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# Technical Report
# Velocity measurements in airplanes: are they reliable ?

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# Contents

## Abstract

Velocity measurement devices are prone to errors. These errors can occur due to the variable physical properties of the air, which are strongly dependent on the altitude, the speed of the aircraft and the position of the instrument along the fuselage. Moreover, the type of the instrument also greatly influences the reliability of the indicated airspeed (IAS), where the Pitot tube distinguishes itself for it's precision. While the errors caused by the air properties can be predicted and compensated with mathematical approaches, the Pitot tubes can suffer unexpected failures. They can be overcome as a result of new technologies.
**Keywords**: Velocity measurement, airspeed, reliability, Pitot tube, subsonic.

# 1 Introduction

Aviation is currently the leading mode of transportation safety-wise due to the technological advances that improved the velocity measurements. Modern planes calculate the airspeed using Pitot-static tubes, which are further explained in section 2.

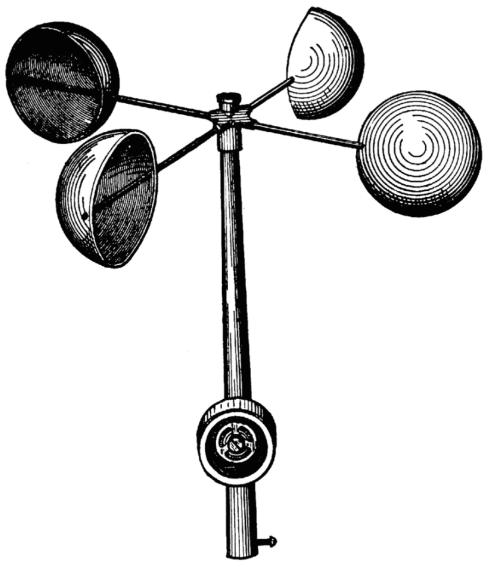

Figure 1: A hemispherical cup anemometer. *Courtesy of ClipArt ETC*

Figure 2: A pressure plate anemometer, *Courtesy of the University of Technology Sydney*

Going back to the early decades of the aviation industry, flying was a hugely risky endeavour. The pilot safety was at its lowest due to the inaccuracy and difficult operating conditions of the airspeed measurement systems. The aircraft's speed was in the first stages calculated with meteorological instruments like the Robinson cup anemometer (Figure 1), which could be used for low speeds. An alternative was the pressure plate anemometer (Figure 2), which indicates the airspeed via the deflection of a plate due to the air flow. Both instruments provided highly inaccurate readings and were quickly replaced by the Pitot tube.

. Total words: 1636

## 2 Fluid Mechanics Principles

### 2.1 Airspeed Measurement Methods

The airspeed is the airplane's speed relative to the air and can be calculated with three different methods:

1. **the velocity method** $v$, requiring cup anemometers and which is independent of the air density and thus of the altitude. However, these instruments cannot be used at the high-speed planes typically fly at.

2. **the velocity-density method** $v\rho$: this method requires instruments measuring the cooling effect of a heated entity. They are typically cumbersome and cannot be used in aviation.

3. **the velocity-squared-density method** $v^2\rho$: the velocity is determined by the measurement of the pressure exerted by the airflow. In this category falls the Pitot-static tube, a more accurate instrument that quickly proved itself in aviation and has been used ever since.

### 2.2 Pitot-static tube types

The Pitot-static tube has had two different design iterations. The first design was obtained by connecting the Pitot and static tubes with an U-shaped conduit containing a liquid (Figure 3). The difference in pressure, hence the airspeed, was given by the height difference of the liquid between the two sides of the U-tube. Because this is a **gravity-driven system**, it can only give plausible readings when the airplane is horizontal. This fatal dependence on tilting and acceleration could cause the crash of the airplane during basic maneuvers.

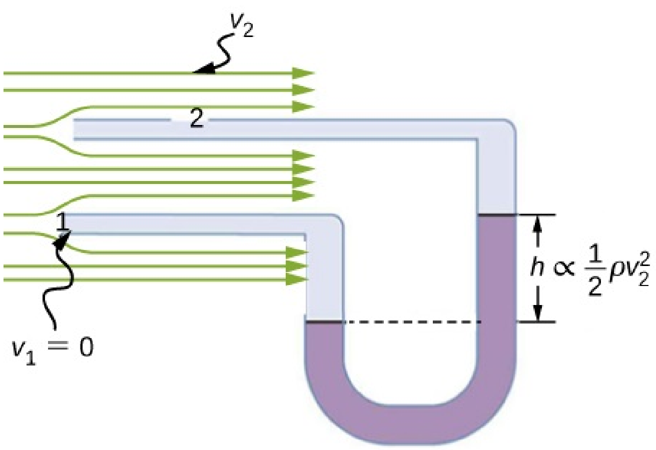


Figure 3: Pitot tube manometer with separate static probe (OpenStax, 2016, 14.6)

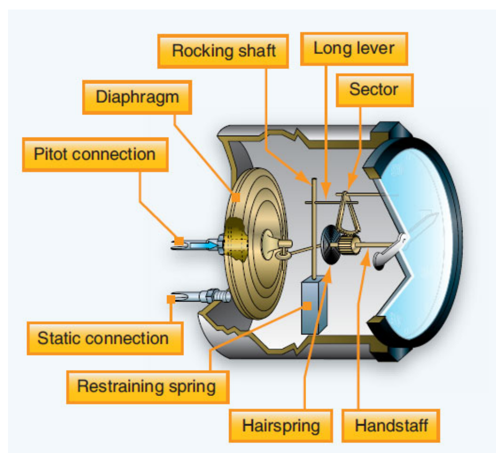


Figure 4: Diaphragm airspeed indicator, *Courtesy of flight-mechanic.com*

The second design is a **spring controlled system**, which did not depend on tilting or vertical acceleration. This instrument measures the difference in pressure between the inside of a closed, elastic diaphragm and the static pressure surrounding it (Figure 4). Therefore, the Pitot tube feeds the inside of the diaphragm, while the static pressure from the aircraft static tube is directed into the case surrounding the diaphragm. The difference in pressure expands the diaphragm, leading to the indication of the airspeed through a calibrated mechanical system.

Although this design was an important step forward, it had its downsides. First, the airspeed measurement required the large volume inside the diaphragm to be filled, which meant that the instrument had a long lag. Moreover, the elastic diaphragm needed increased maintenance and thorough recalibration if the instrument was left unused for long periods. This system is still in use today in small aircraft. However, modern airliners use an improved Pitot-static tube with no lag, based on a differential pressure transducer (Figure 5) and defined by the same mathematical equations.

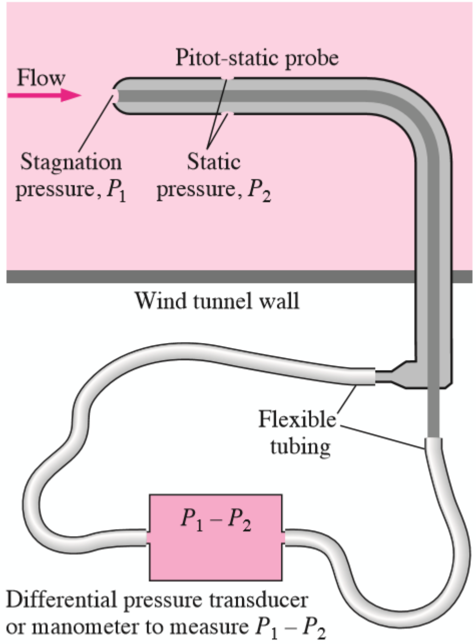


Figure 5: Example of Pitot tube. (Cengel and Cimbala, 2006, 191)

## 2.3 Mathematical approach

### 2.3.1 Assumptions for the validity of Bernoulli's equation

- Bernoulli's equation is developed on the assumption of incompressible fluids[1].
- The flow is considered steady [2].
- The fluid does not produce any shaft work.
- The equation is developed along a streamline.

(Cengel and Cimbala 2006, 190-192)

### 2.3.2 Bernoulli's equation

The working principle of the Pitot-static tube is based on the *Bernoulli's equation.* This relation is developed from the Navier-Stokes equation, with the assumptions claimed before:

$$\rho \frac{D\mathbf{v}}{Dt} = \rho \left[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}.\nabla \mathbf{v} \right] = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho g \tag{1}$$

Bernoulli's equation postulates that the sum of the kinetic, potential and flow energies for incompressible fluids is constant. (Cengel and Cimbala 2006, 189-190)

$$\rho \frac{v^2}{2} + p + \rho g z = constant \tag{2}$$

This equation leads to the energy-balance between two points along a streamline of air:

$$\rho_1 \frac{v_1^2}{2} + P_1 + \rho_1 g z_1 = \rho_2 \frac{v_2^2}{2} + P_2 + \rho_2 g z_2 \tag{3}$$

1. This assumption is generally true for all kinds of fluids with Mach number ratio between the speed and air velocity < 0.3
2. its characteristics are constant over time

As the speed at the stagnation point is reduced to zero, the air-density is considered constant and the heights are roughly equal, the expression is simplified. Consequently, the airspeed is given by:

$$v_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho}} \tag{4}$$

The pressure difference is measured by a differential pressure transducer or a manometer. $P_2$, the static pressure, is measured either on the Pitot tube's side (Pitot-static tube) or through another side-system. $P_1$, the stagnation pressure, is determined by the airflow entering the Pitot tube. It is the sum of the static pressure and a dynamic pressure depending on the relative speed between the aircraft and the air.

# 3 Different types of error on measurements

Although many enhancements were brought to velocity measurement devices, they still suffer from imprecisions. Depending on the conditions and the state of the airplane, these errors may rise significantly and confuse the pilot, deactivate the autopilot and, in worst cases, lead to crashes. In order to consider the effects of these factors on the IAS [3], different modifications must be added.

## 3.1 Position and instrumentation errors

As the aircraft crosses the airflow, it disturbs the streamlines and causes local perturbations in the static pressure. Therefore, the static probe needs an appropriate location along the fuselage to minimize the error between the local and ambient static pressures. The distribution of the normalised error between the two static pressures at figure 6 demonstrates why Pitot-static tubes are generally located under the cockpit.(Haering 1995, 1-22)

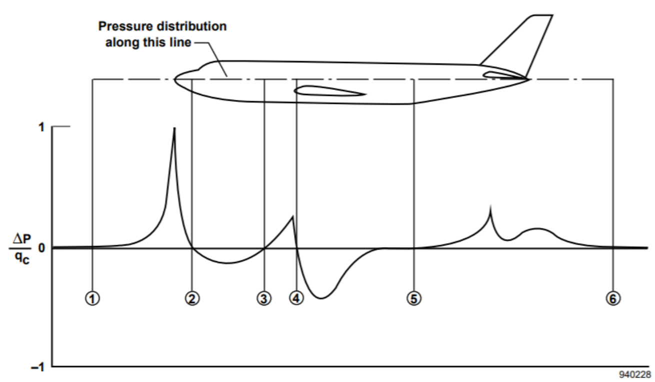


Figure 6: Normalised static pressure distribution along the fuselage. *Courtesy of NASA*

3. IAS is the acronym of Indicated Air Speed, which designates the airspeed indicated by the instrument inside the cockpit. This type of airspeed contains different types of errors.

However, this distribution is changing as the difference between the static pressures below and above the wing varies according to the tilt. This **position error** cannot be realistically reduced to zero. Due to its dependence on the aircraft's geometry, it is impossible to calculate it directly. Aircraft manufacturers make empirical measurements for each model.

Another kind of error derives from the inaccuracy of the measure instrument, the transducer and the analog-to-digital converter. If these electronic devices were perfect, the IAS would be equivalent to the speed calculated with equation 4. (Hashemian and Jiang 2009,1-6)
The total error is expressed as:

$$Total\ error = \sqrt{E^2_{position} + E^2_{transducer} + E^2_{ADC}} \tag{5}$$

Ground and in-flight calibrations allow to subtract the position and instrument errors from the IAS using tables. The airspeed measure obtained is called the CAS[4].

**AIRSPEED CALIBRATION**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FLAPS UP | | | | | | | | | | | |
| KIAS | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 |
| KCAS | 43 | 51 | 59 | 68 | 77 | 87 | 98 | 108 | 118 | 129 | 140 |
| FLAPS 10° | | | | | | | | | | | |
| KIAS | 40 | 50 | 60 | 70 | 80 | 85 | --- | --- | --- | --- | --- |
| KCAS | 42 | 50 | 60 | 69 | 78 | 82 | --- | --- | --- | --- | --- |
| FLAPS 40° | | | | | | | | | | | |
| KIAS | 40 | 50 | 60 | 70 | 80 | 85 | --- | --- | --- | --- | --- |
| KCAS | 40 | 50 | 61 | 72 | 83 | 89 | --- | --- | --- | --- | --- |

Figure 7: Calibration table for a Cessna given by the manufacturer.

## 3.2 Compressibility error

Previously, the airspeed has been calculated without considering the fluid compressibility[5]. Despite its effects being negligible at low speed, they become significant for Mach numbers greater than 0.3, achieved by most airliners at their cruising speed. A part of the planes energy is used to increase the density $\rho$ of the fluid around it. The assumption of incompressible fluids for Bernoulli's equation is no longer respected, making equations 2 and 4 inapplicable. An equivalent of Bernoulli's equation exists for compressible flows:

$$\frac{\gamma}{\gamma-1}\frac{P_2}{\rho_2}\left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} + \frac{|\mathbf{u}|^2}{2} = \frac{\gamma}{\gamma-1}\frac{P_2}{\rho_2} \tag{6}$$

It provides the definition of the EAS[6]:

$$V_{EAS} = K_p.V_{CAS} \tag{7}$$

$$K_p = \frac{\gamma}{\gamma-1}\frac{(P_2/P_1)^{(\frac{\gamma}{\gamma-1})}-1}{P_2/P_1-1} \tag{8}$$

where $K_p$ is the compressibility factor and $\gamma$ the ratio between the specific heat at constant pressure $C_p$ and the specific heat at constant volume $C_v$.

4. Calibrated Air Speed.
5. "The fractional change in pore volume per unit change in pressure" (AUER P 1982,1-126)
6. Equivalent Air Speed.

### 3.3 Altitude measurement error

The last stage before obtaining the TAS[7] consists of introducing the dependence on the altitude into the EAS. As altitude increases, the number of molecules decreases and, thus, less forces are applied on the aircraft. The pressure decreases, leading to lower speed measurement by the Pitot-static tubes. TAS considers the change in density:

$$V_{TAS} = \frac{V_{EAS}}{\sqrt{\sigma}} \tag{9}$$

$$\sigma = \frac{\rho_z}{\rho_0} \tag{10}$$

with $\rho_z$ the density at the aircraft altitude and $\rho_0$ the density at sea-level. (Houghton, Carpenter, Collicott and Valentine 2017, 87-149)

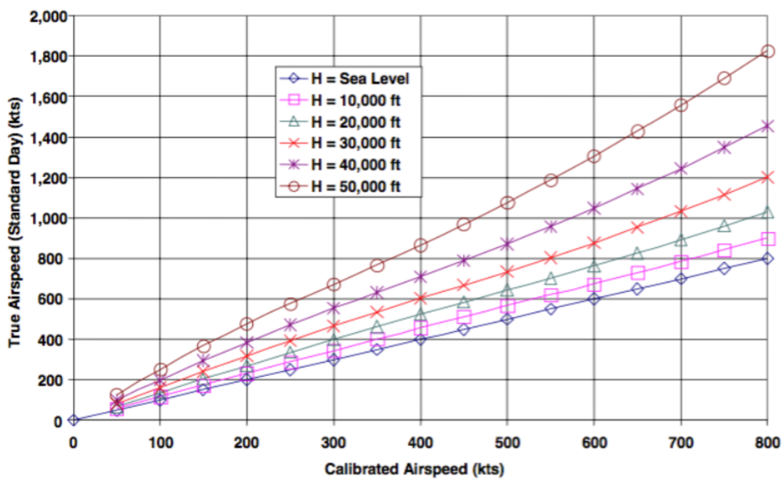


Figure 8: Difference between CAS and TAS. *Courtesy of Air Force Flight Test Center*

Despite all the factors mentioned above, TAS has only an indicative aspect for the pilot, which can seem paradoxical considering the significance of the errors[8]. Instead, except for supersonic airplanes, the IAS/CAS is the airspeed considered even if TAS is displayed using air data computers. TAS is used for navigation and is generally decided by the control towers. In contrast, IAS reflects many aerodynamic properties, such as lift, stress on the airframe and forces on control surfaces. This information is essential for the pilot to evaluate the performance of the aircraft and ensure that the critical speed and the structural limits are not exceeded.

7. True Air Speed is the speed in which the aircraft moves relative to the surrounding air, without any errors.
8. The error between EAS and TAS increases by 2% for every 1000 feet. As an example, the cruising altitude of an airliner typically varies from 33,000 to 42,000 feet (1000ft = 304.8m). As shown by 8, TAS can become up to twice the CAS as altitude reaches 50,000

### 3.4 Blocked Pitot tubes

The most fatal errors are the external factors that affect the state of the instrument. Pitot tubes can be obstructed either by ice formation, insects or human mistakes, such as forgetting to remove the protection tapes from the probes. Depending on which tube is blocked, various measurement errors are noticed:

| Pitot-Static System Failure Modes | | | |
|---|---|---|---|
| **Failure** | **Altimeter Indicator Effect** | **Airspeed Indicator Effect** | **VSI Effect** |
| Pitot tube blocked | Not affected | Acts as an altimeter, increases during climb, decreases during descent | Not affected |
| One static source blocked assuming two Sources | Inaccurate while slipping and skidding | Inaccurate while slipping and skidding | Inaccurate while slipping and skidding |
| Both static sources or the single source blocked | Doesn't change with altitude; if blocked before takeoff, indicates field elevation | Decreases during climb and increases during descent | Indicates the last vertical speed before becoming blocked |
| All static and pitot sources blocked | Indication remains constant regardless of actual changes | Indication remains constant regardless of actual changes | Indication remains constant regardless of actual changes |

Figure 9: Different measurement errors depending on which hole is blocked. (Bencini-Tibo, 2019)

Air France Flight 447 is one of the deadliest crashes, leaving its mark on the history of aviation. It led to the tragic death of 228 people in 2009. The Pitot tubes were obstructed by ice formation, which induced intermittent wrong measures causing the auto pilot disconnection and the loss of control. Two other relevant crashes were caused by obstructed Pitot-static tubes in 1996: Birgenair Flight 301, caused by a nest of wasps and Aeroperú Flight 603, whose static probes were covered by adhesive tape.

### 3.5 Improvements and new technologies

To rectify the measurement errors, air companies are constantly researching new back-up technologies. For instance, *Boeing* is developing a promising LIDAR technology able to measure velocity, atmospheric pressure and temperature in miscellaneous air conditions. It could be employed to assist the Pitot tubes or even to supplant them. Indeed, LIDAR is much more stable, saves weight and drag on the aircraft and has the ability to determine a lot of parameters, where the Pitot tubes are limited. Another new emerging technology is the ice-phobic paint which prevents ice formation on the aircraft and thus on the Pitot tubes. In addition, that paint decreases the washing process frequency, leading to lesser chance of human mistakes. The paint used with a heating system could overcome the ice formation risk. The Pitot tube can be heated either by a simple hot wire heating system or by its clever positioning close to the engine.

# 4 Conclusion

The evolution of Pitot tubes aimed to reduce errors but they persist in actual systems. These errors originate from factors depending on the aircraft's structure, external conditions or human mistakes. Using calibrations as well as air data computers, most of the errors can be suppressed. Nevertheless, unplanned phenomena directly affecting the instrument may still occur and lead to crashes. Special improvements on Pitot tubes, such as heating systems and new technologies, contribute to preventing these phenomena.
Finally, all the corrections were based on the assumption of subsonic flight. For speeds greater than the sound velocity, more complex mathematical equations are needed since the creation of a shock wave disturbs the pressure around the plane.

# References

Auer, Peter. 1982. *Advances in Energy Systems and Technology Volume 3.* New York: Academic Press.

The book has been written by a researcher from the *Sibley School of Mechanical and Aerospace Engineering* of *Cornell University*. This university is part of the *Ivy League*[9] and is regularly ranked as one of the fifteen best universities of the world[10]. The book presents articles that give information and reviews on several topics (including fluid mechanics) in relation with the general field of energy. There are 8 contributors, energy specialist, from different country that add credit to the book. The energy transportation by fluid is precisely developed. Therefore, the source is not only reliable but also relevant.

Bailey, S. C. C., M. Hultmark, J. P. Monty, P. H. Alfredsson, M. S. Chong, R. D. Duncan, J. H. M. Fransson, et al. 2013. “Obtaining accurate mean velocity measurements in high Reynolds number turbulent boundary layers using Pitot tubes.” *Journal of Fluid Mechanics* 715.: 642–70. https://doi.org/10.1017/jfm.2012.538.

The article is made by 8 researchers from mechanical or aeronautic departments all around the world. Furthermore, it has been published in the *Journal of Fluid Mechanics*, a famous international journal releasing various article on computational, theoretical and experiment research. As the article has passed the peer-reviewing inherent to science journal, the trustworthiness is insured. The paper is focused on Pitot tube as it explains the way to obtain good measurement in bad fluid conditions.

Barker, Muriel. 1922. "On the Use of Very Small Pitot-Tubes for Measuring Wind Velocity." *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 101, no. 712: 435-45. www.jstor.org/stable/94161.

Muriel Barker studied aeronautics and was pioneer on Pitot tube measurement. Indeed, she experimented velocity measurement by water flowing around Pitot tubes. This article describes cases where, with small velocity or small Pitot tubes, the difference of pressure loses its dependence on $v^2$ and is directly proportional to $v$. This paper has helped the development of plane and of better velocity measurement tools. Also, it is shared on a lot of university and scientific databases (for example *Harvard* and *JSTOR*). As the previous article, the research has been published by a well-known scientific institute: *Royal Society* and, thus, has been peer-reviewed, which make it more reliable.

Bencini-Tibo, Luca. 2019. "Pitot-Static System Failure." Accessed November 27, 2019. https://www.avweb.com/flight-safety/risk-management/pitot-static-system-failure/.

The contents of this article originally appeared in the March 2019 issue of IFR Refresher magazine, a monthly review of IFR rules and procedures. IFR, initialism for Instrument Flight Rules, is one of the two sets of regulation governing all aspects of civil aviation. The author, Luca Bencini-Tibo, is a graduate from MIT and aircraft owner. He is also the FAASTeam Lead Representative (Federal Administration Aviation Safety Team) and has an expertise in basic flight training, orientation flights, safety and GPS navigation. Therefore, he has good competences for the instrument flying techniques especially Pitot tubes, which is the subject treated in this article.

Bradley, John Kirkham. 1994. "The history and development of aircraft instruments, 1909-1919." PhD diss., Imperial College London.

This doctoral thesis was written by John Kirkham Bradley in 1994 for the *Imperial College London* (University of London), where it was awarded the same year. It was, therefore, reviewed and accepted by his supervisors, which guarantees the relevance of the subjects treated inside. Moreover, this thesis can be found in the

9. a well-known group of the eight best American universities
10. As shown on the QS website in partnership with Elsevier https://www.topuniversities.com/university-rankings/world-university-rankings/2018

University of London awarded theses collection, which grants the title of Imperial author to John Kirkham.

Carpenter, P.W., Steven H. Collicott, E.L. Houghton and Daniel T. Valentine. 2017. "Equations of Motion." In *Aerodynamics for Engineering Students (Seventh Edition)*, 87-149. Woburn: Butterworth-He.

The authors work as researcher or Professor for diverse institution as Clarckson University, Purdue University or Exeter University. The book is aimed to engineering students providing a complete and scientific approach of fluid dynamics. Published in 2017 for its seventh edition, it has consequently been revised several times and is up-to-date, which is a guarantee of relevance.

Cengel, Yunus A. and John M. Cimbala. 2006. *Fluid Mechanics, Fundamentals and Applications First Edition.* New York: McGraw-Hill Education.

The authors are both professors in mechanical engineering, one at Pennsylvania State University and the other at the University of Nevada. Their book is used as reference for fluid mechanics courses in plenty of different universities and, thus, can be considered as reliable. It gives an consistent and scientific-related understanding of the topic. Due to its pedagogic aspect, the book is adapted for comprehension .

Gratton, Guy. 2018. “The Pitot-Static System.” *Initial Airworthiness: Determining the Acceptability of New Airborne Systems*, 45–82. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-75617-2_3.

This book comes from Springer Link, a scientific web browser. The author is an aerospace engineer as well as a commercial and test pilot. He also works as a consultant at Cranfield University. He published 24 articles in peer-reviewed journals. All these facts contribute to the reliability of his statements. His book covers different aspects of the certification of an aircraft including Pitot-static tubes. He discusses the topic with both his view as an engineer and as a pilot, adding personal experiences to the mathematical concepts developed. His book is recent and used as reference for practitioners

Haering, Edward A. Jr. 1995. "Airdata Measurementand Calibration." *NASA Technical Memorandum* 104316. https://www.nasa.gov/centers/dryden/pdf/88377main_H-2044.pdf.

This memorandum has been conducted by an aerospace research engineer working at the flight research center of NASA, a well-known scientific national institution in the aerospatial area and therefore an insurance of reliability. His sayings are developed on both experimental and theoretical approach, making it more relevant. His contribution on 16 other articles about airplanes proves his experience in the field.

Hall, Nancy. n.d. "Similarity Parameters." *NASA Glenn Research Center*. Accessed November 28, 2019. https://www.grc.nasa.gov/WWW/K-12/airplane/airsim.html.

The website is owned by the *Glenn Research Center* which is a branch of the famous *NASA*, guaranteeing the reliability of the information. This center works on the development of new aerodynamic technologies to move the *NASA* explorations forward. The website explains the similarity between viscosity and compressibility and the compressibility-impact on the velocity measurement developed in the section. 3.2.

Hashemian, H.M. and Jin Jiang. 2009. "Pressure transmitter accuracy." *ISA Transactions* 48. no. 4 (October): 383-388. https://doi.org/10.1016/j.isatra.2009.04.008.

H.M Hashemian works at *Analysis and Measurement Services Corporation* and Jin Jiang is Professor of electrical and computer engineering at *Western University*. They describe diverse external factors that can affect the accuracy in pressure transmitters and explain how to avoid them with appropriate calibrations. They have tested different calibrations according to the parameters and present their result in the book, providing complete scientific and non-biased statements.

Hodson, Howard. n.d. "Hot-Wire Anemometers." *University of Cambridge.* Accessed November 27, 2019. http://

www-g.eng.cam.ac.uk/whittle/current-research/hph/hot-wire/hot-wire.html.

This web page was written by Howard Hudson, a professor of Aerothermal Engineering at the *Whittle Laboratory* and also member of Girton College. His domain of expertise is the research on turbine aerodynamics, heat transfer and measurement instrumentation, which is the subject of this web page. He has created a research team with the Post-Doctoral staff and his PhD students at the *Whittle Laboratory* and combine both experimental and numerical approaches for the better understanding of the subjects they research. Therefore, their work is based on good experimental and theoretical basis, suggesting that this source is reliable.

Moebs, William, et al. 2016. *University Physics Volume 1.* Houston:Rice University. OpenStax. https://openstax.org/books/university-physics-volume-1/pages/1-introduction
OpenStax is a nonprofit charity at Rice University, whose mission is to provide students with reliable sources of information for their classes. This source being a e-book, it is constantly updated to ensure that all errors found are corrected. Moreover, all OpenStax textbooks undergo a rigorous review process. University Physics Volume 1 is a book originally written by William Moebs and Jeff Sanny in 1996 and revised and republished as an e-book in 2016 by OpenStax, Rice University. Jeff Sanny has a Ph.D and is a physics teacher at Loyola Marymount University. This e-book has valuable information on the subject of fluid flows and particularly on Pitot tubes, which proved useful for the technical report and coherent with the other sources.

Namer, I. and M.V. Ötügen. 1988. "Velocity measurements in a plane turbulent air jet at moderate Reynolds numbers." *Experiments in Fluids* 6, no. 6 (January): 387-399. https://doi.org/10.1007/BF00196484.

The article has been published in *Experiments in Fluids*, a well-known journal that focus on experiment on flow physics and especially on flow measurement. The journal has a good Impact Factor of 2.443 which assure of the reliability of its articles. In top of that, the authors are working at the department of Mechanical Engineering and Mechanics of Drexel University. The article describes an experiment on the turbulent air jet in a plane and its dependence on the Reynolds Number (making the flow turbulent, in transition or laminar).

Rennie, Nicola. n.d. "Subsonic and Supersonic Flow Through Pitot Tubes." MT4599 Project in Mathematics/Statistics, School of Mathematics & Statistics of University of St Andrews.

This project has been made by an actual postgraduate student at STOR-i CDT[11] at Lancaster University. This project was awarded by being on the Dean's List for 4 years which add credit to the work. Although, it is a student-work, the paper is complete and precise on the mathematical development of the velocity measurement by Pitot tubes in different flow regimes.

11. a statistics and operational research doctoral training centre