

SECTION E

AIRSPEED MEASUREMENTS

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ABSTRACT

This paper presents the results of a research project initiated as part of an ASCI 309 EV Home-Aerodynamics class held on Tuesday evenings during the 11/W1 term. The objective was to measure the airspeed of an automobile using techniques commonly used to measure the airspeed of light aircraft. The outcome of the recently completed project can form the basis for a research project for the next ASCI 309, ASCI 310, ASCI 509, or ASCI 510 course. It should be noted that use is made of material presented in the prerequisite courses: Math 112-Calculus (partial derivatives of multivariate functions), Math 211-Statistics (calculations of the mean and variance), and Phys 102-Physics (Conservation of Energy, Fluid Mechanics, and unit conversions) which lets the student consolidate and apply previously unrelated knowledge.

Introduction

The single most important piece of information a pilot can have is an accurate measurement of his airspeed. This information allows the pilot to make control adjustments and estimation for fuel reserves and destination arrival time. Measuring the airspeed is not a trivial exercise. The airspeed is measured indirectly by measuring the free-stream dynamic pressure, q_∞ , the free-stream static pressure at altitude, p_∞ , and the free-stream static temperature, T_∞ , at altitude.

The purpose was to have students measure airspeed, while providing hands-on appreciation for actual measurement procedures; thus, providing guidance in both experimental procedure and analysis, and report formatting of experimental results.

Background

Embry-Riddle recently announced a program to encourage undergraduate research. The projected student outcomes are to:

Define a research problem

Conduct a literature search

Design a course of action

Identify a research method

Evaluate and apply information

Analyze

Reach a conclusion

Communicate results

In concert with this objective, students enrolled in ASCI 309 EVH, Oct-Dec 2011 on Tuesday evenings, were assigned the task of measuring the airspeed of an automobile - since wind tunnels are not widely available and few in the class were pilots.

The original purpose of this paper was to convey to the students my experience in performing this experiment, give them some guidance in the desired report format, and hopefully help them avoid some experimental pitfalls.

The technique commonly used to measure the airspeed of subsonic aircraft utilizes a Pitot-static tube located under the wing and is based on Bernoulli's equation. This instrumentation is usually calibrated at sea level and corrected for compressibility and density at altitude to obtain the true airspeed.

Method

The problem is to accurately measure the airspeed of an automobile using a technique similar to that used on low-speed aircraft. The technique is based on Bernoulli's equation which is the conservation of energy per unit volume for a flowing gas. $p_{\text{static}} + q = p_{\text{total}} = \text{constant}$. p_{static} may be thought of as the potential energy; $q = \rho U^2/2 = \text{dynamic pressure}$ which may be thought of as the kinetic energy; and p_{total} as the total energy, which is a constant, i.e. conserved. Solving the preceding equation for the airspeed, U , yields $U = \sqrt{2(p_t - p_s)/\rho}$, where: $\rho = p_s/RT$, or simply $U = \sqrt{2q/\rho}$. So to measure the airspeed requires measurement of the dynamic pressure, q , the static pressure, p_s , and the temperature, T .

Precision of a measurement, the number of digits which are read from an instrument, should not be confused with the accuracy of a measurement. The accuracy is inherent in the calibration against a known standard. For example, the temperature probe was checked in an ice bath (0.9 °C) and boiling water (97.3 °C). The use of several instruments measuring the same

parameter lends a bit more confidence in a measurement. Both of these may be overshadowed by random fluctuations in the value of the parameter which can be evaluated by taking multiple measurements at different times and calculating the mean, \bar{U} , and variance, s^2 , of the parameter.

Instrumentation. The primary instrumentation chosen for this experiment was a Pitot-static probe and an inclined manometer for the measurement of the dynamic pressure, q . Vernier Software & Technology equipment was used to measure the static pressure (barometric pressure), p_s , and the ambient temperature, T . The static pressure was checked against the airport barometric pressure reading. The street driven in this preliminary experiment was within 5 miles of the Indianapolis International airport. A relatively calm day was chosen so the airspeeds could be checked against the ground speeds and speedometer readings which were the set points for the experiment.

Test Equipment. The test vehicle was a Chrysler PT Cruiser. To measure the dynamic pressure, a Pitot-static tube marketed by Eagle Tree Systems and a Mark II 0-3" inclined manometer marketed by Dwyer Instruments Inc. (Figure 1).

The remainder of the instrumentation used in this experiment was on-hand having been acquired previously to demonstrate physics phenomena in Physics classes. A Vernier Software & Technology Gas Pressure Sensor to measure the free-stream static pressure (barometric pressure) and a stainless steel temperature probe to measure the free-stream static temperature were used. The temperature measurement was compared to the built-in thermocouples of a number of multimeters. The measured barometric pressure was compared to the reading given by the Indianapolis International airport which was within a few miles of the test site.



Figure 1. Inclined manometer and Pitot-static probe on the road.

Preliminary Experiment. The wind was relatively calm (10 mph gusting to 15 mph). Dynamic pressure measurements were made at speedometer readings of 20, 30, 40 mph for several passes in a cross-wind direction as well as into the headwind and with the tailwind. The calculated airspeeds were thus based on an average of several readings. Data were recorded on a voice recorder and adjustments were to the inclined manometer and the Pitot-static tube distance from the car and the angle of attack of the tube. Since a car moving at subsonic velocities causes convergence of the streamlines upstream of the car, the probe needs to be sufficiently far outboard to avoid these convergent streamlines. The probe was mounted two feet outboard from the car and was visually aligned for zero angle of attack. The probe should not be overly

sensitive to angle of attack since it incorporated four static pressure ports spaced at 90 degree intervals around the periphery of the probe.

Results

Table 1 includes the converted data. The measurements were mixed so they were converted to slug/ft/sec/°R (slug=lb-sec²/ft.).

Table 1

19 Nov 2011

Speedometer groundspeed (mph)	U_∞ Airspeed (mph)
20	21.8±4 crosswind ($\bar{U} \pm s$)
30	30±3 crosswind ($\bar{U} \pm s$) (37.6 headwind)
40	37.6 crosswind (47.2 headwind) (31.8 tailwind)

Note. Light South winds (10 mph gusting to 15 mph), $T_\infty = 510$ °R, $p_\infty = 2104$ psf, $\rho_\infty = p_\infty/RT_\infty = 2104/(1716 \times 510) = 0.00240$ slugs/ft³, $U_\infty = \sqrt{(2q/\rho)}$ (converted to mph for comparison).

Table 2

19 Nov 2011

Speedometer groundspeed (mph)	U_∞ Airspeed (mph)
45	49.6 headwind 46.5 tailwind
50	51.1±0.6 ($\bar{U} \pm s$) tailwind
60	62.7± a lot

Note. Additional measurements: wind SSW at 13 mph quartering winds.

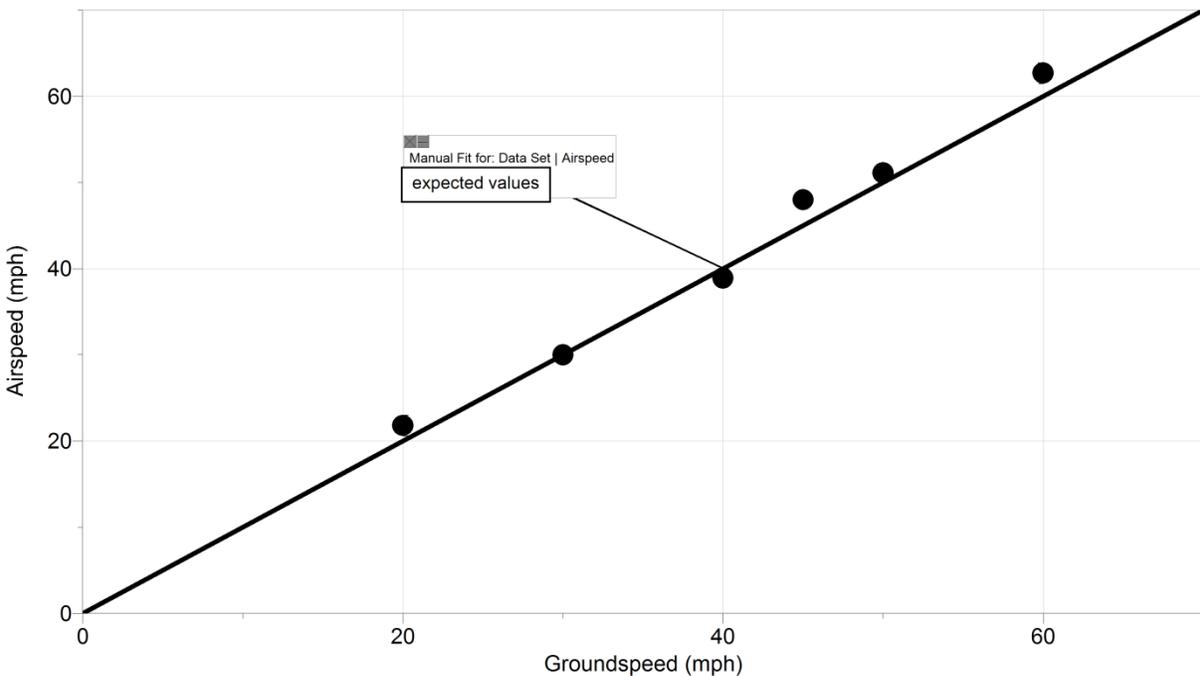


Figure 2. Measured airspeed vs. measured groundspeed.

Since the uncertainty of an automobile speedometer reading is approximately ± 1 mph, the expected airspeed measurement should closely approximate the speedometer reading as illustrated by the straight line in Figure 2. The airspeed measurement depends on the independent measurements of dynamic pressure, static pressure, and temperature, orientation and placement of the Pitot-static probe, and absence of wind gusts. The following analysis yields an estimate of the uncertainty of the airspeed measurement.

Analysis

A requirement by publishers of technical papers and journals is that an uncertainty analysis be made of the measurements which are being reported. As a minimum, the least count/precision of the measuring instrument should be reported. A guide for this analysis may be found in the paper of Kline and McClintock (1953).

We need to estimate the uncertainty in our measurement of the airspeed. $U = \sqrt{(2q/\rho)}$, where: $\rho = p/RT$, or to combine the preceding two equations, $U = \sqrt{(2qRT/p)}$, for the purposes of this analysis. To achieve the uncertainty in our measurement, we have the following definitions and formulas:

$$w_U: \text{uncertainty in } U \quad (1)$$

$$w_q: \text{uncertainty in } q \quad (2)$$

$$w_T: \text{uncertainty in } T \quad (3)$$

$$w_p: \text{uncertainty in } p \quad (4)$$

$$w_U = \{[(\partial U/\partial q)w_q]^2 + [(\partial U/\partial T)w_T]^2 + [(\partial U/\partial p)w_p]^2\}^{1/2} \quad (5)$$

$$\partial U/\partial q = 1/(2\sqrt{q})(\sqrt{(2RT/p)}) = \sqrt{(RT/2pq)} = 4.50 \quad (6)$$

$$\partial U/\partial T = 1/(2\sqrt{T})(\sqrt{(2qR/p)}) = \sqrt{(qR/2pT)} = 0.0901 \quad (7)$$

$$\partial U/\partial p = -1/(2\sqrt{p^3})(\sqrt{(2qRT)}) = -\sqrt{(qRT/2p^3)} = -0.0221 \quad (8)$$

For nominal values, we use the following:

$$q = 2 \pm 0.1 \text{ inches of water} = 10.4 \pm 0.5 \text{ psf } z \quad (1)$$

$$T = 520 \pm 2^\circ R \quad (2)$$

$$p = 2116 \pm 85 \text{ psf \& gas con} \quad (3)$$

$$R = 1716 \text{ ft-lbs/slug-}^\circ R \quad (4)$$

$$w_U = \{[(4.50)0.5]^2 + [(0.0901)2]^2 + [(-0.0221)85]^2\}^{1/2} = 2.9 \text{ fps, i.e. } U = 94 \pm 3 \text{ fps} \quad (5)$$

Conclusions

The preliminary experiment clearly showed that a straight, level road with no camber is desirable due to the high sensitivity of the inclined manometer to curves and tilt of the road. Constant attention must be given to maintaining the manometer level. Attention must also be given to the orientation of the Pitot-static tube to maintain its axis aligned with the free stream direction but that seemed to be less of a problem than maintaining the manometer level. The wakes behind other vehicles cause large fluctuations in the dynamic pressure, so this experiment is best carried out before traffic becomes dense.

The preliminary measurements of airspeed showed good agreement with the measured ground speed (speedometer) when corrected for ambient wind conditions (Figure 2).

Recommendations

As with every experiment, additional avenues for investigation are uncovered. One area for further investigation is the effect on the measurement of the dynamic pressure, q , by varying the angle of attack of the Pitot-static probe. Another area is to evaluate the measured q as a function of the distance of the probe from the vehicle.

Succeeding versions of this project will include more explicit instructions especially concerning plotting the data and diagnosing inconsistencies and their corrections before submitting the final report. Finding the reason for gross differences between the airspeed and ground speed may be the most valuable lesson of the experiment.

General comments

In my previous life with a day job as an experimentalist at the Allison Gas Turbine Engine Research Laboratory, I noticed considerable variation in the barometric pressure as reported by our Test Dept., the Indianapolis airport, and the barometer attached to an isentropic

nozzle used to calibrate hot wire anemometers. This has not changed. The uncertainty in the barometric pressure is responsible for one half the uncertainty in the airspeed measurement.

In ASCI 309-Aerodynamics, almost every calculation involves airspeed. The students now have an appreciation for its measurement as well as realizing a real-world application synthesizing the tenets of Math 112-Calculus, Math 211-Statistics, and Phys 102-Physics. This project also has application to ASCI 310, ASCI 509, and ASCI 510.

References

- Kline, S.J., & McClintock, F.A. (1953). Describing uncertainties in single-sample experiments. *Mechanical Engineering*, 75(1), 3-8.

Appendix A

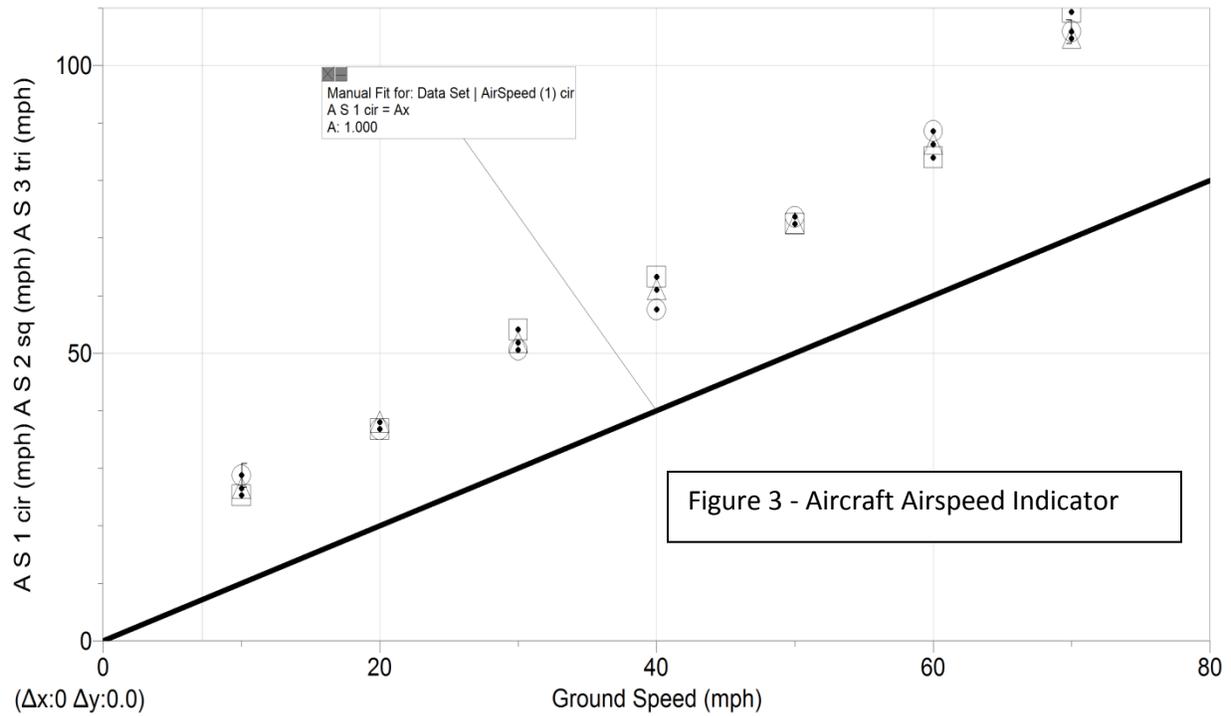


Figure 3. Student Airspeed Measurements 1.

The measurements of seven groups of students are illustrated in Figures 3 and 4. In Figure 3, three groups of students used the same aircraft airspeed indicator and obtained comparable results. The slope appears to be correct however the airspeed indicator appears to have a constant offset of about 20 mph. Probably the instrument zero needs to be adjusted.

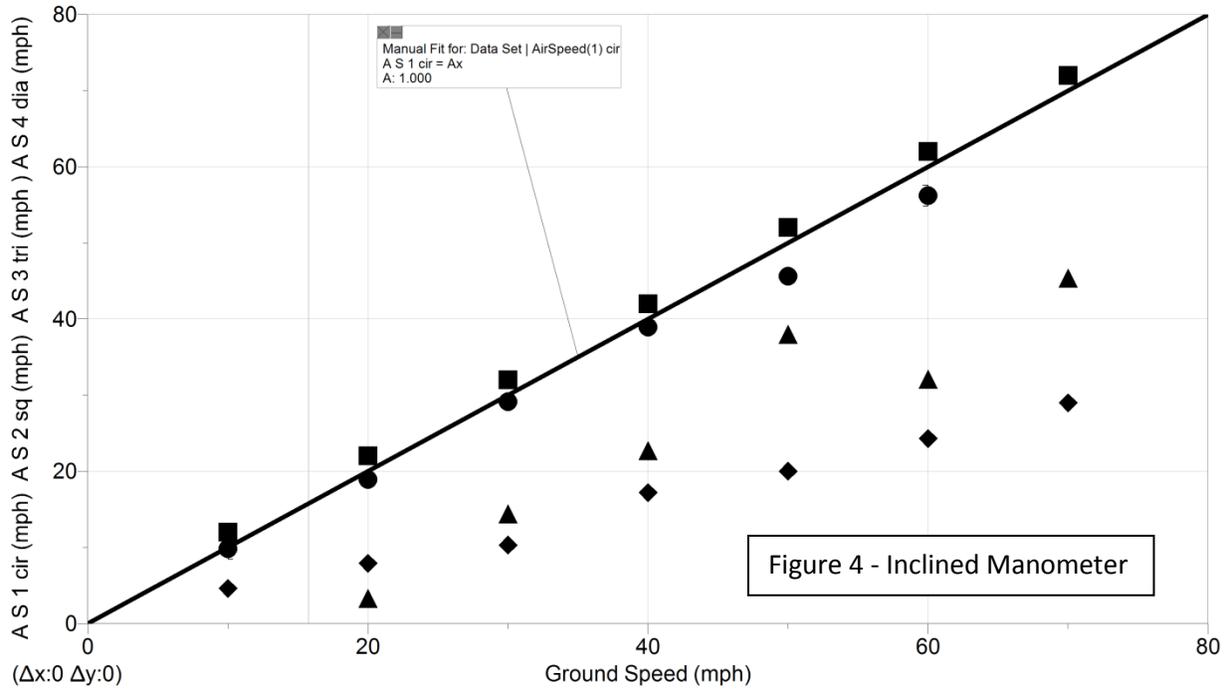


Figure 4. Student Airspeed Measurements 2.

The four groups in Figure 4 used inclined manometers. The two groups designated by filled circles and squares measured an airspeed which agreed with the ground speed. The two groups designated by triangles and diamonds obtained data that could indicate a leak in their total pressure line or the manometer was filled with the wrong fluid, which gave them a measured airspeed about one-half the expected airspeed.

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