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Vilniaus Gedimino technikos universitetas											
Antano Gustaičio aviacijos institutas											
Aeronautikos inžinerijos katedra											
ISBN	ISSN										
Egz. sk.											
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Antrosios pakopos studijų Aerokosmoso inžinerijos programos magistro baigiamasis darbas											
Pavadinimas	Orlaivio Cessna 172 avionikos prietaisų tikslumo tyrimas										
Autorius	Kanan Gasimov										
Vadovas	Darius Rudinskas										
	Kalba: anglų										
Anotacija											
Skrydžio greičio matavimo tikslumas yra labai svarbus saugiam ir efektyviam skrydžiui. Kita vertus, skersvėjo aplinkybės gali sukelti klaidų oro greičio rodmenyse, gaunamuose naudojant standartines orlaivyje sumontuotas pitot vamzdžių sistemas. Šio tyrimo tikslas – ištirti šoninio vėjo aplinkybių poveikį Cessna-172 orlaivio oro greičio rodmenų tikslumui, naudojant SkyDemon, Carly ir ANSYS programinės įrangos įrankių derinį. Realaus laiko oro greičio duomenis teikia populiarį skrydžių navigacijos ir planavimo programa „SkyDemon“. Carly, diagnostikos programa, suteikia prieigą prie įvairių orlaivių sistemų ir informacijos. Pažangi skaičiavimo skysčių dinamikos (CFD) programa ANSYS leidžia nuodugniai ištirti skysčio srautą ir susijusius reiškinius. Tyrimas apima daugybę skraidymo eksperimentų įvairiais šoninio vėjo scenarijais, kai vėjo greitis ir kampai skiriasi. Oro greičio rodmenys iš Pitot vamzdžių sistemos buvo lyginami su etaloninėmis oro greičio vertėmis, nustatytomis pagal GPS matavimus kiekvieno bandymo metu. Duomenys, gauti skrydžio bandymo metu, buvo įvertinti statistiškai, siekiant nustatyti Pito vamzdžio klaidų dydį šoninio vėjo sąlygomis. CFD modeliavimas taip pat buvo atliktas naudojant ANSYS, siekiant ištirti skysčio srautą aplink orlaivį ir įvertinti šoninio vėjo įtaką Pito vamzdžių sistemos veikimui. Esant šoniniam vėjui, tyrimas atskleidė didelius skirtumus tarp Pito vamzdžių sistemos užfiksuotų oro greičio verčių ir etaloninių oro greičio verčių. Nustatyta, kad pastebėti netikslumai priklauso nuo vėjo greičio, vėjo kampo ir kitų aerodinaminių kintamųjų. Šis tyrimas suteikia išsamių žinių apie Pitot vamzdžių klaidas šoninio vėjo sąlygomis, derinant SkyDemon, Carly ir ANSYS galimybes. Rezultatai padeda padidinti oro greičio matavimo tikslumą ir gali būti naudojami kuriant geresnes Pito vamzdžių sistemas arba taikant tinkamus klaidų taisymo metodus.											
Prasminiai žodžiai: Pito vamzdžio klaidos, šoninio vėjo sąlygos, Cessna-172, SkyDemon, Carly, ANSYS, oro greičio matavimas, skrydžio bandymai, skaičiavimo skysčio dinamika (CFD).											

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Vilnius Gediminas Technical University											
Antanas Gustaitis' Aviation Institute											
Department of Aeronautical Engineering											
ISBN	ISSN										
Copies No.											
Date-.....-.....											
Master Degree Studies Aerospace Engineering study programme Master Graduation Thesis											
Title	Research of Accuracy of Aircraft Cessna 172 Avionics Devices										
Author	Kanan Gasimov										
Academic supervisor	Darius Rudinskas										
<table><tr><td></td><td>Thesis language: English</td></tr></table>			Thesis language: English								
	Thesis language: English										
Annotation Airspeed measurement accuracy is critical for safe and efficient flight operations. Crosswind circumstances, on the other hand, can create mistakes in airspeed readings acquired by standard pitot tube systems mounted on aircraft. The purpose of this research is to examine the effect of crosswind circumstances on the accuracy of airspeed readings on a Cessna-172 aircraft utilizing a mix of SkyDemon, Carly, and ANSYS software tools. Real-time airspeed data is provided by SkyDemon, a popular flight navigation and planning program. Carly, a diagnostic program, provides access to a variety of aircraft systems and information. The advanced computational fluid dynamics (CFD) program ANSYS allows for thorough investigation of fluid flow and related phenomena. The research includes a series of flying experiments in diverse crosswind scenarios with varying wind velocities and angles. Airspeed readings from the pitot tube system were compared to reference airspeed values determined from GPS-based measurements throughout each test. The data acquired during the flight testing was then evaluated statistically to determine the magnitude of pitot tube errors in crosswind circumstances. CFD simulations were also run using ANSYS to examine the fluid flow around the aircraft and evaluate the influence of crosswind on the functioning of the pitot tube system. In crosswind situations, the investigation revealed considerable differences between the recorded airspeed values from the pitot tube system and the reference airspeed values. The observed inaccuracies were discovered to be wind velocity, wind angle, and other aerodynamic variables dependent. This research gives a full knowledge of pitot tube errors in crosswind circumstances by combining the capabilities of SkyDemon, Carly, and ANSYS. The findings help to increase airspeed measurement accuracy and may be used to design better pitot tube systems or to apply appropriate error correction methods.											
Keywords: Pitot tube errors, crosswind conditions, Cessna-172, SkyDemon, Carly, ANSYS, airspeed measurement, flight tests, computational fluid dynamics (CFD).											

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DECLARATION OF AUTHORSHIP IN THE FINAL DEGREE PROJECT

May 25, 2023

I declare that my Final Degree Project entitled „Research of Accuracy of Aircraft Cessna 172 Avionics Devices“ is entirely my own work. I have clearly signalled the presence of quoted or paraphrased material and referenced all sources.

I have acknowledged appropriately any assistance I have received by the following professionals/advisers:
Assoc Prof Doctor Darius Rudinskas.

The academic supervisor of my Final Degree Project is Assoc Prof Doctor Darius Rudinskas.

No contribution of any other person was obtained, nor did I buy my Final Degree Project.

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DEPARTMENT OF AERONAUTICAL ENGINEERING

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**RESEARCH OF ACCURACY OF AIRCRAFT CESSNA 172 AVIONICS
DEVICES**

Master's degree Thesis

Study programme AEROSPACE ENGINEERING,

Code 6211EX060

Vilnius, 2023

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INTRODUCTION

Investigation problem:

The purpose of this study is to look at the possibility of errors in airspeed measurement due to crosswind conditions when utilizing a pitot tube on a Cessna 172 aircraft. Accurate measurements from the pitot tube, a vital tool for measuring airspeed, are essential for safe flight. Crosswind, however, is thought to have the ability to induce errors in the airspeed data, posing possible safety hazards. This research aims to characterize and evaluate the magnitude of such errors and suggest mitigation actions for precise airspeed readings in crosswind conditions.

Object of Project:

1. Determine the extent of errors in airspeed measurement introduced by crosswind conditions.
2. Identify the factors contributing to these errors, such as wind speed, wind direction, aircraft configuration, and pitot tube design.
3. Investigate the impact of these errors on various angles of wind direction.
4. Develop recommendations and potential solutions to mitigate pitot tube errors during crosswind on the Cessna-172.

Tasks to solve the problem:

1. Review literature: Conduct a thorough review of relevant literature, research papers, and technical documentation to gain better understanding of the current state of knowledge and prior studies on pitot tube errors, crosswind effects, and airspeed measurement accuracy.
2. Data collection: Gather data including wind speed, wind direction, and other relevant atmospheric parameters. on crosswind condition or on different angles of wind direction during Cessna-172 flights or to make some similar experiments. This can be done through meteorological data, or onboard sensors.
3. Data analysis: Analyze the collected data to identify patterns and correlations between crosswind conditions and pitot tube errors. Use statical methods and data visualization techniques to determine the extent of airspeed measurement errors under different crosswind scenarios.
4. Simulation experiments: Perform simulated pitot tube experiments in controlled environments or wind tunnels to replicate crosswind conditions and measure the resulting pitot tube errors. Vary the wind speed, wind direction to evaluate their effects on airspeed accuracy.
5. Error mitigation strategies: Develop recommendations and guidelines for pilots and aircraft maintenance personnel to minimize or compensate for pitot tube errors during crosswind conditions.

The novelty of the theme:

1. Limited research: There is limited existing research specifically focusing on the errors associated with pitot tube measurements during crosswind conditions on the Cessna-172 aircraft. This study can contribute to filling this research gap and expanding the knowledge in this area.
2. Unique combination: The combination of pitot tube errors and crosswind conditions is a specific context that has its own set of challenges and potential errors sources. Investigation the interaction between these factors and their impact on airspeed measurements can provide valuable insights not previously explored extensively.

The relevance of the theme:

1. Flight safety: Precise airspeed measurements are vital for flight safety, as they are crucial for various flight operations, including takeoff, landing, and in-flight maneuvering. Investigation and mitigation pitot tube errors during crosswind conditions directly contributes to improving flight safety and reducing potential risks.
2. Practical implication: The outcome of this research can have practical implications for pilots and aircraft maintenance personnel. By identifying the sources and magnitude of pitot tube errors during crosswind, the study can provide recommendations and guidelines to enhance airspeed measurement accuracy and support informed decision-making during flight operations.

1. ANALYSIS OF THE LITERATURE

In this chapter we will explore the configuration of Cessna 172, its design, pitot tube design and positioning, and its impact on airspeed measurement accuracy. Additionally, we'll get knowledge about static ports, and the typical errors that occur in mechanical instruments such as altimeter, airspeed indicator, and also how the blockage occurs in pitot-static system.

1.1. General information about CESSNA 172

The Cessna 172 Skyhawk is a four-seat, single-engine, high-wing, fixed-wing aircraft manufactured by Cessna Aircraft Company in the United States. Since their first flight in 1955, more 172s have been constructed than any other kind of aircraft. It was based on the 1948 Cessna 170, but with tricycle undercarriage rather than taildragger.

The Cessna 172 is the most successful airplane in history, based on its durability and popularity. Cessna introduced the first production model in 1956, and by 2015, the business and its partners had produced over 44,000 units. The plane is still in production today. (Wikipedia, 2022).

1.2. Design and development

The Cessna 172 began as a tricycle landing gear variation of the taildragger Cessna 170, with modest standard equipment. Cessna flew a modified Cessna 170, a Continental O-300-A-powered Cessna 170C with wider elevators and a more angular tailfin, in January 1955. Despite the fact that the variation had been tested and approved, Cessna opted to modify it with tricycle landing gear, and the modified Cessna 170C took to the skies again on June 12, 1955. To simplify the time and expense of certification, the Model 172 was added to the Cessna 170 type certificate. The 172 was later awarded its own type certificate. The 172 was an instant success, with over 1,400 constructed in 1956, its first full year of production.

Early 172s were similar in appearance to the 170s, with the same straight aft fuselage and tall landing gear legs, although the 172 had a straight tailfin while the 170 had a rounded fin and rudder. In 1960, the 172A incorporated revised landing gear and the swept-back tailfin, which is still in use today. (Fig. 1.)



Figure 1. A 1960 Cessna 172A (Cessna 172, 2023)

The final aesthetic development, found in the 1963 172D and all later 172 models, was a lowered rear deck allowing an aft window. Cessna advertised this added rear visibility as "Omni-Vision."

Production halted in the mid-1980s but resumed in 1996 with the 160 hp (120 kW) Cessna 172R Skyhawk. Cessna supplemented this in 1998 with the 180 hp (135 kW) Cessna 172S Skyhawk SP (Cessna 172, 2023).

1.3. Pitot Static System

Measuring air pressure provides information to some of the most critical flying equipment. The pitot-static system collects and distributes various air pressures for flight instrumentation. The three most popular pitot-static instruments are the altimeter, airspeed indicator, and vertical speed indicator. (Omar Khan, 2016).

1.3.1. Pitot Tube

On simple aircraft, this may consist of a pitot-static system head or pitot tube with impact and static air pressure ports and leak-free tubing connecting these air pressure pickup points to the instruments that require the air for their indications. A pitot tube is open and faces into the airstream to receive the full force of the impact air pressure as the aircraft moves forward. (Fig 2.)

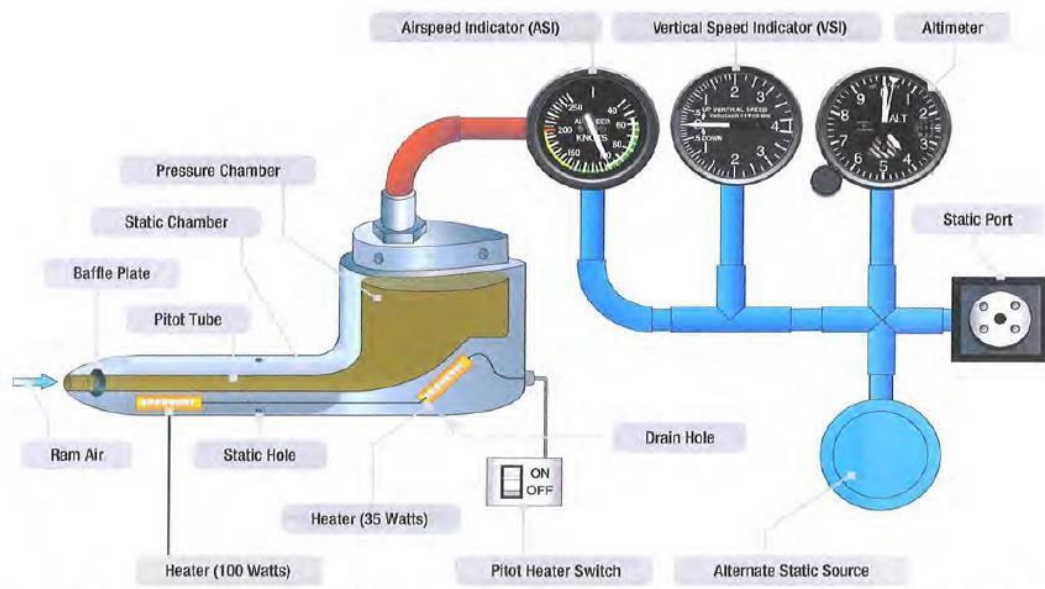


Figure 2. A typical pitot-static system head, or pitot tube, collects ram air and static pressure for use by the flight instruments (Omar Khan, 2016)

This air goes through a baffled plate designed to keep moisture and debris out of the tube. A drain hole is created beneath the baffle to allow moisture to escape. The ram air is channeled rearward to a chamber in the assembly's shark fin. This pressurized air is routed from the pitot assembly to the airspeed indicator through an upright tube, or riser. The aft part of the pitot tube has tiny holes on the top and bottom surfaces that are meant to collect static, or still, air pressure at atmospheric pressure. The static part also includes a riser tube, and air is routed by tubes from the pitot assembly to the altimeter, airspeed indicator, and vertical speed indicator. Heating elements are used in many pitot-static tube heads to avoid icing during flight. When ice-forming conditions occur, the pilot can transmit electric current to the element through a switch in the cockpit. This switch is frequently linked to the ignition switch so that when the aircraft is turned off, a pitot tube heater that has been left on mistakenly does not continue to draw electricity and drain the battery. Caution should be exercised when near the pitot tube, as these heating elements make the tube too hot to be touched without receiving a burn. The pitot-static tube is mounted on the outside of the aircraft at a point where the air is least likely to be turbulent. It is pointed in a forward direction parallel to the aircraft's line of flight. The location may vary. Some are on the nose of the fuselage and others may be located on a wing. A few may even be found on the empennage. Various designs exist but the function remains the same, to capture impact air pressure and static air pressure and direct them to the proper instruments. Most aircraft equipped with a pitot-static tube have an alternate source of static air pressure provided for emergency use. The pilot may select the alternate with a switch in the cockpit should it appear the flight instruments are

not providing accurate indications. On low-flying unpressurized aircraft, the alternate static source may simply be air from the cabin. On pressurized aircraft, cabin air pressure may be significantly different than the outside ambient air pressure. Another type of pitot-static system provides for the location of the pitot and static sources at separate positions on the aircraft. The pitot tube in this arrangement is used only to gather ram air pressure (Omar Khan, 2016).

1.3.2. Static Ports

Static ports (vents) are used to collect static air pressure information. Usually, these are located flush on the side of the fuselage. (Fig 3.). There may be two or more vents. A primary and alternate source vent is typical, as well as separate dedicated vents for the pilot and first officer's instruments. Also, two primary vents may be located on opposite sides of the fuselage and connected with a "T" or "Y" tubing for input to the instruments. The "Y" arrangement helps to average out any measurement errors, a technique called 'Static balancing'. This is done to compensate for any variations in static air pressure on the vents due to the aircraft's attitude and correct any errors associated with asymmetrical flight (slip-skid). Vent pipes are typically angled downwards to drain any water or contaminants which may block the airway.



Figure 3. Static ports (Omar Khan, 2016)

To avoid impairing thermal efficiency of static ports, they must not be painted, a warning to this affect is generally imprinted adjacent to static ports. Regardless of the number and location of separate static vents, they may be heated as well as the separate ram air pitot tube to prevent icing. If failure of the primary pitot static pressure source should occur, for example icing up of a pitot or pressure head due

to a failed heater circuit, errors may be introduced in the instrument readings and other areas dependent on such pressure. As a safeguard against partial failure, a standby system may be installed in some aeroplanes, whereby static pressure and/or pitot pressure from alternate sources can be selected and connected into the primary system. A blockage of the pitot source is not serious, as it will only affect the ASI. A blockage of the static source will however affect all of the instruments, and it is thus common practice to provide an alternate static supply (Omar Khan, 2016).

1.4. Pitot Static System Errors

In this subchapter, the typical errors that occur in pitot-static system will be discussed, and how it affects the gauge readings will be mentioned.

1.4.1. Blocked Pitot System

The pitot system can become blocked completely or only partially if the pitot tube drain hole remains open. (Fig 4.). If the pitot tube becomes blocked and its associated drain hole remains clear, ram air no longer is able to enter the pitot system. Air already in the system vents through the drain hole, and the remaining pressure drops to ambient (outside) air pressure. Under these circumstances, the ASI reading decreases to zero, because the ASI senses no difference between ram and static air pressure. The ASI no longer operates since dynamic pressure cannot enter the pitot tube opening. Static pressure is able to equalize on both sides since the pitot drain hole is still open. The apparent loss of airspeed is not usually instantaneous but happens very quickly. If both the pitot tube opening and the drain hole should become clogged simultaneously, then the pressure in the pitot tube is trapped.

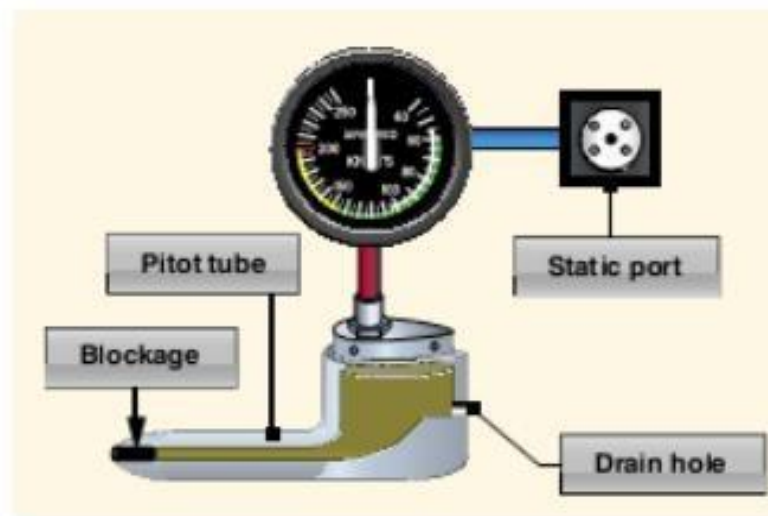


Figure 4. A blocked pitot tube, but clear drain hole (A.K.Bhardwaj, 2014)

If the airspeed increases or decreases, the airspeed indicator does not change. If the static port is unblocked and the aircraft changes altitude, the ASI records the change. The difference is due to a change in static pressure rather than a change in airspeed. The overall pressure in the pitot tube does not vary as a result of the obstruction, but the static pressure does. Because airspeed indicators rely on both static and dynamic pressure, a blockage in any of these systems has an impact on the ASI reading. Remember that the ASI has a diaphragm that accepts dynamic air pressure. The static pressure, which originates from the static ports, is located behind this diaphragm. The diaphragm pressurizes against this static pressure and as a result changes the airspeed indication via levers and indicators (A.K.Bhardwaj, 2014).

1.4.2. Blocked Static System

If the static system becomes blocked but the pitot tube remains clear, the ASI continues to operate; however, it is inaccurate. (Fig 5.)

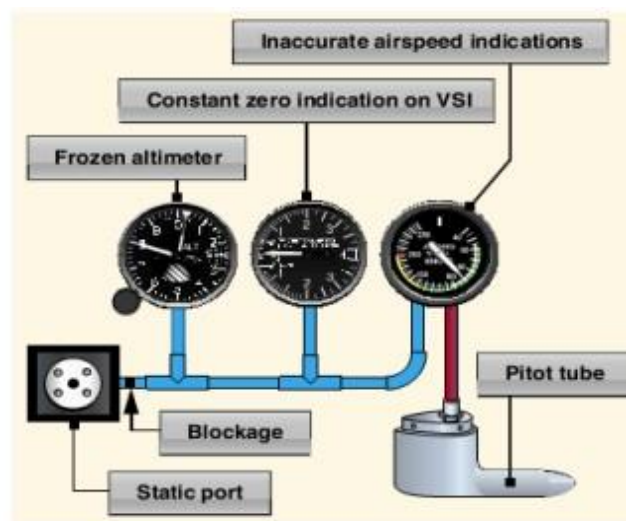


Figure 5. Blocked static system (A.K.Bhardwaj, 2014)

The airspeed indicates lower than the actual airspeed when the aircraft is operated above the altitude where the static ports became blocked, because the trapped static pressure is higher than normal for that altitude. When operating at a lower altitude, a faster than actual airspeed is displayed due to the relatively low static pressure trapped in the system. Revisiting the ratios that were used to explain a blocked pitot tube, the same principle applies for a blocked static port. If the aircraft descends, the static pressure increases on the pitot side showing an increase on the ASI. This assumes that the aircraft does not actually increase its speed. The increase in static pressure on the pitot side is equivalent to an increase in dynamic pressure since the pressure cannot change on the static side. If an aircraft begins to climb after a static

port becomes blocked, the airspeed begins to show a decrease as the aircraft continues to climb. This is due to the decrease in static pressure on the pitot side, while the pressure on the static side is held constant. A blockage of the static system also affects the altimeter and VSI. Trapped static pressure causes the altimeter to freeze at the altitude where the blockage occurred. In the case of the VSI, a blocked static system produces a continuous zero indication (A.K.Bhardwaj, 2014).

1.4.3. Pitot Tube Drain Block

We consider the effects of the drain and the pitot tube becoming blocked together. This is a scenario common to pitot icing, the entire probe ices and becomes completely blocked. The air that was contained in the diaphragm at the time of the block becomes trapped. As the aircraft ascends above the blockage altitude, the static air becomes less dense allowing the denser air trapped inside the diaphragm to expand and cause the airspeed indicator to increase as the altitude increases, opposite of the true airspeed. Similarly, as the aircraft descends below the blockage altitude, the static air becomes more dense causing the diaphragm to compress and show a decreasing airspeed as the altitude decreases, opposite of the true airspeed (A.K.Bhardwaj, 2014).

1.5. Introduction To the Instrument Systems and Errors

Accurate speed and altitude readings are critical for aircraft safety and efficiency. Accurate speed measurements are required, for example, to avoid loss of control at low speeds (stall condition) and to avoid exceeding the aircraft's aerodynamic and structural limitations at high speeds, whereas accurate altitude measurements are required to ensure clearance of terrain obstacles and to maintain prescribed vertical separation minima along the airways.

The altimeter, airspeed indicator, true-airspeed indicator, Machmeter, and rate-of-climb (or vertical-speed) indicator are all equipment used to measure speed and altitude. All of these instruments are controlled by pressures, with the exception of the true airspeed indicator, which is also controlled by air temperature.

Two basic pressures, static pressure and total pressure are used to actuate instruments. The static pressure is the atmospheric pressure at the flight level of the aircraft, while the total pressure is the sum of the static pressure and the impact pressure, which is the pressure developed by the forward speed of the aircraft. The relation of the three pressures can thus be expressed by the following equation (1.1):

$$p(t)=p+q(c) \quad (1.1)$$

where $p(t)$ is the total pressure, p is the static pressure, and $q(c)$ the impact pressure.

The static pressure is used to actuate both altimeter and the rate of climb indicator. Although this pressure varies from day to day, the decrease in static pressure with height is generally continuous at any one time and place. Accordingly, a pressure-height relation based on average atmospheric conditions has been adopted as a standard. Measurements of static pressure are then used to provide indications of height in terms of pressure altitude and indications of vertical speed in terms of rate of change in the pressure altitude.

For the three forward-speed indicators, impact pressure is derived as a differential pressure from measurements of total pressure and static pressure in accordance with equation. The airspeed indicator is actuated solely by impact pressure and is calibrated to indicate true airspeed at sea level density in the standard atmosphere; at altitude, however, the indicated airspeed is lower than the true airspeed. The true airspeed indicator, on the other hand, combines the measurement of impact pressure with measurements of static pressure and temperature to indicate true airspeed independent of altitude. The Machmeter (named for the Austrian physicist, Ernst Mach) combines measurements of impact pressure and static pressure to provide indications of true airspeed as a fraction or multiple of the speed of sound (sonic speed).

The airspeed indicator, true-airspeed indicator, and Machmeter measure speed with respect to the air mass. Since the air mass can move with respect to the ground, the measurement of ground speed, the speed of basic importance to air navigation, must be derived from inputs from ground navigational aids.

The pressures and temperatures that actuate the instruments are derived from pressure and temperature sensors located at positions on the aircraft which are remote from the instruments. The problem of designing and location the sensors for the accurate measurement of pressure and temperature is complicated by many factors. Therefore, the pressures and temperatures registered by the sensors, can be in error by amounts which, in some cases, produce sizable errors in the indication of the instruments. The indications of an instrument can also be in error because of imperfections in the instrument itself. Additional errors may be introduced because of a time lag in the transmission of the pressures to the instruments whenever the pressure at the pressure source is changing rapidly, as in the case of high-speed climbs or dives (William Gracey, 1980).

1.6. Instrument System and Errors

As noted, beforehand, the two basic pressures that are employed in the measurement of speed and altitude are total pressure and static pressure. Total pressure is sensed by an opening in a forward-facing tube called a total pressure tube or pitot tube (named for the French physicist, Henri Pitot). The static pressure

is sensed by orifices in the side of another type of tube, called a static-pressure tube, or by a set of holes in the side of an aircraft fuselage, called fuselage vents or static ports. Since the pitot tube and the static pressure tube can be combined into a single tube, two types of pressure-measuring installations are possible: a pitot-static tube installation or a pitot tube in combination with a fuselage-bent system. (Fig 6.)

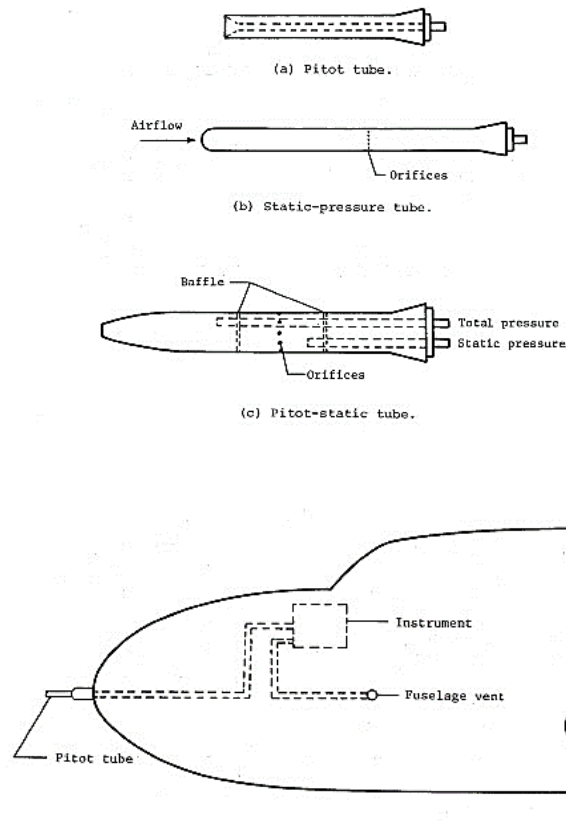


Figure 6. Diagrams of pressure tubes and pitot tube installation (William Gracey, 1980)

The pressures that are sensed by the pitot tube and the static pressure tube (or fuselage vents) are conveyed through tubing to pressure-sensing elements which are generally in the form of capsules, diaphragms, or bellows.

The pressure capsules are formed by joining together two corrugated diaphragms which are about 2 in. in diameter. Two types of capsules are used in aircraft instruments: one for measuring absolute pressure and the other for measuring differential pressure. The absolute-pressure (or aneroid) capsule is evacuated and sealed, while the differential pressure capsule has an opening that is connected to a

pressure source. The absolute –pressure capsule reacts to the pressure inside the instrument case, while the differential pressure capsule reacts to the difference between the pressure inside the capsule and the pressure in the instrument case. Thus, for both types of capsules, the instrument case is used as a pressure chamber to form one element of the pressure-measuring system.

Also shown in figure 7. are the directions of the deflection of the capsules for a given pressure change. These deflections, which are very small, are amplified through a system of gears and levers (gear train) to rotate a pointer in front of the scale on the dial of the instrument.

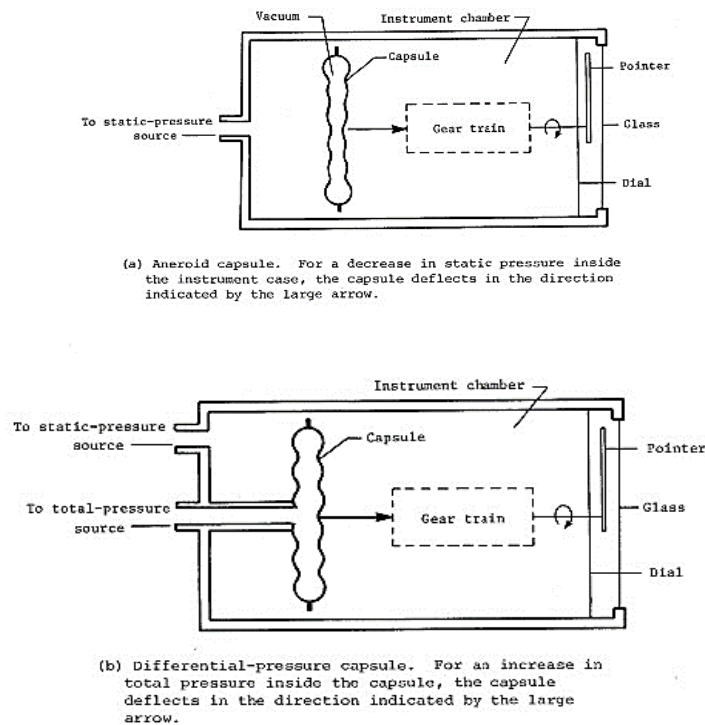


Figure 7. Aircraft instruments with two types of pressure capsules (William Gracey, 1980)

The static-pressure tube is connected to all the instruments, whereas the total pressure tube is connected only to those instruments that measure forward speed. The temperature probe, which is connected to the true airspeed indicator, is a type used with liquid-pressure thermometers. The pressure tubing from the total pressure and static pressure tubes is generally about 0.2 to 0.3 in. in inside diameter, whereas the capillary tubing from the temperature probe is about 0.01 to 0.02 in.

In the rate of climb indicator, the static pressure tube is connected to a differential pressure capsule and to a capillary tube that opens into the instrument case. With a change in static pressure, the simultaneous flow of air into, or out of, the capsule and the capillary tube is adjusted (by the size of

the capillary leak) so that the capsule deflects in terms of a rate of change of pressure, which is calibrated to yield a measure of vertical speed.

The pressure-sensing element of the airspeed indicator is a differential-pressure capsule that expands as the total pressure increases. Since the pressure inside the case is the static pressure, the instrument performs a mechanical subtraction of total and static pressures to yield a measure of impact pressure in accordance with equation.

The Machmeter contains both an aneroid capsule and a differential-pressure capsule to provide measures of static pressure and impact pressure. The deflections of the two capsules are coupled to yield, mechanically, the ratio of impact pressure to static pressure ($q(c)/p$) is a function of Mach number.

The true-airspeed indicator contains two differential pressure capsules to provide measures of impact pressure and air temperature and an aneroid capsule to provide a measure of static pressure. Since the true airspeed is a function dynamic pressure, derived from the measured impact pressure and static pressure and the air density, derived from static pressure and temperature, the deflections of the three capsules can be coupled to yield a measure of true airspeed.

The pressures ($p(t)'$ and p') sensed by the total and static pressure tubes and the temperature (T') sensed by the temperature probe. For any one flight condition, the differences between $p(t)'$ and the free-stream total pressure $p(t)$ and between (T') and the free-stream air temperature T depend primarily on the design characteristics of the pitot tube and the temperature probe. The difference between p' and the free-stream static pressure p depends on both the design of the static pressure tube and on the location of the tube in pressure field surrounding the aircraft.

The difference between $p(t)'$ and $p(t)$ called the total-pressure error. $\Delta p(t)$ is defined by

$$\Delta p(t) = p(t)' - p(t) \quad (1.2.)$$

The difference between (T') and T , the temperature error ΔT is defined by

$$\Delta T = T' - T \quad (1.3.)$$

The indications of the instruments may be affected by errors due to the time lag in the transmission of the pressures and to imperfections in the instrument mechanism. The errors associated with the instrument mechanism depend on the elastic properties of the pressure capsule (scale error, hysteresis, and drift) and the effects of temperature, acceleration, and friction on the linkage mechanism. The scale

error is the difference, for a given applied pressure, between the value indicated by the instrument and the correct value corresponding to the applied pressure.

From the foregoing discussion, the overall error of an instrument system is a combination of

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

The magnitude and nature of the errors vary widely, so that different means are used to minimize different errors.

The total pressure static pressure and temperature errors for example are systematic; that is, for a given flight condition, the errors are essentially repeatable and hence can be determined by calibration. The static pressure error can be quite large, whereas the total pressure error is generally negligible.

The errors due to pressure lag are transitory and vary with the rate of climb or descent of the aircraft. For a given rate of change of altitude, the magnitude of the lag error depends primarily on the length and diameter of the pressure tubing and on the volume of the instruments connected to the tubing. Accordingly, the lag errors of a particular pressure system are kept within acceptable limits by proper design of the system.

Of the various instrument errors, the scale error is systematic, while the other errors are generally random. The scale error is usually the largest of the instrument errors and can be determined by laboratory calibration. The remaining errors are kept within acceptable limits by careful design, construction, and adjustment of the instrument mechanism.

The instrument errors and the errors of the pitot-static installation are required to meet specified tolerances (allowable errors). The tolerances for the instrument errors can be combined to yield an "instrument error," and this error can be combined with the tolerance for the static-pressure error to yield an "instrument system error"(Gilsinn, 1976).

Since the scale error of the instrument and the static-pressure error of the installation can be determined by calibration, corrections for these two errors can be applied. With mechanical instrument systems, corrections for these errors are applied by means of correction charts, or cards, that are supplied to the

pilot. With electrical instruments, the corrections are applied automatically by some form of computer. For systems in which corrections for the two errors are applied, the instrument system error is usually much lower than the error derived from a summation of the instrument and static pressure error tolerances (William Gracey, 1957).

1.7. Aircraft Instrument Errors

Aircraft instruments are required to meet specified standards of accuracy. These accuracies are expressed in terms of error tolerances (allowable errors) which may be stated as a percent of the measured quantity, as a percent of the full-scale range of the instrument, or as a series of individual tolerances for given values of the measured quantities.

The specified accuracies of the instruments vary depending on the type of instrument and on the state of the art at the time the instrument was developed. The accuracy of the "precision" mechanical altimeter, for example, is greater than that of the older "sensitive" altimeter. Similarly, the accuracies of electrical instruments are greater than those of the mechanical types, and of the two electrical instrument systems, the electronic pressure-transducer system is somewhat more accurate than the served instrument systems.

Until recent years, mechanical instruments were used in all types of aircraft: they are still widely used in general aviation aircraft and in older civil transport and military aircraft. Served instrument systems, a later development, have been used for some years in turbojet transport and military jet aircraft, while electronic pressure-transducer systems, an even later development, are now being used in some turbojet transport and military jet aircraft.

The Federal Aviation Administration specifies the accuracy of instruments used in civil aircraft, while the U.S. Air Force, Army, and Navy specify the accuracy of instruments used in military aircraft. For the instruments discussed in this chapter, the accuracies have, for the most part, been extracted from instrument standards specified by the Air Force (Gracey William, 1980).

1.7.1. Mechanical Instruments

As noted beforehand, the scale error (i.e., the difference between an instrument indication and the correct value) is generally the largest of the various instrument errors. Thus, the determination of this error is the primary concern of the laboratory testing of the instruments.

When it has been determined that the scale errors of a particular instrument conform to the specified tolerances, the instrument is considered acceptable for operational use. However, since the scale error is

systematic (repeatable), many aircraft operators require that corrections for the error be applied in order to achieve an accuracy greater than the specified accuracy.

1.7.2. Altimeter errors

The altitude display of the mechanical altimeter is a circular scale with one or more rotating pointers. Examples of dial-type altitude displays are the three-pointer display of figure 8 (a) and the drum-pointer (or similar counter-pointer) display of figure 8 (b). With the three-pointer display, the long pointer rotates one revolution per 1000 ft, the short pointer one revolution per 10 000 ft, and the pointer with the triangular index one revolution per 100 000 ft. With the drum pointer (or counter-pointer) display, the pointer rotates one revolution per 1000 ft and the drum (or counter) rotates to indicate 1000-ft or 10 000-ft increments. Thus, for altimeters with an 80 000-ft range, the long pointer on both types of displays rotates 80 times (Technical Manual Pressure Altimeter Manual, 1960).

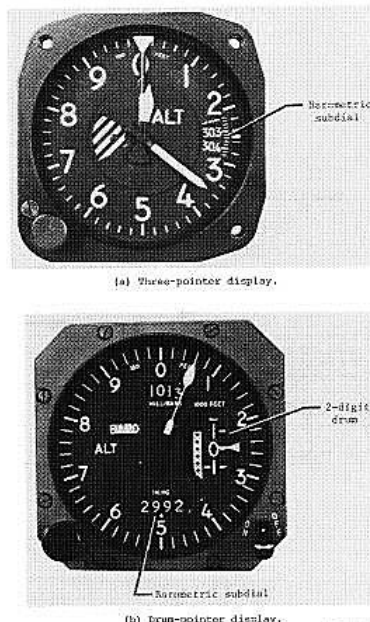


Figure 8. Pressure altimeters with different altitude displays (Technical Manual Pressure Altimeter Manual, 1960)

Since the scale of the altimeter is uniform, whereas the decrease in pressure with height is exponential, the pressure increment corresponding to a given height increment decreases with altitude (for example, the increment is 76 lb/ft² per 1000 ft at sea level, 19 lb/ft² per 1000 ft at 40 000 ft, and 3 lb/ft² per 1000 ft at 80 000 ft). As a result, measurement of pressure altitude becomes increasingly difficult at higher altitudes. As is shown later, this measurement difficulty is reflected in the much larger scale errors that are allowed at higher altitudes.

As a consequence of the great scale sensitivity of the altimeter, errors due to hysteresis and drift can be of significance. These errors, together with the errors due to aftereffect (hysteresis at sea level pressure) and recovery (drift at sea-level pressure), are illustrated in a description of a scale error calibration (Fig 9).

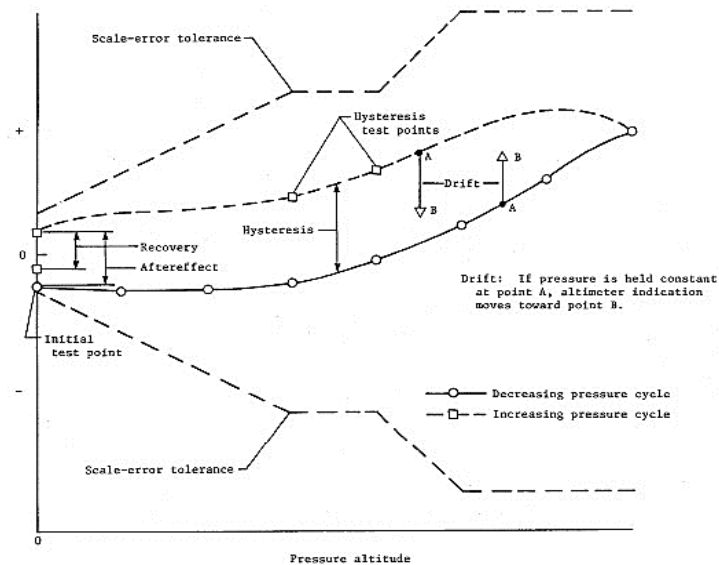


Figure 9. Illustration of scale error calibration of a pressure altimeter
(Technical Manual Overhaul Pressure Altimeter, 1960)

For the scale-error calibration of an altimeter, the instrument is connected to a mercury barometer and a suction pump. The barometric subdial of the altimeter is set to 29.92 (Fig 8(a)), and the system pressure is adjusted to 29.92 in. Hg. The altimeter indication at this initial test point is noted, and then the pressure is reduced, at a rate corresponding to about 3000 ft/min, to the next test point (Fig 9.). At each test point, the pressure is held constant for about 2 min and the instrument is vibrated before the altimeter indication is noted. When the test point at the maximum test altitude has been reached, the pressure is increased to two hysteresis test points, and thereafter to the initial test pressure. The altimeter indication at this point is higher than the initial indication (because of aftereffect) and decreases slowly toward the initial indication (because of recovery effect). After a sufficient time lapse, the indication returns to the initial indication (called the rest point). The recovery error is the extent of this return during a specified time period.

As indicated in figure 9, the hysteresis is the difference, at a given test pressure, between the instrument indications determined when the pressure is decreasing and when it is increasing. If the pressure is

held constant at a given value during the pressure cycle (as at point A in figure 9), the instrument indication drifts toward point B. This drift is always in a direction to "close" the hysteresis loop.

For the certification of an altimeter for operational use, the scale errors: determined at decreasing pressures are required to fall within the scale-error tolerance band (fig 9.) defined by the specified error tolerances. These scale errors (circular test points in fig 9.) are the values used in the preparation of correction charts or for the scale-error corrections in air data computers.

The scale-error tolerances for two types of sensitive altimeters) and two types of precision altimeters are presented in table 1. Also tabulated are the hysteresis tolerances at two test altitudes and the aftereffect tolerance at sea-level pressure. Note that the calibration standards for these instruments do not require tests for the drift and recovery errors. A comparison of the scaleerror tolerances for the four altimeters provides an indication of the improved accuracy that has been achieved through the years.

Table 1. Error tolerances for four types of altimeters (Altimeter, Pressure Actuated, Sensitive Type, 1959)

Test-point altitude, ft	Sensitive altimeters		Precision altimeters	
	^b Type C-12	^b Type C-13	^b Type MA-1	^b Type AAU-B/A
Scale-error tolerance, ft				
0	±50	±50	±30	±30
5 000	±150	±100	±55	±55
10 000	±175	±150	±80	±80
15 000	±235	±200	±105	±105
20 000	±300	±200	±130	±130
25 000	±375	±300	±155	±155
30 000	±450	±300	±180	±180
35 000	±525	±300	±205	±205
40 000	±600		±300	±230
45 000	±675		±400	±255
50 000	±750		±500	±280
60 000			±800	±800
70 000			±1200	±1200
80 000			±1500	±1500
Hysteresis tolerance, ft				
16 000	----	±70	----	----
18 000	----	±70	----	----
20 000	±150	----	±100	±100
25 000	±150	----	±100	±100
Aftereffect tolerance, ft				
0	±60	±50	±50	±50

^aAbbreviated list of test points.

^bU.S. Air Force types.

Determination of the hysteresis at two test points, specified by standard test procedures, defines only a part of the hysteresis cycle. In tests to determine the complete hysteresis cycles of three types of altimeter, a number of type C-12, C-13, and MA-1 altimeters were calibrated throughout the hysteresis cycle. The calibrations of representative instruments of each altimeter type are presented in figure 10. In table 2, values of hysteresis errors (at the standard test points) for all the instruments are compared with the hysteresis tolerances. Also tabulated are the aftereffect errors and tolerances. These results

are of interest in showing the hysteresis and aftereffect errors of the precision-type altimeter to be very much lower than the specified tolerances.

Table 2. Hysteresis and aftereffect of three types of altimeter (Altimeter, Pressure Actuated, Sensitive Type, 1959)

Altimeter type	Minimum	Maximum	Average	Tolerance
Hysteresis, ft				
C-12	80	160	112	150
C-13	60	110	87	70
MA-1	10	45	25	100
Aftereffect, ft				
C-12	25	60	41	60
C-13	25	55	33	50
MA-1	5	20	10	50

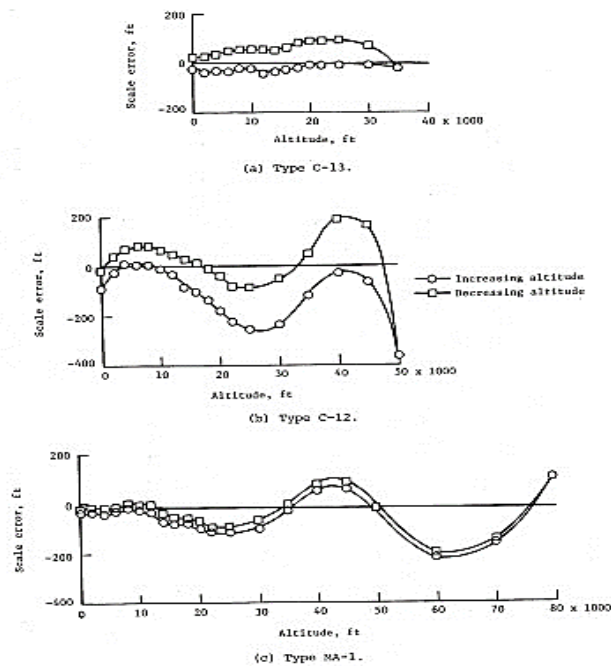


Figure 10. Scale errors and hysteresis of three types of altimeters (Gracey, William 1961)

In further tests of the three types of altimeters, the drift errors were determined through 1-hour and 6-hour test periods. The drift errors of a representative instrument of each altimeter type are shown in

figure 11. These data show the major part of the 6-hour drift occurs within a short period after the start of the test (Altimeter, Pressure Actuated, Sensitive Type, 1959).

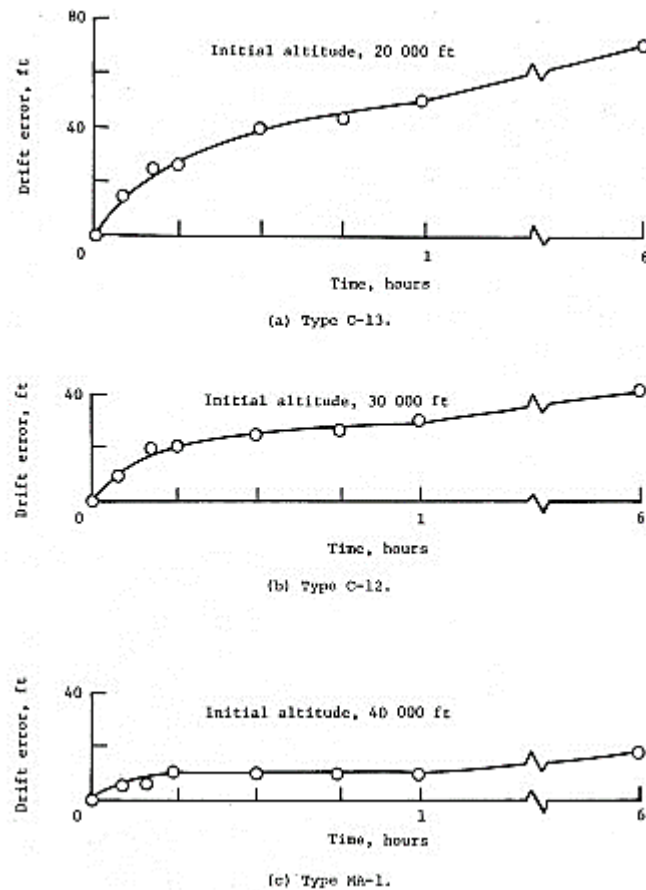


Figure 11. Typical errors of types of altimeters (Gracey, William, 1961)

1.7.3. Airspeed indicator errors

An example of a mechanical-type airspeed indicator is the disk-pointer instrument shown in figure 12.



Figure 12. Airspeed indicator (Technical Order Overhaul Instructions - Sensitive Airspeed Indicator, 1967)

The range of this indicator is 50 to 650 knots and the scale-error tolerances through this speed range are given in table 3 (Technical Order Overhaul Instructions - Sensitive Airspeed Indicator, 1967).

Table 3. Scale error tolerances of airspeed indicator (Technical Order Overhaul Instructions - Sensitive Airspeed Indicator, 1967)

Calibrated airspeed, knots	Tolerance, knots
50	±4.0
80	±2.0
150	±2.5
250	±3.0
300	±4.0
550	±5.0
650	±5.0

^aAbbreviated list of test points.

The airspeed indicator is calibrated by applying pressures to the pitot port of the instrument and measuring the difference between these pressures and the existing atmospheric pressure with a mercury manometer. The differential pressures corresponding to given values of calibrated airspeed are listed in tables A9 and All of appendix A.

1.8. Conclusion from the analysis

Firstly, the literature consistently highlights the importance of the pitot-static port system for precise airspeed measurement in aircraft. The pitot tube, combined with static port, plays a critical role in providing reliable airspeed information for flight operations.

Secondly, the literature emphasizes the importance of proper pitot tube design, installation, and maintenance to mitigate errors during crosswind and other hazardous factors. Factors such as shape and orientation of the pitot tube, the presence of protective covers or vanes, and the use of anti-icing measures can influence the system's susceptibility to crosswind-induced errors.

Additionally, the analysis of the literature underscores the significance of understanding and mitigation errors in mechanical instruments. By implementing proper maintenance practices, conducting regular inspections, and adhering to calibration procedures, pilots and maintenance personnel can help ensure the accuracy and reliability of these instruments.

By building upon the knowledge gained from literature, future research can focus on developing advanced techniques, methodologies to explore those errors and ultimately contributing to safer and more efficient flight operations.

2. ANALYSIS OF RESEARCH METHODS

In this section, we will examine and critically assess the research methods employed in the present study which investigates accuracy of pitot tube during crosswind condition.

The present study utilizes ANSYS, a widely used CFD software, to simulate the performance of a pitot tube, which is a fundamental, instrument for measuring airspeed in aerospace applications.

The primary objective of this analysis is to investigate the performance characteristics of the pitot tube under specific flow conditions, such as during crosswind scenarios. By employing ANSYS simulation, we can gain insights into the flow patterns, pressure distribution, and accuracy of the airspeed measurements obtained from the pitot tube. The analysis of the research methods aims to evaluate the validity and reliability of the simulation results, as well as to assess the suitability of the ANSYS software for modeling the behavior of the pitot tube.

To achieve the research objectives, this analysis will adopt a systematic approach. First, we will discuss the selection and justification of ANSYS as the chosen simulation software. We will explore the capabilities of ANSYS in accurately capturing the flow physics, its compatibility with modeling the pitot tube geometry, and its ability to provide reliable results for subsequent analysis.

Next, we will outline the steps involved in the simulation process. This includes the construction of a suitable computational domain, the mesh generation to discretize the domain, and the selection of appropriate boundary conditions to represent the operating environment of the pitot tube. We will provide a detailed description of the simulation setup, including the assumptions made, input parameters defined, and any simplifications or idealizations implemented.

Subsequently, we will delve into the solver settings and numerical methods utilized in the ANSYS simulation. We will discuss the selection of appropriate turbulence models, convergence criteria, and solution strategies to ensure accurate and efficient simulations. Furthermore, we will address the validation and verification process employed to assess the reliability of the ANSYS simulation results by comparing them with experimental data or analytical solutions, where available.

Throughout this analysis, we will critically evaluate the strengths and limitations of the ANSYS simulation approach. We will assess its ability to accurately capture the flow behavior within and around the pitot tube, as well as its capability to predict the airspeed measurements under different flow conditions. Additionally, we will discuss the potential sources of uncertainty and error associated with the simulation process, such as mesh resolution, boundary condition assumptions, and solver settings.

By conducting a comprehensive analysis of the research methods employed in the present study using ANSYS simulation, we aim to provide valuable insights into the performance characteristics and accuracy of the pitot tube. This analysis will contribute to a deeper understanding of the applicability and limitations of CFD simulations in modeling and analyzing the behavior of pitot tubes. The findings and recommendations derived from this analysis can potentially inform future design improvements and calibration procedures for pitot tubes in aerospace applications.

2.1. The Main Objective

The objective of this simulation is to analyze how a Pitot static tube is used on a small private airplane to determine the aircraft's velocity.

Initial data:

Test section dimensions: 0.685m X 0.410m X 0.385m (L x W x H) (Figure 13.)

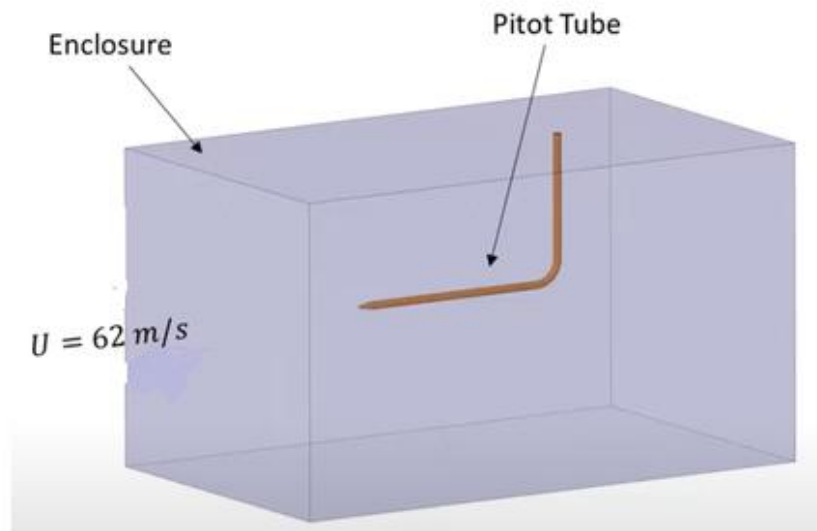


Figure 13. Test Enclosure

The operating conditions reflect the flight conditions of a small airplane cruising at 3500m above sea level.

Inlet velocity is 62 m/s which corresponds to Mach number of 0.19. Effects of air compressibility are, in general, negligible when Mach number is less than 0.3.

The fluid is air and is assumed to be incompressible:

- $\rho_{air} = 0.8636 \text{ kg/m}^3$ and $\mu_{air} = 1.6780 \times 10^{-5} \text{ kg/ms}$
- $p_{air} = 65780 \text{ Pa}$

Boundary conditions (Fig.14):

Inlet: velocity inlet

Outlet: pressure outlet

Enclosure sides: slip walls

Pitot tube and pressure ports: no slip wall

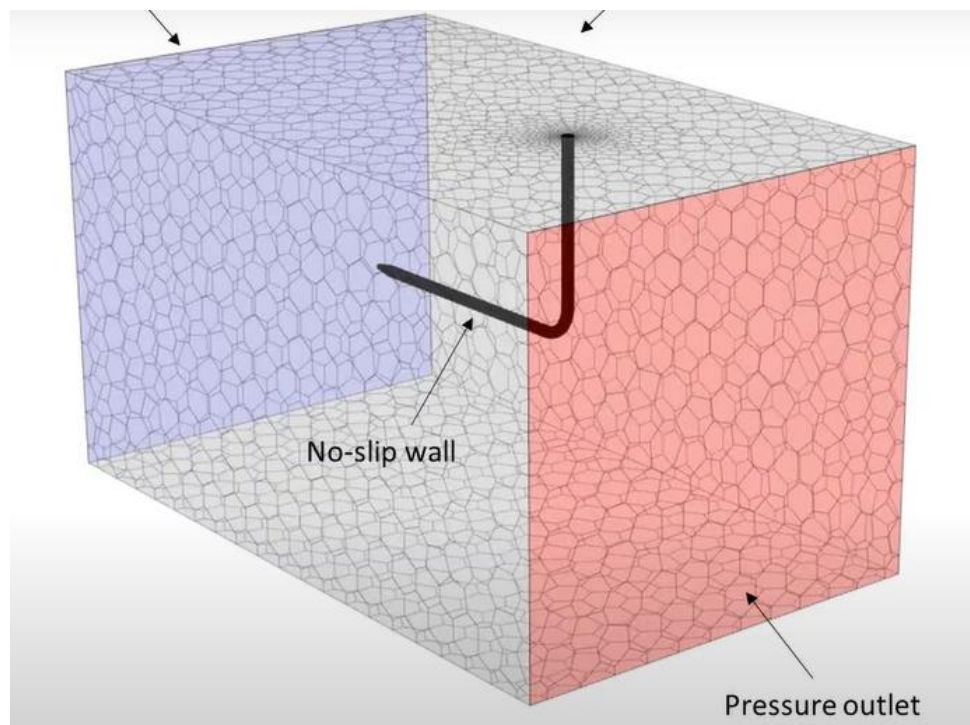


Figure 14. Boundary conditions

2.2. Results

The static pressure contours and velocity contours are shown on centerline plane through the domain. (Fig.15)

The pressure contours show the effect of the orientation of the ports on the pressure measurements:

- The pressure rises as the air comes to a stop inside the central pipe of the Pitot tube. This pressure is equal to the total pressure of the fluid.

- The pressure in the other two pipes is lower than in the central pipe and is equal to the surrounding air pressure. This is the static pressure of the fluid.



Figure 15. Contours of static pressure

The velocity contours show zero air velocity inside the internal pipes of the Pitot tube: (Fig.16)

- In the central pipe the air cannot move further and comes to a stop.
- Air flows parallel to the static pressure ports, and it does not enter into the other two pipes.

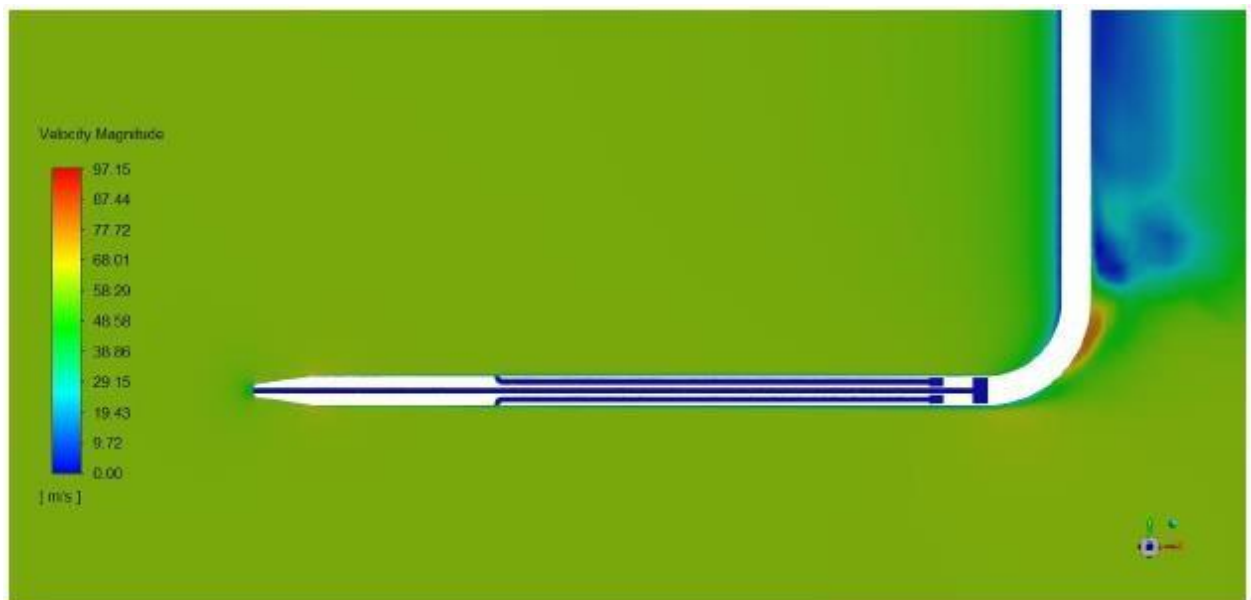


Figure 16. Contours of velocity magnitude.

The area-weighted average of the local static pressure on the pressure ports gives us an estimate the total and static pressure of the fluid (Fig.17):

- Static pressure 65779.2 Pa
- Total pressure 67472.6 Pa

Using Bernoulli's equation (recalling that the flow is incompressible) we can use the Pitot tube readings to calculate the airplane velocity:

$$U = \sqrt{\frac{2(p_{tot} - p_s)}{\rho}} = 62.6 \text{ m/s} \quad (2.1)$$

Area-Weighted Average Static Pressure	(pascal)
static-pressure-port	65779.227
total-pressure-port	67472.61

Figure 17. Pressure measurement on the static and the total pressure ports

2.3. Convergence

The continuity residual does not decrease further due to the intrinsic unsteadiness of this case. Indeed, the vertical part of the Pitot tube generates intrinsically unsteady wake.

Static and total pressures at monitor locations are not affected by the wake unsteadiness and their values can be calculated from the steady-state solution.

The residuals and the monitored quantities do not show significant variations after running for 300 iteration. For the scope of this exercise this is an adequate level of convergence, given that the mass flow rate is also conserved. (Fig.18, 19, 20)

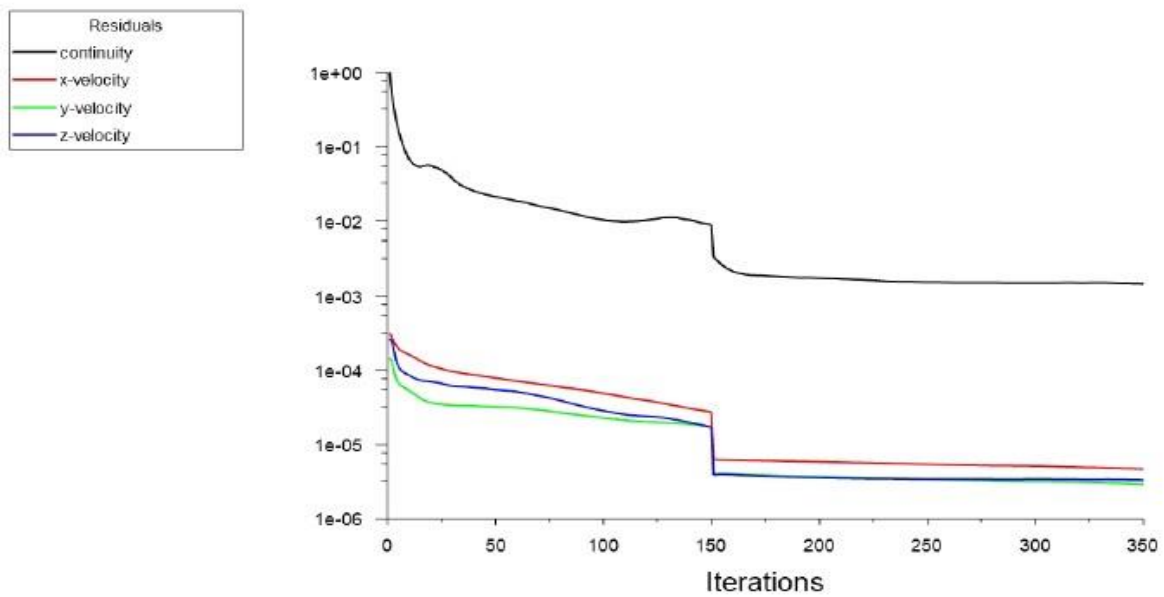


Figure 18. Plot of the solution residuals.

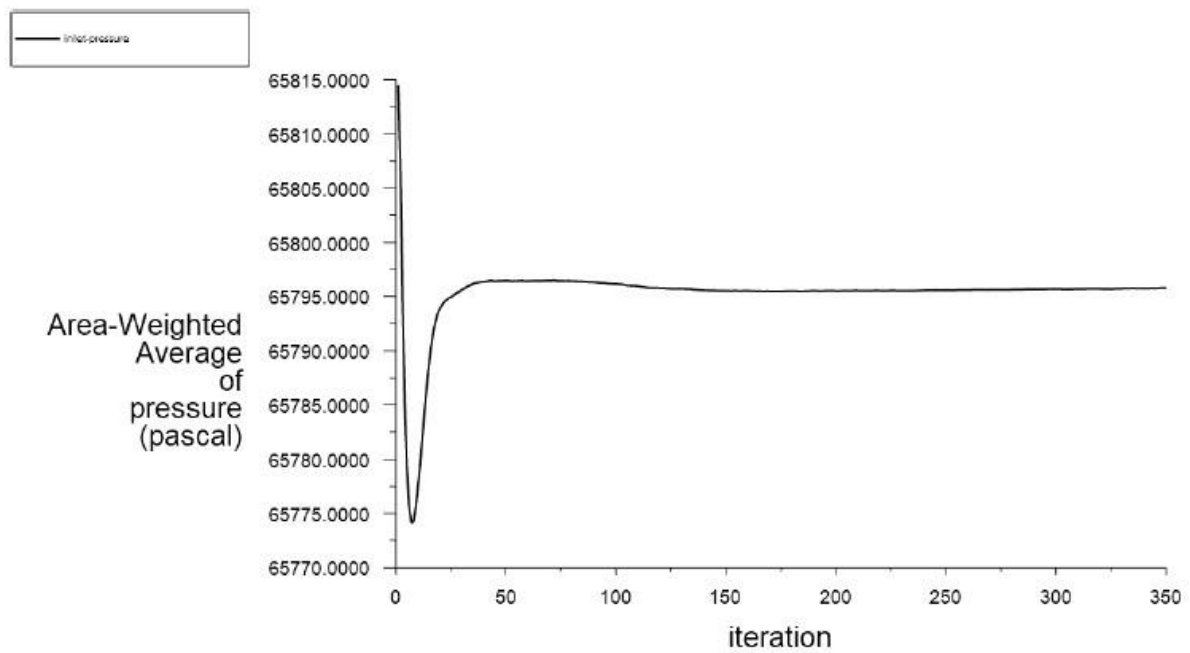


Figure 19. Plot of the inlet static pressure.

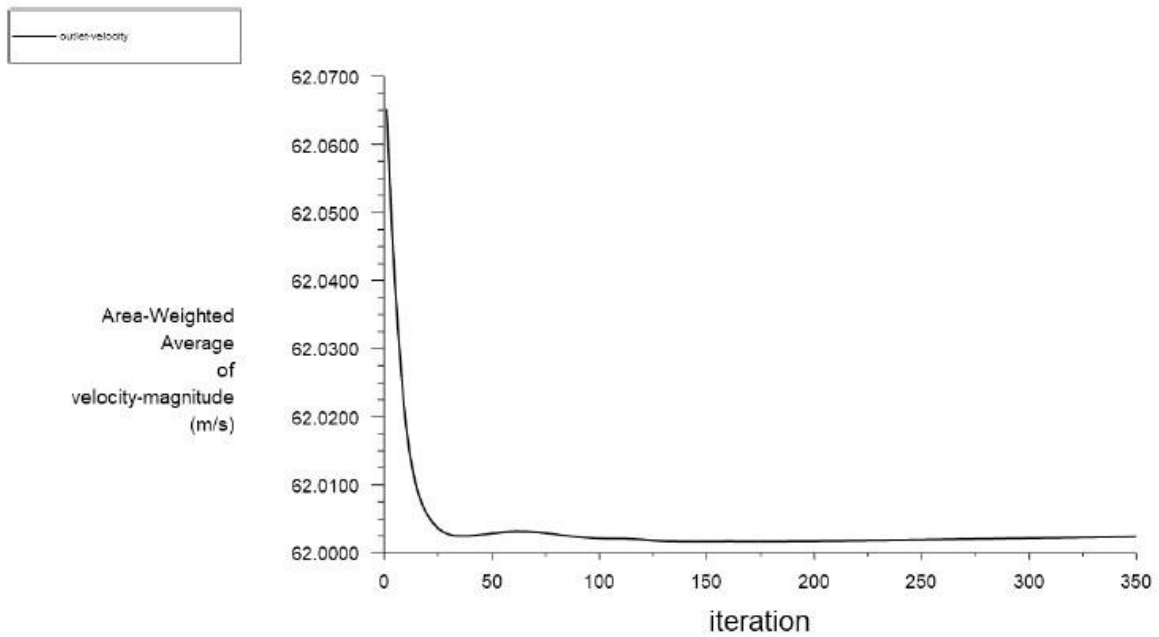


Figure 20. Plot of the outlet velocity magnitude.

2.4. Viscous Settings

The Reynolds number based on the Pitot tube diameter is $Re=3.2 \times 10^4$.

- The external flow over the tube is laminar. (Fig 21.)
- Inside the tube the air does not move.

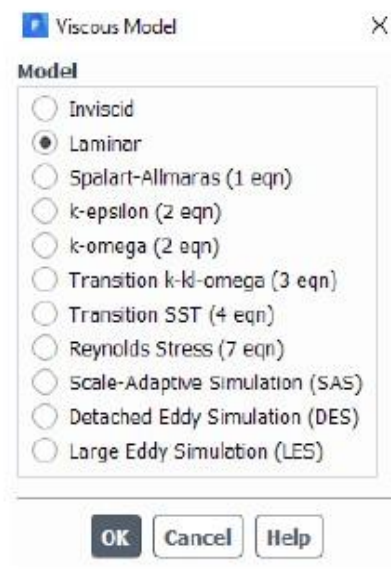


Figure 21. Snapshot of the Viscous Model settings

2.5. FMG initialization

The Full Multigrid (FMG) initialization is used in external aerodynamics to obtain a better initial solution to decrease the overall cost of the simulation (Fig.22, 23, 24):

- The FMG initialization requires an initial condition on the field to start with. Then it calculates a solution on coarser grids and interpolates it back on the main grid.
- The initialization can be performed from the Ansys Fluent Console typing the following TUI command:

`-solve/initialize/fmg-initialization yes`

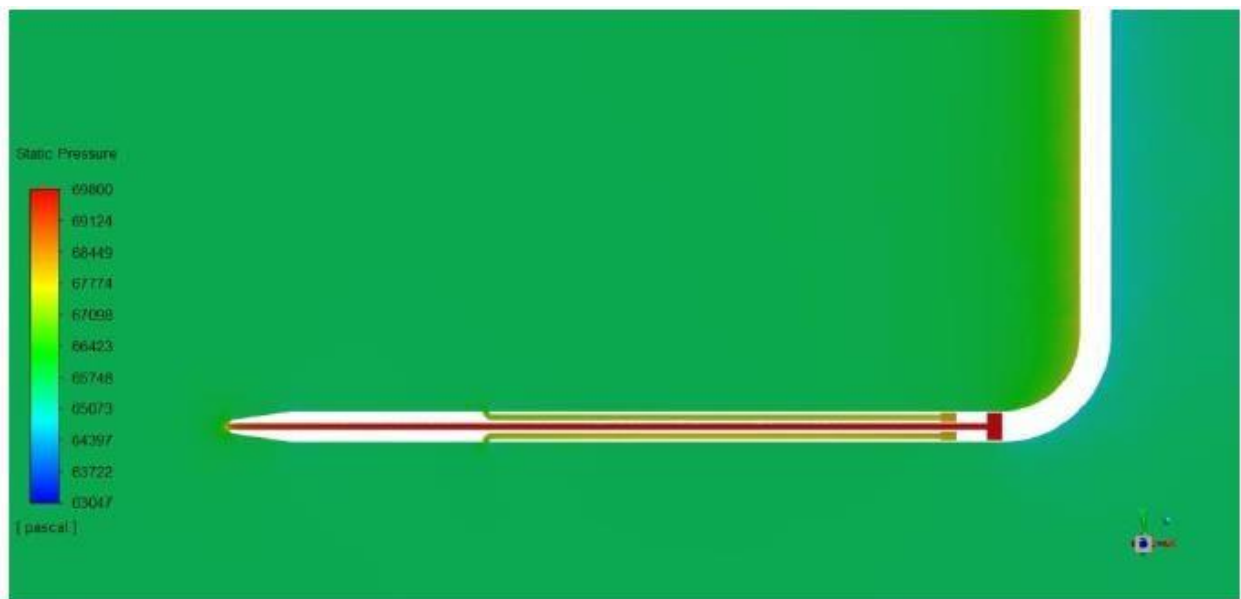


Figure 22. Pressure distribution after FMG initialization

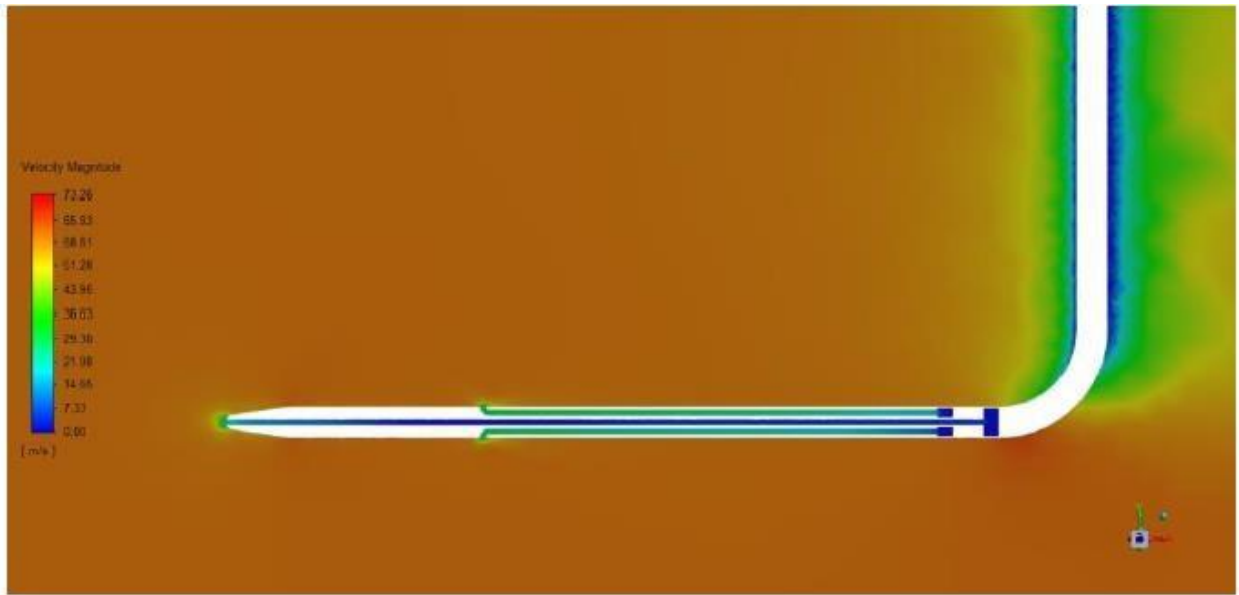


Figure 23. Velocity distribution after FMG initialization



Figure 24. Snapshot of the Console TUI menus

2.6. The Main Objective for Crosswind Condition

The objective of this simulation is to analyze the errors by changing the direction of wind (45°) on simulated Pitot-tube used in Cessna and get the total pressure and velocity.

2.7. Results for crosswind condition

The static pressure contours and velocity contours are shown on centerline plane through the domain.

The pressure contours show the effect of the orientation of the ports on the pressure measurements (Fig 25.):

- The pressure rises as the air comes to a stop inside the central pipe of the Pitot tube. This pressure is equal to the total pressure of the fluid.
- The pressure in the other two pipes is lower than in the central pipe and is equal to the surrounding air pressure. This is the static pressure of the fluid.

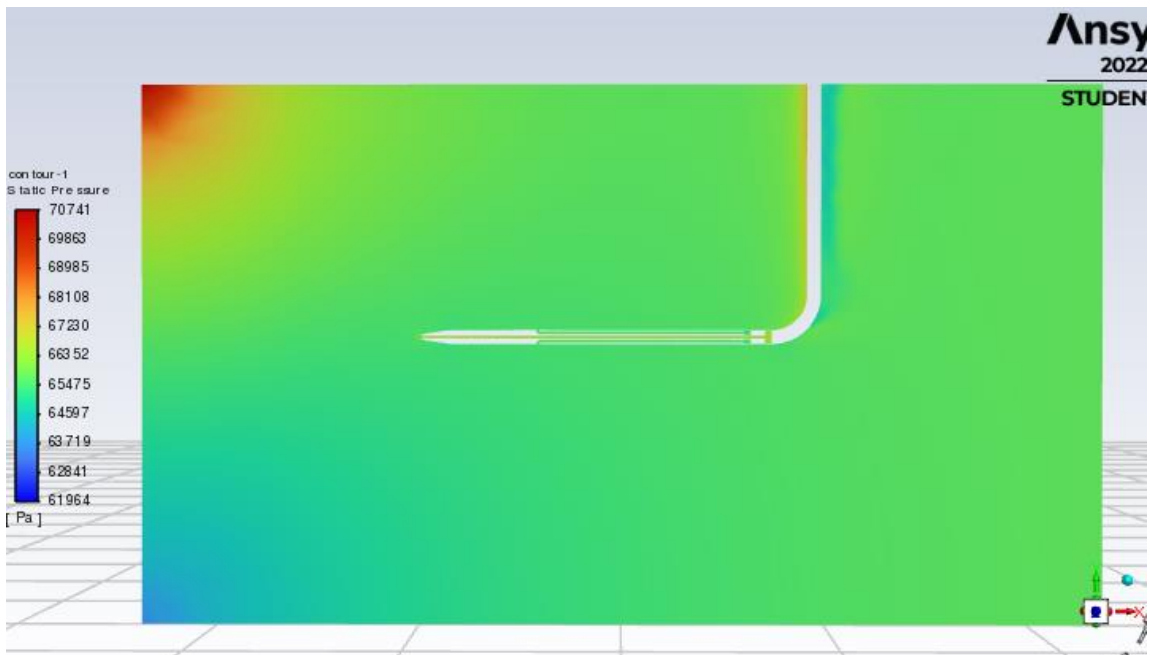


Figure 25. Contours of static pressure

The velocity contours show zero air velocity inside the internal pipes of the Pitot tube (Fig.26):

- In the central pipe the air cannot move further and comes to a stop.
- Air flows parallel to the static pressure ports and it does not enter into the other two pipes.

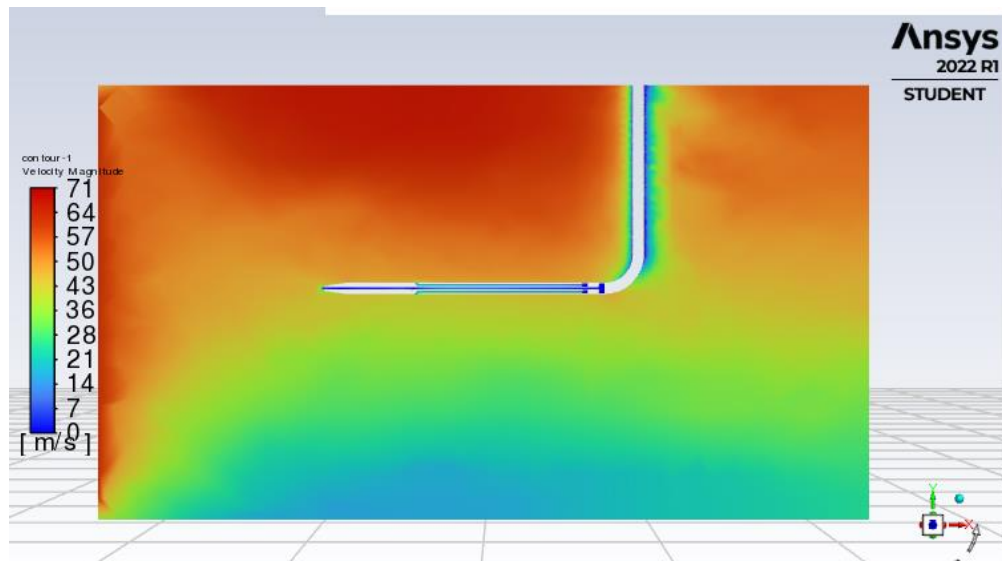


Figure 26. Contours of velocity magnitude.

The area-weighted average of the local static pressure on the pressure ports gives us an estimate the total and static pressure of the fluid (Fig.27):

- Static pressure 65503.2 Pa
- Total pressure 66499.9 Pa

Using Bernoulli's equation (recalling that the flow is incompressible) we can use the Pitot tube readings to calculate the airplane velocity:

$$U = \sqrt{\frac{2(p_{tot} - p_s)}{\rho}} = 48.04 \text{ m/s} \quad (2.2.)$$

Area-Weighted Average Static Pressure	[Pa]
static-pressure-port	65503.233
total-pressure-port	66499.849
Net	66030.391

Figure 27. Pressure measurement on the static and the total pressure ports

2.8. Convergence for crosswind condition

The continuity residual does not decrease further due to the intrinsic unsteadiness of this case. Indeed, the vertical part of the Pitot tube generates intrinsically unsteady wake.

Static and total pressures at monitor locations are not affected by the wake unsteadiness and their values can be calculated from the steady-state solution.

The residuals and the monitored quantities do not show significant variations after running for 300 iterations. For the scope of this exercise this is an adequate level of convergence, given that the mass flow rate is also conserved (Fig.28, 29, 30).

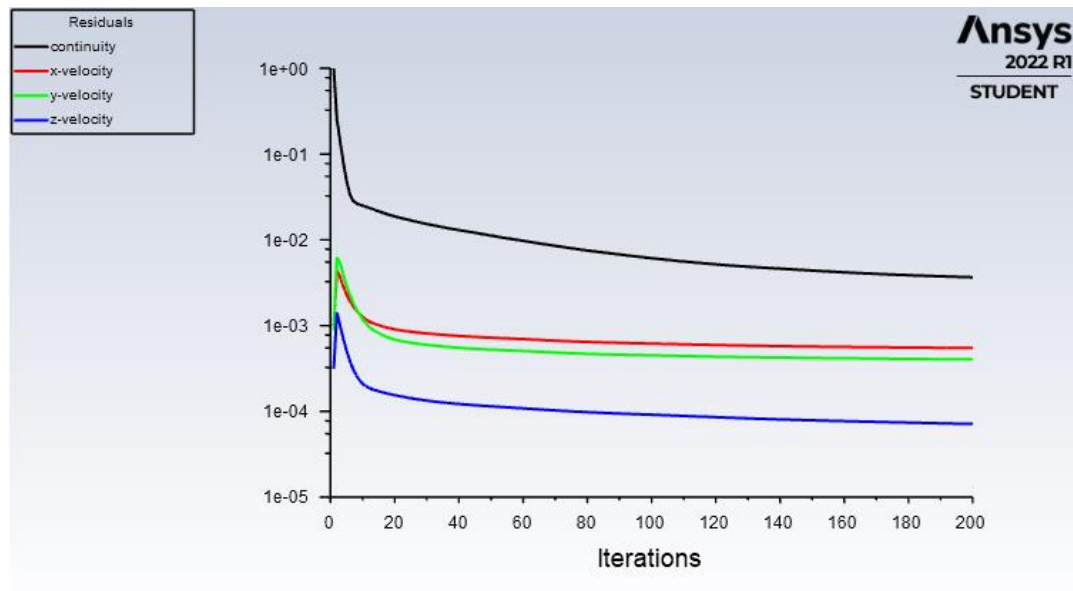


Figure 28. Plot of the solution residuals.

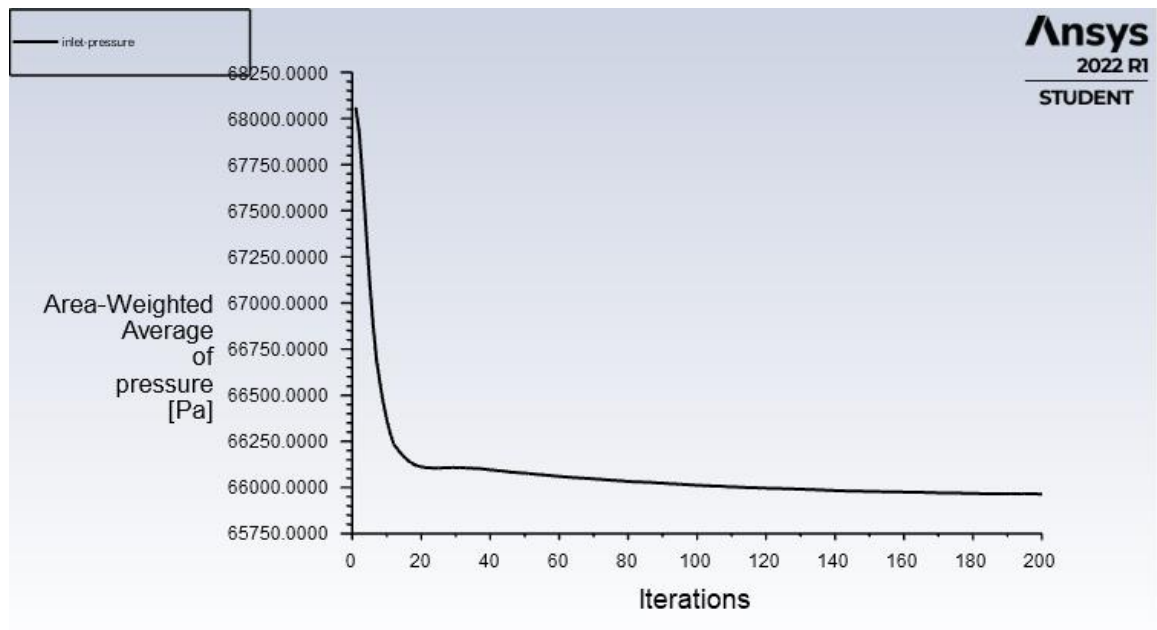


Figure 29. Plot of the inlet static pressure.

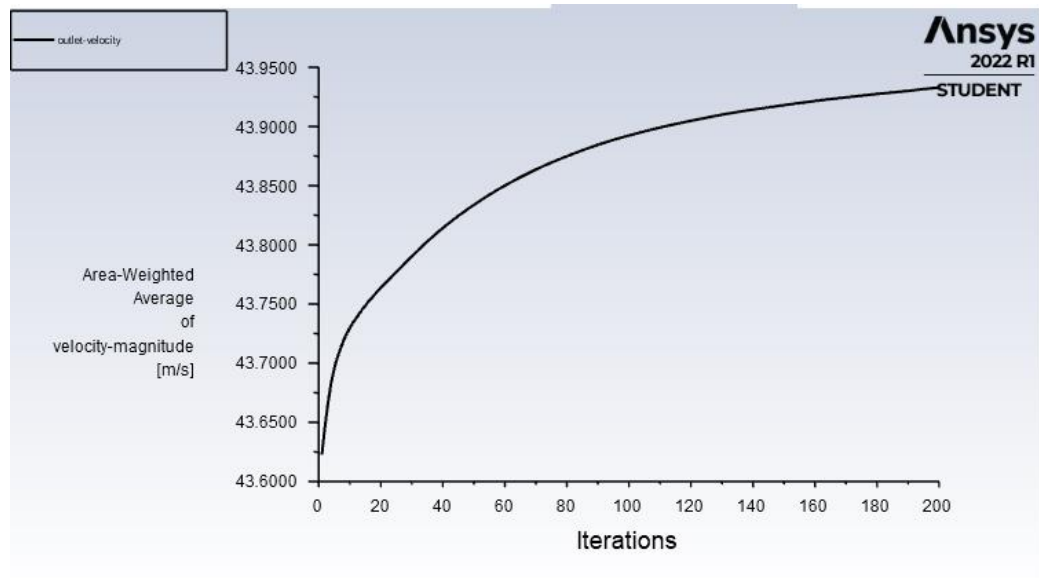


Figure 30. Plot of the outlet velocity magnitude.

2.9. Viscous Settings

The Reynolds number based on the Pitot tube diameter is $Re=3.2 \times 10^4$.

- The external flow over the tube is laminar (Fig.31);
- Inside the tube the air does not move.

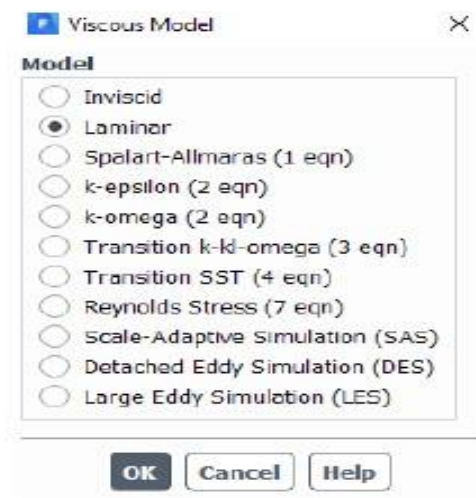


Figure 31. Snapshot of the Viscous Model setting

2.10. Conclusion from analysis

Through the application of ANSYS simulation, we gained a deeper understanding of the flow behavior and pressure distribution around the pitot tube under specific conditions such as crosswind scenarios. The simulation results offered valuable information regarding the accuracy of airspeed measurements obtained from pitot tube and allowed us to assess potential errors associated with the measurement process. By comparing the simulation outcomes with experimental data or analytical solutions, where available, we could determine the level of agreement and evaluate the overall accuracy of the simulation approach. This verification process instilled confidence in the simulation results and reinforced the validity of the findings.

3. RESULTS AND ANALYSIS

In this study, we focus on investigating the errors associated with pitot tubes and airspeed indicators experimentally conducted in a car. The results and analysis section aims to present and interpret the findings obtained from the experimental measurements, shedding light on the performance and potential sources of errors in airspeed indication systems.

In this section, we will present the results obtained from the experiments and conduct a detailed analysis of the data. The analysis will include a statistical evaluation of the measured airspeed values, examining parameters such as mean, standard deviation, and correlation coefficients between the pitot tube readings and reference measurements. Additionally, we will explore the systematic errors, such as bias and offset, as well as the random errors, including measurement noise and variability, that may influence the accuracy of the airspeed indication system.

Furthermore, we will discuss the potential sources of errors identified during the experiments. Factors such as wind effects, calibration drift, instrument inaccuracies, and environmental conditions (e.g., temperature and humidity) will be considered as possible contributors to the observed errors.

We'll use Skydemon app as a tool for navigation and situational awareness in an experimental setting, also Carly programming to monitor vehicle speed in various ways.

3.1. Mounting Pitot tube

To start the experiment, we mounted the pitot tube on a car with different angles (50, 60, 70, 90, 180 degrees). (Fig.32, 33, 34, 35, 36, 37)



Figure 32. Pitot tube mounted 60°



Figure 33. Pitot tube mounted 80°



Figure 34. Pitot tube mounted 90°



Figure 35. Pitot tube mounted 0°



Figure 36. Pitot tube mounted 50°



Figure 37. Fixed Mounted pitot tube view

3.2. Skydemon app usage

Using Skydemon app we identified Groundspeed while driving, as well since it takes GPS navigation information, we can view the movement. (Fig.38)

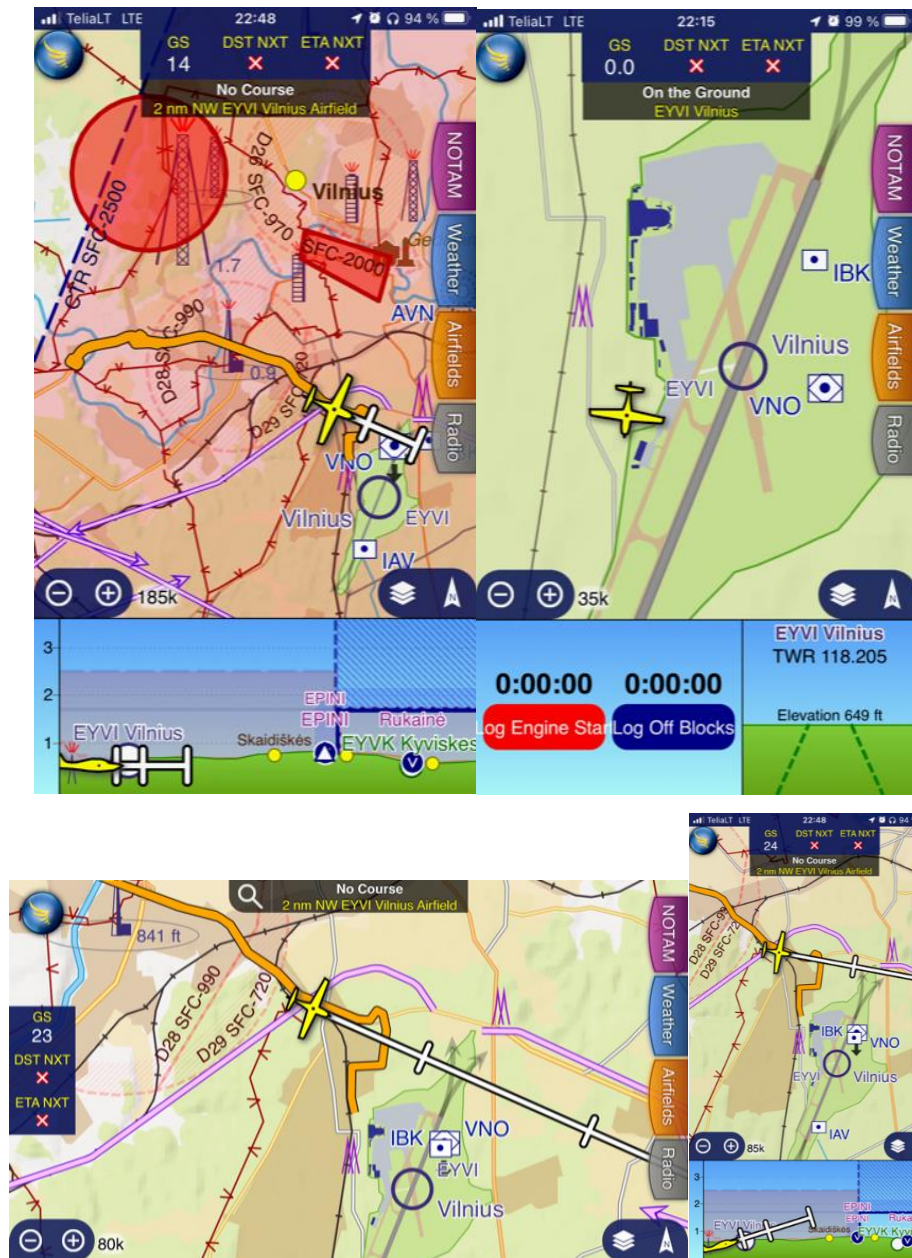


Figure 38. Skydemon screenshots

3.3. Weather information

We also need the weather information which is on experimental day. We got wind speed information from Meteogram. (Fig.39)

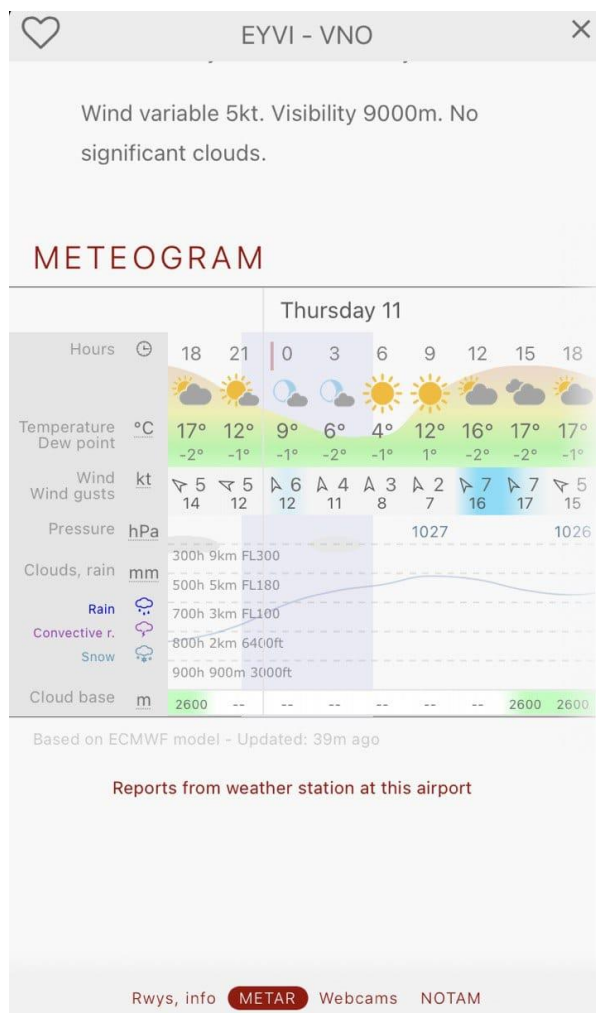


Figure 39. Meteogram screenshot

3.4. Results

In the table 4, we can clearly see the IAS (which airspeed indicator shows) variations in different angles, and the speeds we got from Skydemon and CARLY.

Firstly, we calculate the crosswind component by getting the information from Metar (wind speed and angle of wind), during experiment day the wind speed was 5 knots and the angle of wind 140 degrees from South East, and the direction of car was North (0 degrees), so the angle between the direction of travel and wind direction is 140 degrees. We calculate the crosswind component by this formula:

$$\text{Wind speed} \times \sin(\text{wind correction angle}) = 5 \times \sin(140) = 3.21 \quad (3.1)$$

So the crosswind component result is 3.21. To calculate the IAS error in Cessna-172, we can use a rule of thumb that states for every 10 knots of crosswind component, there is an approximate 2 knot increase in indicated airspeed. So the error will be by dividing the crosswind component result to 10, it will be 0.321 kT.

Table 4. Airspeed results table

VEH (Vehicle Speed)	SKYDEMON Readings	CARLY Readings	IAS (Indicated Airspeed)	Angle of direction (degrees)	IAS Errors (TAS- GS)	Crosswind Component (140 degrees)
90 km/h	GS 45Kt	84,99 km/h	44 kT/50MPH	0	0.321 kT	3.21
	GS 45Kt	84,92 km/h	40 kT/ 44MPH	15	0.321 kT	3.21
	GS 45Kt	84,92 km/h	N/A/ 35 MPH	30	0.321 kT	3.21
	GS 45Kt	84,92 km/h	N/A	45, 60, 90	0.321 kT	3.21
80 km/h	GS 40Kt	75,48 km/h	39 kT/42MPH	0	0.321 kT	3.21
	GS 40Kt	75,48 km/h	0/39MPH	15	0.321 kT	3.21

	GS 40Kt	75,48 km/h	N/A / 30MPH	30	0.321 kT	3.21
	GS 40Kt	75,48 km/h	0	45	0.321 kT	3.21
	GS 40Kt	75,48 km/h	0	60	0.321 kT	3.21
	GS 40Kt	75,48 km/h	0	90	0.321 kT	3.21
100 km/h	GS 52 kT	96,42 km/h	50kT/ 59MPH	0	0.321 kT	3.21
	GS 52 kT	96,42 km/h	45 kT/ 50MPH	15	0.321 kT	3.21
	GS 52 kT	96,42 km/h	0 kT/ 0 MPH	30, 45, 60, 90	0.321 kT	3.21
110 km/h	GS 62 kT	105, 46 km/h	61kT/ 70MPH	0	0.321 kT	3.21
	GS 62 kT	105, 46 km/h	49kT/ 53 MPH	15	0.321 kT	3.21
	GS 62 kT	105, 46 km/h	0 KT	30, 45, 60, 90	0.321 kT	3.21

3.5. Conclusion from Results and Analysis

In conclusion, the results of the experiment conducted to analyze pitot tube errors and airspeed reading in different angles using SkyDemon and Carly in a car have provided valuable insights into the performance and accuracy of these tools. The following conclusions can be drawn from the results:

Pitot Tube Errors: The experiment revealed that pitot tube errors can significantly impact the accuracy of airspeed readings in a car. Variations in angle of attack, crosswind, and other factors can lead to deviations in the measured airspeed compared to the true airspeed. These errors must be taken into consideration when relying on airspeed readings for navigation and flight planning purposes.

SkyDemon Performance: The analysis of airspeed readings using SkyDemon in the car showed that the app provides real-time airspeed information based on GPS data. While the app offers useful features for

flight planning and navigation, the accuracy of airspeed readings may be influenced by the limitations of GPS technology and potential signal disruptions in a ground-based vehicle environment. Thus, it is essential to consider the limitations and potential errors associated with GPS-based airspeed measurements.

Carly Performance: Carly, being primarily designed for automotive diagnostics and coding, does not directly provide airspeed readings. However, the experiment demonstrated that Carly can still be valuable for monitoring and analyzing other vehicle-related parameters and systems. It can assist in diagnosing potential faults or errors that might impact the accuracy of airspeed readings, such as issues with speed sensors or the speedometer.

Calibration and Verification: The experiment highlighted the importance of calibrating and verifying airspeed instruments in a car to mitigate errors and ensure accuracy. Periodic calibration and maintenance of the pitot tube system and associated sensors can help minimize errors and maintain reliable airspeed measurements.

In summary, the experiment shed light on the challenges and limitations associated with airspeed measurements in a car using tools like SkyDemon and Carly. Pitot tube errors, reliance on GPS-based measurements, and the influence of external factors all play a significant role in the accuracy of airspeed readings. Careful calibration, understanding the limitations of the tools, and considering the influence of external factors are essential for obtaining reliable airspeed information. Additionally, understanding and considering weather conditions, particularly wind effects and atmospheric properties, is crucial for accurate airspeed readings, flight planning, and ensuring safe operations. Incorporating weather data into the results and analysis provides a comprehensive understanding of the factors influencing airspeed measurements and aids in making informed decisions.

CONCLUSION

In conclusion, the thesis topic addressing the errors in pitot tube measurements during crosswind conditions on a Cessna-172, as well as the analysis of literature, research methods, and experimental results using tools like SkyDemon and Carly, has provided valuable insights into the accuracy and reliability of airspeed readings.

This thesis has shed light on the complexities of pitot tube errors, airspeed measurements, and the importance of considering weather conditions. It highlights the significance of calibration, understanding the limitations of tools, and incorporating weather information for accurate and reliable airspeed readings. The findings contribute to the existing knowledge and provide valuable insights for aviation professionals, researchers, and enthusiasts in their pursuit of safe and accurate airspeed measurements.

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