha: deciding do the test from -25o to +25o with intervals of 5 grades for each speed.
- Intervals for the angle beta: doing the test from -20o a +20o with intervals of 5 grades for each speed.
- As additional information we decided to do a mix test: we put into practice a turn of 45 degrees on the right and an inclination of -10o i +10o from the horizon for the same three speeds. We wanted to analyze the error's effect when we combine alpha and beta. Using trigonometry we can find the angles of alpha and beta through the probe's inclination.

The values that we acquired from the probe are those of dynamic pressure [Pd], static pressure [Ps], angles *alpha* [α] and *beta* [β]. Those measurements were not done with the correct magnitudes; they were done in counts of the A/D converter.

When we decided how to proceed, we started the test applying the modification in the angle alpha. After having started the test we realized that the probe wasn't installed correctly, for this reason the first test was the angle beta and not alpha. During the test we realized that the potentiometer blind area that measures angle alpha is located at 22 negative degrees. We analyzed this situation and we concluded that it did not cause any serious problem for the system.

5.2.3 Results

When we have ended the test we can start analyzing the results, using Matlab again. The process is a polynomial interpolation of the dynamic pressure values in front of the speed and the two angles. One thing that we have detected in the tunnel is the dependence of the qc respect to these three parameters. A summary about the influence of the error is:

Table 5.12 Data calibration pitot-boom.

Maximum error % of Pd over α	4.9770 %
Maximum error % of Pd over β	20.0478 %
Maximum error % of Pd over α / β	2.4456 %

In order to have a better evaluation about the error we should have done more tests. Analyzing the summary of the errors, it looks strange the 20% of the error with respect beta. However, this value has been obtained using the maximum angle and speed [20o and 55 m/s], difficult flight conditions to achieve; this 20% is not acceptable, if we compare alpha and beta.

Finally we have the graphs about the dynamic pressure error (Cp) in front of alpha, beta and a combination of both.

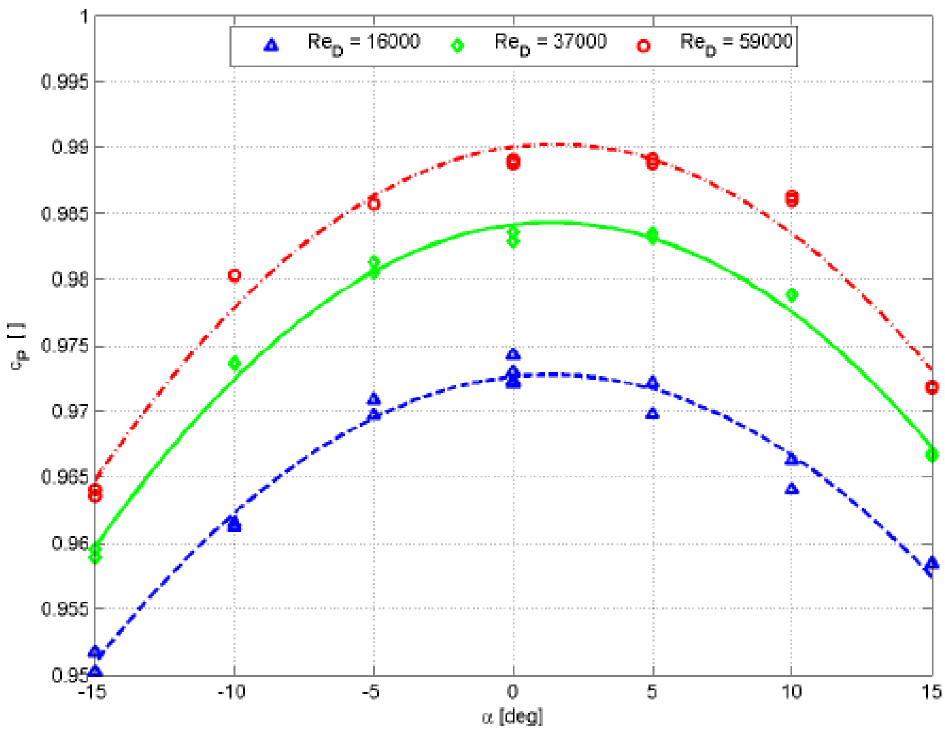

Fig. 5.24 Correction of the dynamic pressure respect angle alpha.

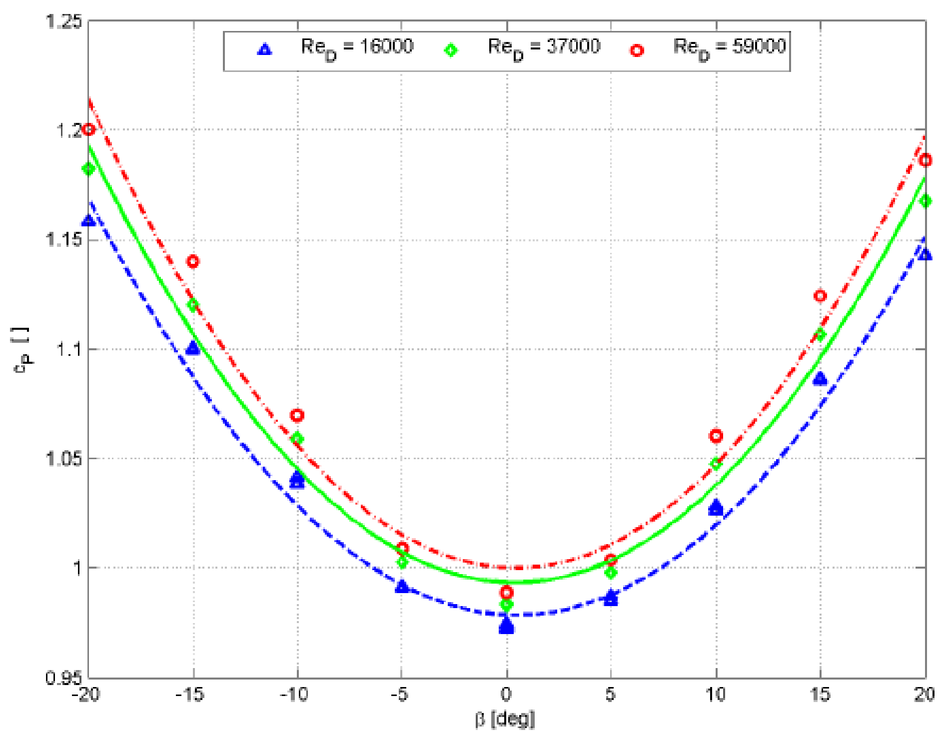

Fig. 5.25 Correction of the dynamic pressure respect angle beta

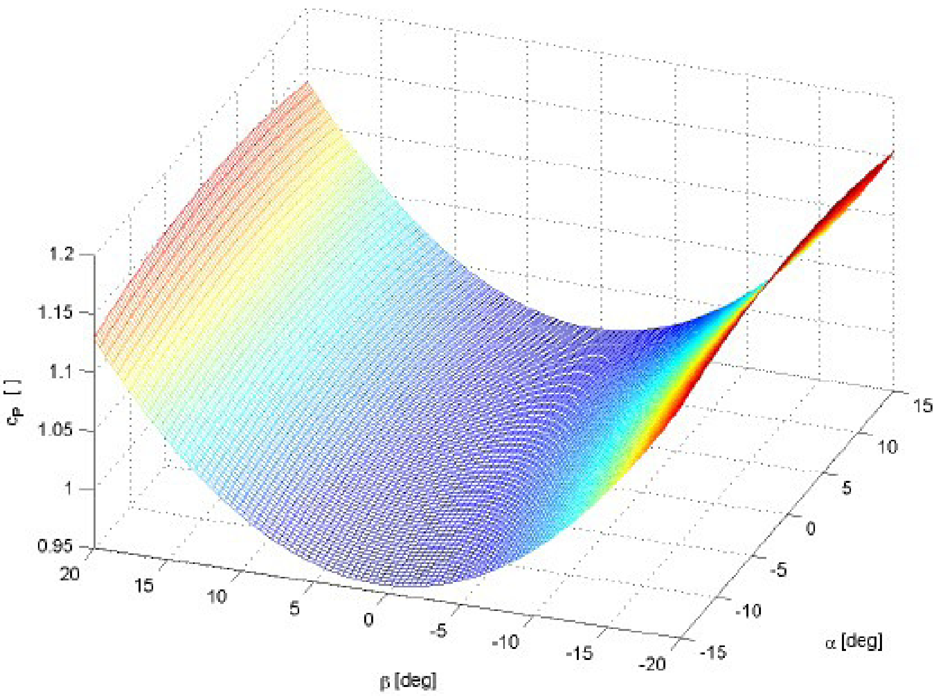

Fig. 5.26 Correction – alpha and beta – for Red = 37000

5.3 Estimation of the pressure sensor error

We can found the characteristics of the transducers in the section 1.2.

FSS: Full Scale Span is the difference between Vout_max and Vout_min, its value is 4V.

The best way to know the error in a sensor is calculating the difference between the real value and the measured value. In a transducer the most important error is located in the conversion from analogical data to digital data; this process is made by the converter A/D. For this reason we are going to analyze only the converter A/D, the other errors as the general sensor error and the environment error are minimum compared with the converter error.

5.3.1 Converter A/D

A digital converter of n bits is an electronic circuit which transforms an analogical tension whose value is between the interval [V1, V2] into a digital word of n bits. The method used to obtain this transformation is:

$$\Delta V = \frac{(V2 - V1)}{2^n} \quad \textbf{(5.1)}$$

The resolution of our converter is 0.122 mV/code.

Quantization error is the error inherent in all A/D conversions. Since even an ideal converter has finite resolution, any analog voltage that falls between two adjacent output codes will result in an output that is in accurate by up to ½ resolution.

In our case: +/- 6.1 * 10 -4 V/code.

Also exists other kinds of errors that we could only calculate through an experimental test.

Zero error: is the difference between the ideal input voltage and the actual input voltage that just causes a transition from an output code of zero to an output code of one.

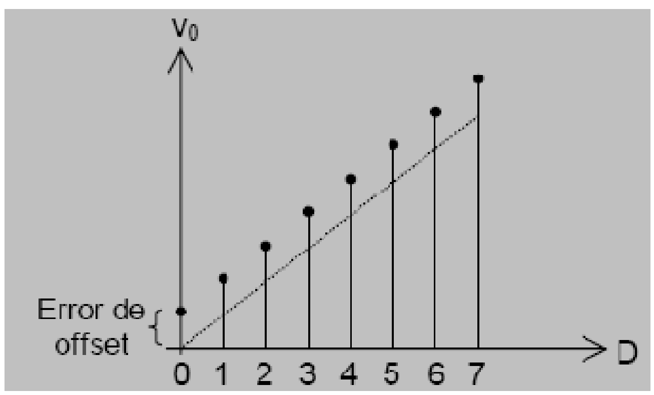

Fig. 5.27 Zero error graph.

Full Scale error: is a measure of how far the last code transition is from the ideal.

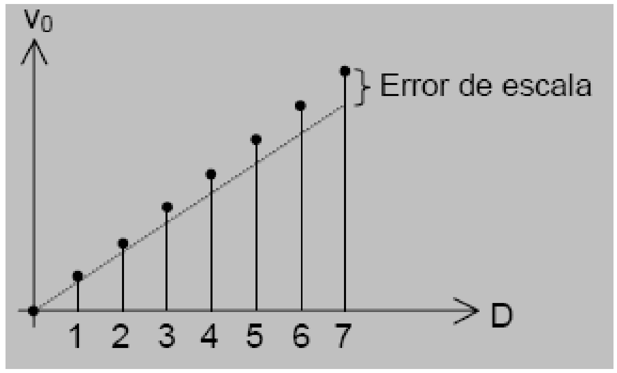

Fig. 5.28 Full Scale error graph.

The second transducer has a converter A/D of 12 bits and the same full scale span than the previous one.

Proceeding in the same way as before we find a resolution of 0.9765 mV/code and the value of the quantization error is +/- 4.88*10-4 V/code.

5.4 Analysis about Pitot error impact above ADS information

First of all we are going to analyze how the error in the pressure values can affect to the other information that is calculated from its. The altitude, speed and Mach number are obtained and corrected using the previous pressures. For that reason if these ones have errors also the other ones. In order to do this analysis, previously we have had to calculate or studied the error in the pitot tube. In our case we have done it in a test in the wind tunnel.

5.4.1 Calculation

Our process is described below:

- We are going to choose an environment inside the limits of P92. We are going to select a speed and an altitude.
  Inputs => Hp [m] V [m/s]
- From these values we can obtain the calibrate pressures, so also the real ones, that we would have in this conditions.
  Constants => Pa0=101325 [N/m2]; a0=340.s94 [m/s]
  A consideration => our maximum altitude is under the limit of 11000 m from the troposphere.
- From Hp we obtain Pa according to the document ESDU.86031a, in the same way from V we obtain qc.

$$Pa = Pa_0[1-22.5577\times10^{-6}\ Hp]^{5.25588}$$

$$qc = Pa_0\ [\{0.2\ (V/a_0)^2 + 1\}^{3.5} - 1] \qquad \textbf{(5.2)}$$

ref. ESDU 86031a pag. 8-9.

Note => We have to calculate the plane's Mach number.

$$M = [5\ (Pp/Pa)^{\ 1/3.5} - 5]^{\ 0.5} \qquad \textbf{(5.3)}$$

- Once we have the pressures calibrated, using the error that we obtained in the wind tunnel, we can know the values of the indicated pressures. Considerations => as we have seen in the result of the wind tunnel test, we can consider that the only error is present in the dynamic pressure.

$$\begin{aligned} Pp &= qc + Pa \\ qc_i &= qc - \varepsilon qc \\ Pp_i &= Pa + qc_i \\ Ps_i &= Pa \end{aligned} \qquad \textbf{(5.4)}$$

- If we want to know the error's impact we will suppose that the plane's air data system uses the pressure values without applying any correction to calculate the altitude, speed and Mach number. We are going to do the same previous calculations from ESDU 86031a but following the opposite way.

$$Hp_i = 44339.7\ [1 - (Ps_i/Pa_0)^{0.190263}]$$

$$V_i = a_0\ [5\ \{qc_i/Pa_0 + 1\}^{\ 1/3.5} - 5]^{\ 0.5}$$

$$M_i = [5\ (Pp_i/Ps_i)^{1/3.5} - 5]^{0.5} \qquad \textbf{(5.5)}$$

Ref. ESDU 86031a pag.8,9,10.

Consideration => As a result of the previous consideration the measure of Hp will be clean of errors. For the same reason the result of the Mach error will be a function similar in form to the result of V.

- Finally comparing the values that has been introduced in the beginning with the values that we have obtained, we can determine the influence of the pressure error.

$$\varepsilon Hp_i = Hp - Hp_i$$
$$\varepsilon V_i = V - V_i$$
$$\varepsilon M_i = M - M_i \quad \textbf{(5.6)}$$

εHpi , εVi i εMi .are the outputs of the program. We are going to make a graph about every of them in front of the inputs.

5.4.2 The Program

In order to execute these calculations and have a global vision about the error's impact we are going to use the tool named Matlab. Specifically we are going to build a program which can do the calculations and extract the values.

5.4.2.1 Program structure

Our program is organized in functions installed as a script of Matlab (*.m). Every one of these functions executes a specific task, as a core of the program we are going to create a *main.m* where the data output and input are going to be executed, also the user's options.

The program is going to have three different ways to introduce all the data:

- An enter: the operations that involve this variable can only be evaluated for one value. Its main function is the introduction of error data, because it is a specific and constant value. On the other hand we also use it if we want to draw results only for one speed or a concrete altitude.
- Vector: this option creates a vector where we can indicate its beginning, its end and also the value of the space. Its main use is drawing a graph, about Hp or V, only depending on the data that we introduce.
- Vector with multiple enters: the aim of this way to introduce the information is showing in a same graph the results of different speeds and altitudes. Consequently we can analyze the error's evolution when V or Hp changes.

5.4.2.2 The Functions

The program's functions are *main.m*, *errorevolo.m*, *grafandsave.m, loadata.m* and *galleria_load.m.* Below we have a detailed explanation about how it works.

main.m

As we have already said, the core of the program contains the user's interface and also the declaration of every variable and the call of the other functions.

The first action of the *main* is a clear about the existing variables in the work's space; this avoids using variable from the previous calculations.

Using a while, the option menu and a series of if, else if, the main menu is created, where the user can choose one of the three options. If the user does not follow the correct process, the program is going to show him an error.

```
while op<=3

    op=menu('Scegli uno dei seguenti', '1- Introduire dati', '2-
Calcolare Errori', '3- Graficare e Salvare Errori', '4- Exit')
```

The first option is loading the information in the following way, the function *loadata* returns a structure that in the *main* we named it dati where all the inputs are saved.

```
if op==1

        dati=loadata;
```

The second option is the error's calculation. In this case the function returns a structure which we named errori with the three error results.

```
elseif op==2

        errori=errorevolo(dati.Hp, dati.V, dati.EPpi, dati.EPsi);
```

Finally the last option creates a graph and saves it in order to use it later. The program let us choose which error we want to draw in function of which input. The program saves the string of the variable that we indicate so it can create the name of the axis, the title and the summary as also save the file automatically.

```
elseif op==3
        a=menu('Che errori voli graficare:', 'Altura', 'Velocita', 'Numero
di Mach');
        b=menu('In funcioni di che dati: ', 'Altura', 'Velocita');
        namesy=fieldnames(errori);
        namesx=fieldnames(dati);
        if a==1
            Y=errori.EHpi;
            ylabl=char(namesy(1,:));
            Ylab=[char(namesy(1,:)) '  [m]'];
        elseif a==2
            Y=errori.EVi;
            ylabl=char(namesy(2,:));
            Ylab=[char(namesy(2,:)) '  [m/s]'];
        elseif a==3
            Y=errori.EMi;
            ylabl=char(namesy(3,:));
            Ylab=char(namesy(3,:));
        end
        if b==1
            X=dati.Hp;
            xlabl=char(namesx(1,:));
            Xlab=char(namesx(1,:));
        elseif b==2
            X=dati.V;
            xlabl=char(namesx(2,:));
            Xlab=[char(namesx(2,:)) '  [m/s]'];
        end
        figure
        titolo=[ylabl ' in funcione di ' xlabl];
        filename=[ylabl '.funcionedi.' xlabl];
        grafandsave(X, Y, Xlab, Ylab, filename, titolo, dati, a);
    end
```

When we have ended choosing the last option, we finish the program's execution.

loadata.m

As it name indicates this function asks the user for all the information and saves it letting us do the calculations with it. As we have said before, it has three options for the four inputs. Knowing which function is necessary for each data is the user's work, instead there is a warning system in order to warn possible errors.

We create a menu with the three inputs and a option to close the while and leave the function.

```
while ldm<=4

     ldm=menu('Scegli i dati', '1- Hp', '2- V', '3- 'Eqc', '4- Tutti dati anno
stato introduto');
```

Inside every input we have one submenu which includes the three ways to introduce it. The values are saved in a structure named data which is the function's output.

```
if ldm==1

            ldh=menu('Quali  possibilità  di  inserimento  dati  vuoi',  'Numeri
interi',  'Creare  un  vettore  da  A  a  B  con  spaziatura  N',  'Vettore  di  interi,
multiple graphic');
```

As a whole number

```
if ldh==1

            data.Hp=input('Altura in metri: ');
```

As a vector

```
elseif ldh==2

            iniHp=input('Inicio di vettore altura: ');

            fiHp=input('Fine di vettore altura: ');

            interHp=input('Valore della spaziatura dell vettore altura: ');

            nHp=(fiHp-iniHp)/interHp;

            data.Hp=linspace(iniHp, fiHp, nHp
```

As a whole vector. In this the values has to be introduced as the program indicates us.

```
elseif ldh==3

                data.Hp=input('Immettere  i  valori  di  vettore  Hp  con  forma
Maltab [a; b; c; ecc]: ');
```

When everything is correct, the user choose the option 4 to return to the main menu. Before that a check is done in order to certify that all the values have been introduced correctly, so the calculation and the graph can be possible.

```
elseif ldm==5

        a1=size(data.Hp,2);

        b1=size(data.V,2);

        a2=size(data.Hp,1);

        b2=size(data.V,1);

        if a1>1 && b1>1

                ldm=input('Non posso fare il calcolo con Hp e V come due
vectori, introduce 0 per reprobare: ');

        elseif a1==1 && b1==1

                ldm=input('Hp o V debbe essere vectore per podere fare la
representacione, introduce 0 per reprobare: ');

        elseif a2>1 && b2>1

                ldm=input('Non posso fare il calcolo con Hp e V come due
vectori, introduce 0 per reprobare: ');

        end
```

If one of the previous cases appears, the user can return to the menu *loadata* in order to correct the values without the interruption of the program.

To introduce the error the user can not select any of these options. The program automatically loads data from a file called data.dat containing all the data from wind tunnel test.

galleria_load.m

In addition to upload the data this function also performs the calculation, selection and management of the dynamic pressure error.

```
dat = load('dati.dat');
    dat = sortrows(dat,[1,2,4]);

%esclusione dei dati
    A_ = find((dat(:,1)~=25)&(dat(:,1)~=-25)&...
               (dat(:,1)~=20)&(dat(:,1)~=-20));%&...
               %(dat(:,2)~=20)&(dat(:,2)~=-20));
dat = dat(A_,:);
```

The first task is loading the data from the file and discarding those angles that we don't select. Then it puts every variable separately.

```
%dati
    R = 287;
    D = 15.75e-3;
    alpha = dat(:,1);
    beta = dat(:,2);
    qc_misurato = dat(:,3);
    qc_effettivo = dat(:,4);
    p = dat(:,5);
    T = dat(:,6);
```

Then the function selects only the limit angle, as these are the worst conditions that we could have.

```
B=find((alpha(:,1)~=0)&(alpha(:,1)~=5)&(alpha(:,1)~=-5)&(alpha(:,
1)~=7.107076000000000)&...
    (alpha(:,1)~=-7.107076000000000)&(alpha(:,1)~=10)&(alpha(:,1)
~=-10));
C=find((beta(:,1)~=0)&(beta(:,1)~=5)&(beta(:,1)~=-5)&(beta(:,1)~=
7.05302200000000)&...
    (beta(:,1)~=-7.05302200000000)&(beta(:,1)~=10)&(beta(:,1)~=-1
0)&(beta(:,1)~=15)&(beta(:,1)~=-15));
```

NOTE: We tried to implement this selection taking only the angles that interests us, but the program gave us an error that we have not been able to belt. So we used the opposite operation.

Finally the function calculates the error of qc for every angle and every velocity and put this all together in the variable erroreqc.

```
k=1;
N=12;
for i=1:2:N
    r1=B(i,1);
    r2=B(i+1,1);
    eqc1=qc_effettivo(r1,1)-qc_misurato(r1,1);
    eqc2=qc_effettivo(r2,1)-qc_misurato(r2,1);
    erroreqc(1,k) = (eqc1 + eqc2)/2;
    k=k+1;
end
for j=1:2:N
    r1=C(j,1);
    r2=C(j+1,1);
    eqc1=qc_effettivo(r1,1)-qc_misurato(r1,1);
    eqc2=qc_effettivo(r2,1)-qc_misurato(r2,1);
    erroreqc(1,k) = (eqc1 + eqc2)/2;
    k=k+1;
end
```

errorevolo.m

It is the core of the calculation, so it contains all the mathematic operations that we have explained in the part 1.1. The altitude, speed and the error from the test in the wind tunnel are the inputs. The process has been detailed before.

grafandsave.m

This function let us obtain a graph and save it in order to us it in documents. Previously we have already commented that some parameters are automatically generated, we are going to explain it deeper below.

First of all we need to know which parameters are received by the function.

```
function grafandsave(x, y, xlab, ylab, filename, titolo, dat, c)
```

x: is the variable for the X axis.

y: is a matrix with the results of the error that we select to represent.

xlab: contains the string which represents the data saved in the variable x.

ylab:contains the string which represents the data saved in the variable y.

filename: is the string generated in the *main* that contains the name of the file.

titolo: is the string generated in the *main* that contains the title for the graph.

dat: is the structure with all the values introduced by the user.

c: is a parameter that indicates which error we are representing.

`color=['b', 'g', 'r', 'y'];` It let us change the graph's color if we have more than one data.

`marca=['+','*','o','x'];` It let us change the symbol.

`e1=size(y,1);` By this way we can know how many error's values we have to show.

If we only want to show one graph, the orders which the program executes are showed below. First the program draws the graph and later analyzes if it is showing for V or Hp in order to create the summary.

```
if e1==1

    plot(x,y,'b', 'Linewidth', 2);

    if strcmp ('V', xlab)

        leg=[num2str(dat.Hp) ' m'];

        legend(leg,'Location','Best');

    else

        leg=[num2str(dat.V) ' km/h'];

        legend(leg,'Location','Best');

    end
```

If we need to represent more than one execution, the program works as we show below. The process is the same one above but in the last part (summary) we need to establish a small correction in order to not have any incompatibility inside the string.

```
else
    for j=1:N
        for z=1:4
            rep=[color(1,z) marca(1,z)];
            plot(x(j,1),y(j,z),rep ,'Linewidth',2);
        end
    end
    if c==1
        axis([0 60 -0.5 0.5]);
    elseif c==2
        axis([0 60 y(j,z)-1 y(j,z-3)+1]);
    else
        axis([0 60 -0.025 0.005]);
    end
    leg(1,:)='angle alpha -15  ';
    leg(2,:)='angle alpha  15  ';
    leg(3,:)='angle beta  -20  ';
    leg(4,:)='angle beta   20  ';
    legend(leg,'Location','Best');
end
```

When we already have all the information represented we proceed establishing the name of the axis, the graph's title and the file's name.

```
grid on;
xlabel('','Interpreter','latex','String',xlab,'FontSize',16,'FontWeight','bold')
ylabel('','Interpreter','latex','String',ylab,'Rotation',90,'FontSize',16,'FontW
eight','bold')
title('','Interpreter','latex','String',titolo,
'FontSize',16,'FontWeight','bold')
```

Finally if everything is correct, we save the graph.

```
print( gcf, '-depsc ', [filename '.eps'] )
```

5.4.2.3 How the program Works

The way that this program works is very intuitive, therefore it is not prepared for errors when the user executes it in a way not logical. Executing main.m it shows us the following screen:

Fig. 5.29 Main menu

First of all we have to introduce the information that we are going to use in the calculations, if we choose some of the other options the program will not do anything and it will show us this screen again. So we choose the first option and the following screen appears:

Fig. 5.30 Data menu

From this menu on we are going to choose one by one every data that we need to introduce in order to achieve the last option and return to the main menu. As we have already said we have three ways to introduce the values, this selection is made in the following screen that is opened after click in one of the previous three options.

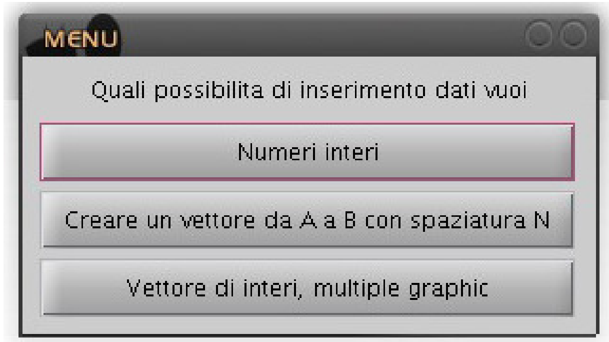

Fig. 5.31 Ways to introduce the values

Whatever is the option we choose, the variable introduction will be done through the instruction's line of Matlab. When we finish we can choose the last option to return to the main menu. If we have done some error through the data introduction (if the program is not going to be able to execute the calculations and make the graph) it will show us an error message.

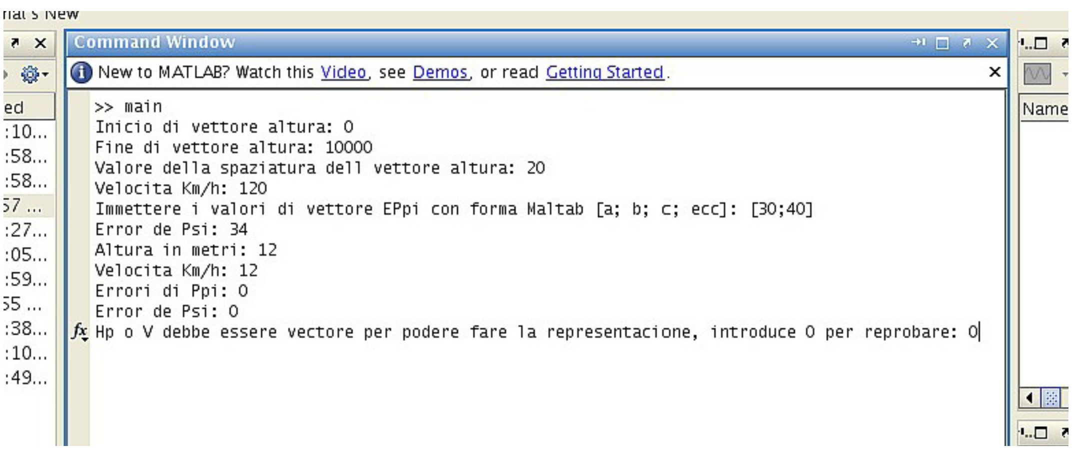

Fig. 5.32 Error message

If we have not obtained any error, we can continue doing the calculation so we choose the second option in the main menu. In this process the program do not show us any other screen, if everything is correct it will show us the main menu again in order to proceed with the third option. This program let us do a graph depending on the variable that we want; this selection is made with the following two screens.

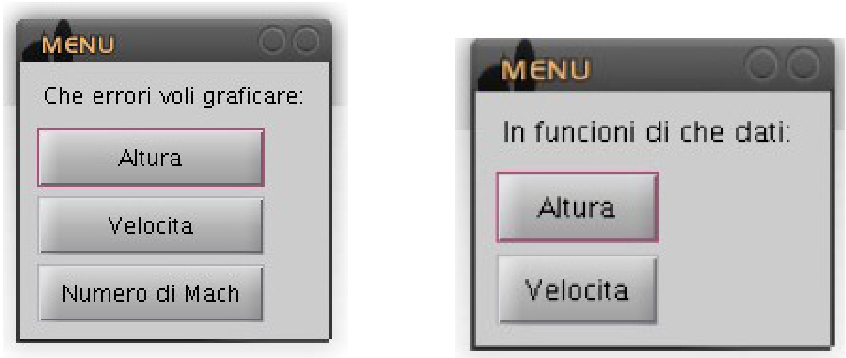

Fig. 5.33 Graph options

We need to choose the error we want to show in the graph and in function of which data. In order to have a coherent graph we have to do this process keeping in mind the values we have introduced at the beginning.

The following image is not a real calculation, is just to show what the result is

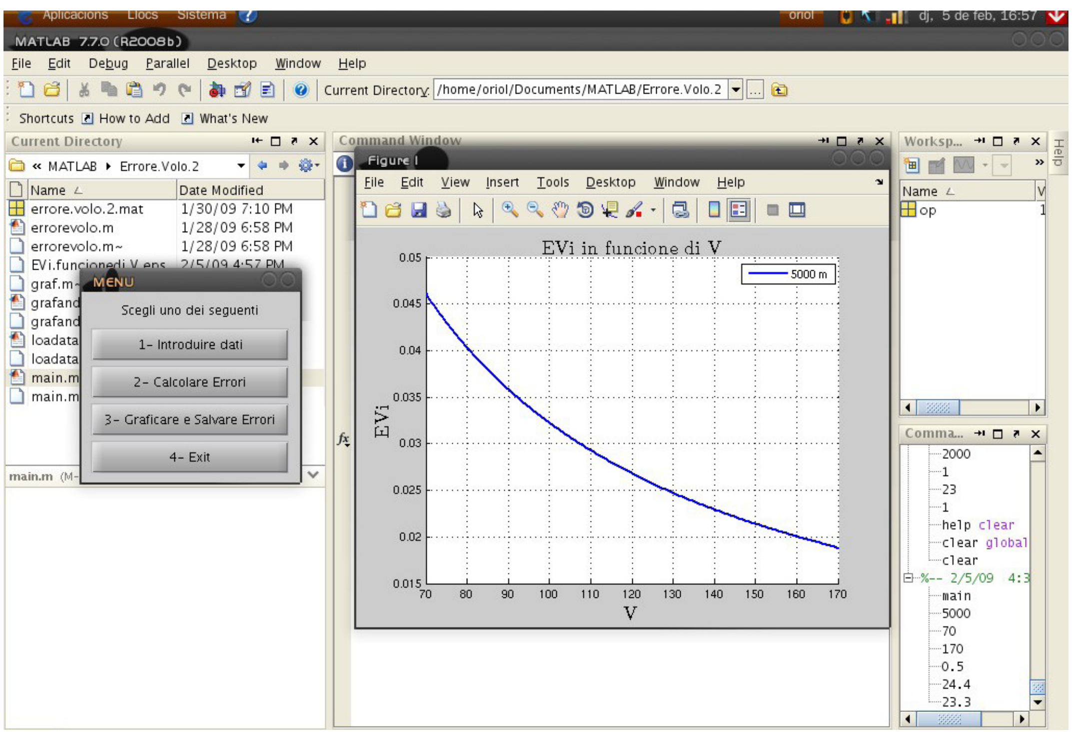

Fig. 5.34 Graph

Our program also creates a file *.eps with the same name as the graph's title.

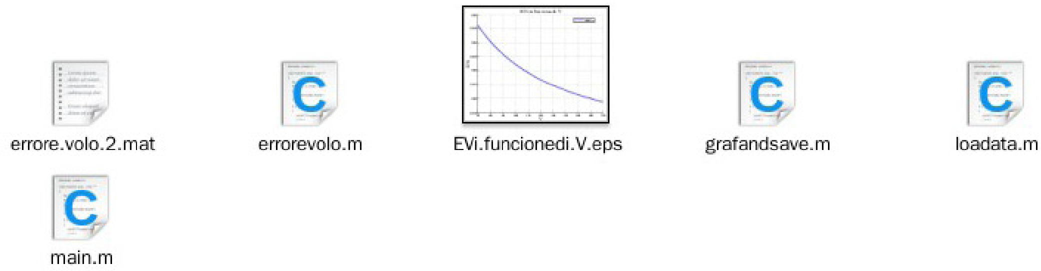

Fig. 5.35 Saved files

Finally the file with the last graph looks like as you can see below:

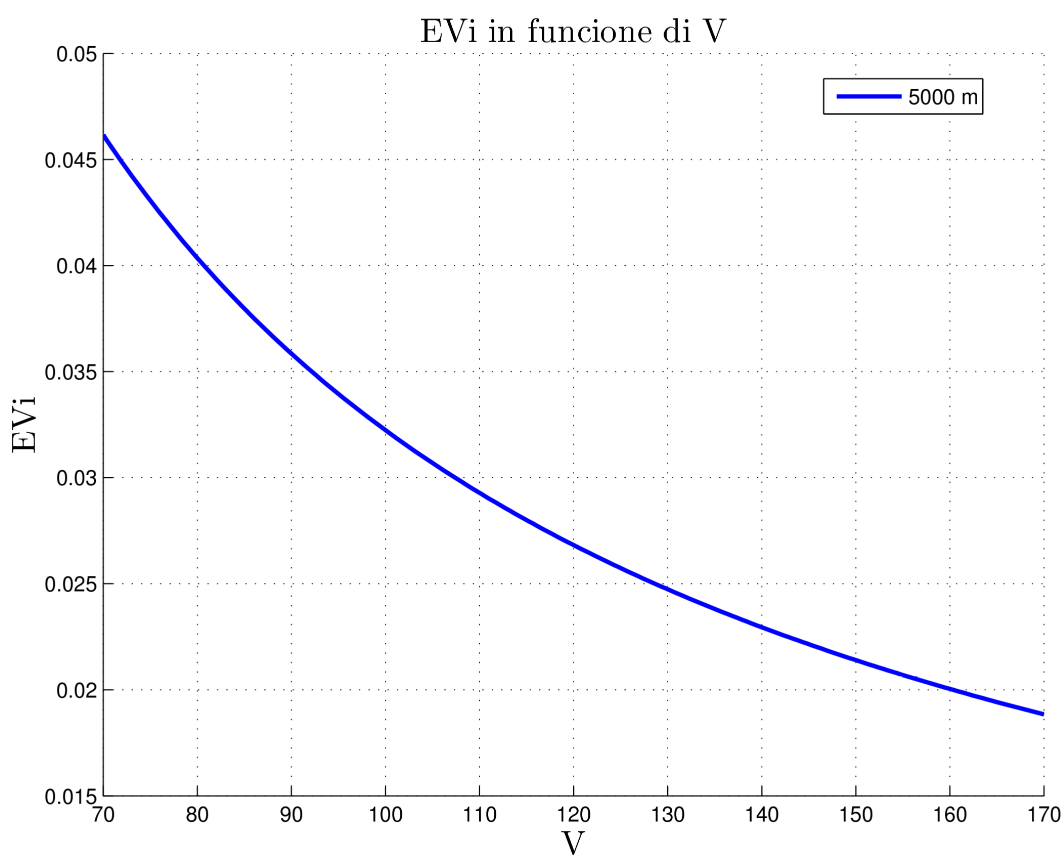

Fig. 5.36 Final graph

When we obtain our first result we can do as many graphs as we wish, we only need to be careful that it will be done with the same data as we have introduced in the beginning. In order to change it we have to click in the first option in the main menu and introduce the new values. Finishing the description of the program if we want to close it there is the option *exit*.

5.4.3 The results

As we explain at the beginning of this section, the test in the wind tunnel show us that we only consider the error in the dynamic pressure. This means that it has a dependency from the velocity.

For this reason the error introduced in the calculation of the variable is the different between qc_effective and qc_reed. We only select the data from the limit angle that are -15o and 15o from alpha and -20o and 20o from beta. The representation is made in function of the velocities, to be more exact in function of the 3 speeds that we used in the test [15,35,55] m/s. With this inputs the results are:

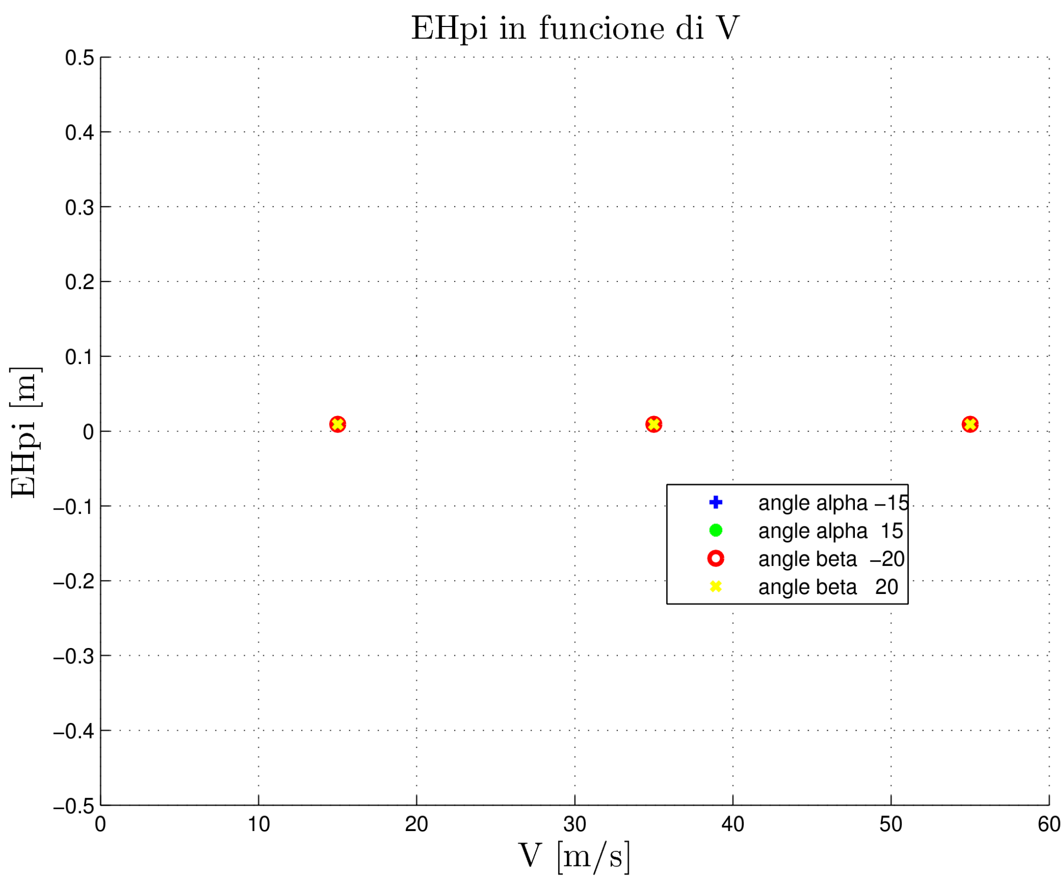

Fig. 5.37 Error of altitude in function of V and alpha – beta.

Comment: as we said the altitude doesn't show any error due to not correct the errors from the pitot tube.

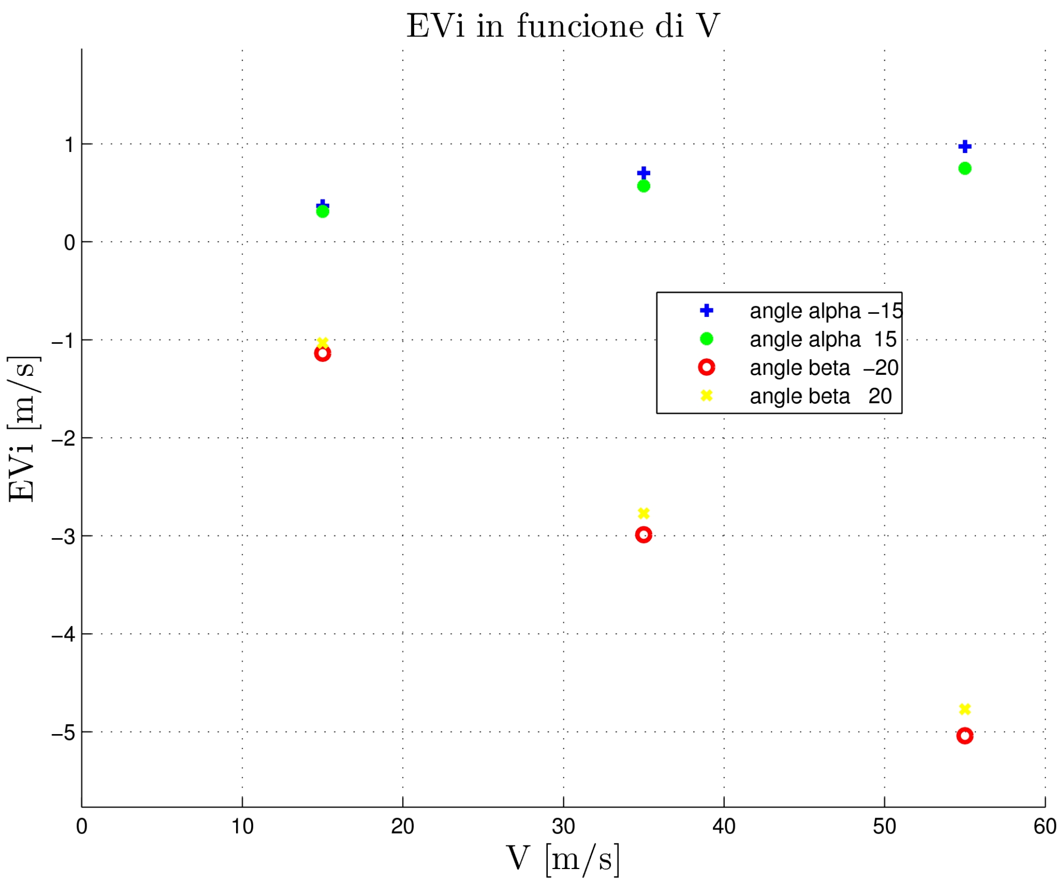

Fig. 5.38 Error of velocity in function of V and alpha – beta.

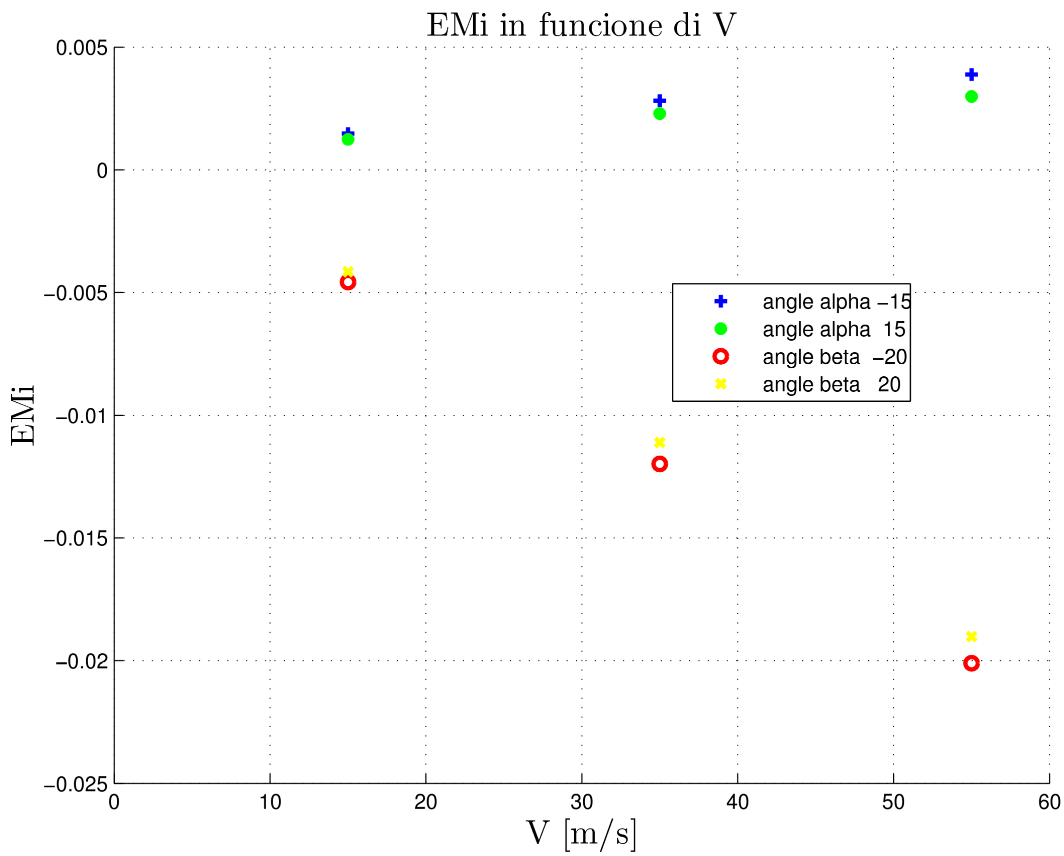

Fig.5.39 Error of Mach number in function of V and alpha – beta.

Comment: as the results of the test show us, we have a worse influence when beta is modified.

As a conclusion we could say that the influence of the error in V and in M when we have elevated angles beta could be a problem. So if we would use this instrument to measure parameters in real time, we have to include the correction.

5.5 Non accuracy due to refer the pitot errors to qc

Through the test in the wind tunnel we can characterize the different errors that appear when we measure Ps and Pt due to the presence of pitot tube inside the airflow. We have done the test at different speeds and angles alpha-beta. In order to make the correction easier we decided to represent the errors as a impact pressure fraction [Error/qc]. This choice was not trivial, we analyzed the tests made before and the characteristics of our pitot tube, we observed that the error's behavior in this way was more linear so this means it would be easier to characterize. On the other hand, there is a problem, it is due to the system that does the calculations with one variable (qc) that has been obtained from the difference between two variable which already have errors.

$$qc = Pt - Ps \tag{5.7}$$

Once we have applied the corrections in Ps and Pt, these values will not be real. We could interpret these values as a first approximation. There is no doubt that these values are more accurate than the ones obtained directly from the sensors, and this means that the calculations will be better. However, exists one method that we can use to eliminate these errors until acceptable levels, it is a recursive calculation, we need to apply the error's correction repeated times:

- Through Pti and Psi which are the values obtained from the sensors. Doing $qc = Pt_i - Ps_i$ we can calculate qci.
- Using qci and the results from the test in the wind tunnel which lets us know how the error's behavior is; we can calculate Pt1 and Ps1. We use the sub index 1 because these ones are not the latest values.
- It is a cyclic calculation through Pt1 and Ps1 we calculate again a new qc => qc1.
- With qc1 we do the process in the point 2 in order to achieve a Pt2 and a Ps2.
- We are going to do this process as many times as we determinate that it is necessary.

In every cycle iteration the last value of Pt and Ps obtained is more approximated from the real ones. We could think that an ideal solution would be doing as many cycles as we can, but not all is advantages, for example this kind of calculations is not complicated but it means a long time in front of the simple calculation. For that reason we need to determinate a number of necessary cycles and the problems that can appear. First of all we have to know how this error is.

In order to know if we are in front of a serious problem, we create a small program in Matlab which will do the following operations.

- We know that what we want to obtain is the difference between qc i qci. So what we are searching for is $qc - qc_i$.
- We know that $qc = Pt - Ps$ in the same time $qc_i = Pt_i - Ps_i$ so $\mathcal{E}qc = (Pt - Ps) - (Pt_i - Ps_i)$. **(5.8)**
- The pressure with the sub index $_i$ are the ones that we obtain directly from the sensors, the system calculates the other ones by the following way:

$$\begin{aligned} Pt &= Pt_i + \mathcal{E}pt_i \\ Ps &= Ps_i + \mathcal{E}Ps_i \end{aligned} \tag{5.9}$$

- Ɛqc will be:

$$\mathcal{E}qc = (Pt_i + \mathcal{E}pt_i - Ps_i - \mathcal{E}ps_i) - (Pt_i - Ps_i) \tag{5.10}$$

- In this equation we can delete Psi and Pti in the end Ɛqc is: $\varepsilon qc = \varepsilon pt_i - \varepsilon ps_i$ or also can be $qc - qc_i = \varepsilon pt_i - \varepsilon ps_i$ **(5.11)**

- As we have said the errors are expressed as $\varepsilon pt_i / qc$ and $\varepsilon ps_i / qc$ if we divide this expression for qc we obtain:

  $\frac{(qc - qci)}{qc} = \frac{\varepsilon pti}{qc} - \frac{\varepsilon psi}{qc}$ putting in order $\frac{qci}{qc} = 1 - \left(\frac{\varepsilon pti}{qc} + \frac{\varepsilon psi}{qc}\right)$

(5.12)

If we analyze this last expression we observe that if the errors we have found are nearly 0, the addition will be nearly 0 and the relationship between qc i qci will be 1, this means that qc i qci are practically the same. On the other hand as more errors we have qc i qci more different will be.

The problem is that we project the error with a constant independent of speed and a variable with the angle. We have seen in the test that it has a non constant behavior with the speed which complicates the possible use of the recursive method.

This is why as the document NASA RP 1046 show us we represent the error as:

$$Cp = (qc_{measured} - qc_{real}) / qc_{measured} \quad \textbf{(5.13)}$$

Using a polynomial interpolation of the representative error with qc_measured.

$$Cp = A + B * qc_{mes} + C * qc_{mes}^2 + D * alfa + E * alfa^2 + F * Beta + G * Beta^2$$

(5.14)

From that knowing alpha, beta and both qc or the difference we can get the results. At the moment we have only been able to solve the polynomial taking beta = 0 and for variations of alpha and qc_measured.

If we can find the polynomial using all the variables we can solve the problem of qc without resorting to the iterative calculation.

FINAL CONCLUSIONS

After this project, we can conclude saying that the new system has a better quality than the old system.

In the test we could calculate the dynamic pressure so there is no way to calculate the error in the altitude. This parameter has not a correction.

The results of the wind tunnel test show us how the new system interacts with an airflow. Analyzing the results during the calibration of the angle alpha, we obtain great results with accuracy in the measurement about 0.85 degrees. On the other hand, the results of the angle beta are not as accurate as in the angle alpha, we obtain an accuracy about 1.91 degrees. The error in the beta should be corrected because it means a big difference from the real value.

We also realized that the new system has the potentiometer for the measurement of the angle alpha fixed on the opposite sense finding the blind zone in an incidence angle of -23 degrees. Although it should not become a problem.

Creating a Matlab program help us in the analysis of the results showing us graphs about the influence of the errors in each parameter, so we know that we have a worse influence when beta is modified and it becomes a dangerous problem when the speed and the Mach number increase, for this reason we should improve the beta's accuracy.

Finally we should say that after applying a correction on beta, the new system will achieve a satisfactory improvement and doing a test during a real flight will be the best way to prove that the redesign of Urania has met its objectives and is ready to be integrated as a new node in Mnemosyne.

PERSONAL EVALUATION

After analyze the final results of this project we can say that we have achieved the main aim.

Testing this new pitot - boom in a real flight is the last part that we cannot do but indeed we have been able to attend in the calibration test in the wind tunnel.
As aeronautical engineer students we have to say that participating in this project has become a great experience, we have been able to see all the work necessary before an experimental test.

We have learned knowledge that during our career are not taught, as the calibration of the pitot tube, the pressure sensors and temperature sensor, also the test in the wind tunnel has become a big source of new challenges.

Working in a group, appearing problems and learning how to result them, having five different brains and ways to view everything analyzing the same things, arriving in the same conclusions are experiences that we have acquired doing this project.

BIBLIOGRAPHY

AGARD Wuest, W., 'Flight Test Instrumentation Series - Pressure and flow measurement', Technical report, Advisory Group for Aeronautical Research and Development, 1980.

ESDU, E. S. D. U., 'ESDU.86031a', 2008.

Gracey, W., 'Measurement of Aircraft Speed and Altitude', Technical report, NASA, 1980.

Gualdoni, F., 'Progettazione e realizzazione di un sistema d'acquisizione dati aria per prove di volo', Master's thesis, Politecnico di Milano, 2008.

Rolando, A., 'Development of an Integrated Flight Test Instrumentation System for Ultra Light Machines', PhD thesis, Politecnico di Milano, 2008

SensorTechnics, 'HCA-BARO Series', 2008.

SensorTechnics, 'HCLA Series', 2008.