AC 2008-522: WIND TUNNEL EVALUATION AND CALIBRATION OF MODEL ROCKET NOSECONE PITOT-STATIC PROBES

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Wind Tunnel Evaluation and Calibration of Model Rocket Nosecone Pitot-Static Probes

Abstract

As part of an instrumentation course for third-year Electro-Mechanical Engineering Technology students, model rockets were used as an experimentation platform. The nosecones of several model rockets were modified to form Pitot-static probes to measure the velocity of the rockets in flight. An electronic pressure sensor was used to measure the differential pressure between the static and stagnation ports of the probe. Students evaluated the performance of the nosecone Pitot-static probes in the controlled conditions of a wind tunnel facility. The actual performance data was compared to the theoretical predictions of Bernoulli's theorem. The students used the wind tunnel test data to create a calibration table for each Pitot-static probe that was then used in the analysis of the actual rocket flight data. In this paper, the construction of the modified model rocket nosecones is described in detail. Nosecone geometry and port placement considerations are also presented. The wind tunnel testing data is presented and compared to the theoretical predictions. Actual rocket flight data and its analysis is also presented and discussed. Details of the data acquisition systems used for the wind tunnel testing and in-flight data recording are also provided.

Introduction

As part of an instrumentation course for third-year Electro-Mechanical Engineering Technology students, model rockets were used as an experimentation platform. Sensors onboard the model rocket were used to measure the rocket's acceleration, speed, and altitude. The measurements were acquired with an analog to digital converter and stored in onboard nonvolatile memory under the control of a microcontroller (PIC16F688). After rocket recovery, the stored data was then downloaded and analyzed.[1]

The acceleration of the rocket was measured with a MEMS accelerometer (MMA2201D) manufactured by Freescale Semiconductor.[2] The rocket's altitude was measured with a MEMS absolute pressure sensor (MPX5100) also manufactured by Freescale.[3] The speed of the rocket was measured with a Pitot-static probe that was created by modifying the nosecone of the rocket itself. The shape of a model rocket nosecone is very near that of the ISO standard Pitot tube profiles.[4] To determine airspeed from a Pitot-static probe, a differential pressure measurement must be made.[5] This differential pressure measurement was made using a Freescale sensor (MPVZ5004G). [6]

To test and calibrate the nosecone Pitot-static probes, a controlled flow of air is required. This controlled flow was obtained using a wind tunnel facility. Figure 1 shows a photograph of the wind tunnel test setup. The main body tube was rigidly mounted in the center of the wind tunnel flow area. Each nosecone under test was then mounted onto the front of this main body tube as shown in Figure 2.

Figure 1. Wind tunnel test setup.

Figure 2. Interchanging nosecones to be tested.

Pitot-static Probe

A Pitot-static probe is used for the measurement of fluid flow velocity. The probe is placed into the fluid flow as shown in Figure 3. The probe is bent such that it can be mounted on or passed through a surface perpendicular to the flow. By measuring the difference between the total pressure (also called stagnation pressure) and the static pressure, the velocity of the fluid at the point of insertion into the flow can be determined.
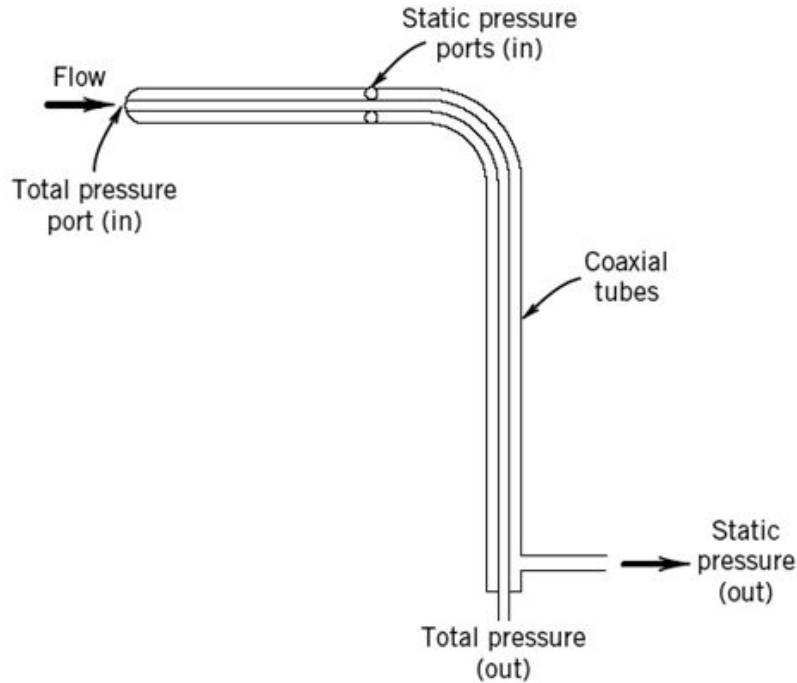

Figure 3. Basic Pitot-static probe construction.

Assuming steady one-dimensional flow of an incompressible frictionless fluid, the following result for fluid velocity can be derived from Bernoulli's equation [7],

$$V = \sqrt{\frac{2(p_{Total} - p_{Static})}{\rho_{Fluid}}} \tag{1}$$

where,

$$V = \text{Fluid velocity in m/s}$$
$$p_{Total} = \text{Total pressure in Pa}$$
$$p_{Static} = \text{Static pressure in Pa}$$
$$\rho_{Fluid} = \text{Density of fluid being measured in kg/m}^3$$

The differential pressure, $(p_{Total} - p_{Static})$, is referred to as the *dynamic pressure* and is typically measured with a single pressure transducer configured for differential measurement.

The placement of the static pressure sensing holes of the Pitot-static probe affects the performance of the probe. The static port holes should be far enough downstream from the probe tip such that the flow streamlines are again aligned parallel to the probe.[8]
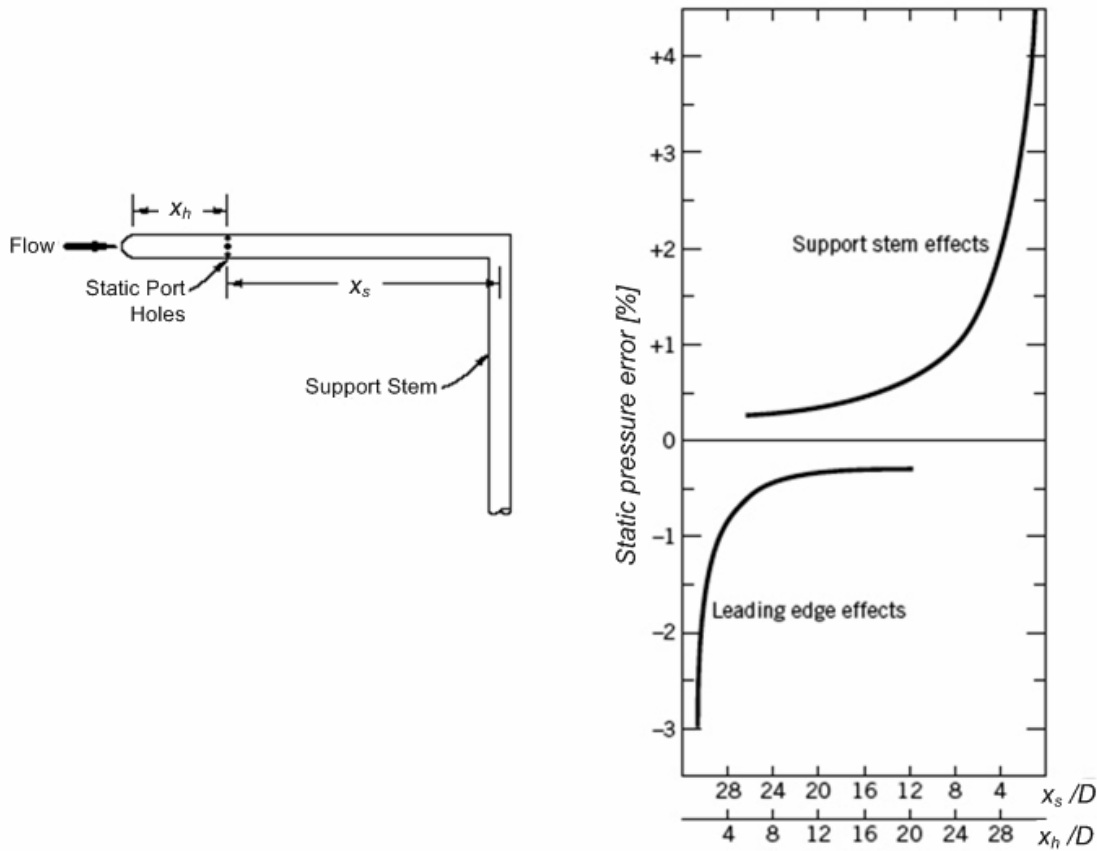

Figure 4. Static pressure errors due to static port hole placement.

In practice, equation (1) is modified to account for non-idealities in the fluid flow and probe construction.[9] For SI units, equation (1) becomes,

$$V = 44.72136 \cdot K_{Pitot} \cdot \Gamma_{Pitot} \sqrt{\frac{\Delta p}{\rho_{Fluid}}}$$
(2)

where,

$$V = \text{Fluid velocity in m/s}$$
$$K_{Pitot} = \text{Pitot coefficient } (0.8 - 1.0)$$

$$\Gamma_{\text{Pitot}} = \quad \text{Fluid compression factor (1.0 for liquids)}$$
$$\Delta p = \quad \text{Dynamic pressure in Pa}$$
$$\rho_{\text{Fluid}} = \quad \text{Density of fluid being measured in kg/m}^3$$

For the nosecone Pitot-static probe, the probe construction is fixed, the velocities are small enough that fluid compression is negligible, and the fluid is always air. Therefore, the calibration process reduces to determining one coefficient:

$$V = K_{\text{Nose}} \sqrt{\Delta p} \tag{3}$$

The effect of Pitot probe misalignment with the gas flow axis is quite small for angles less than about 15°. [5] For the rocket nosecone Pitot-static probe, however, the axis of interest is that of the path of rocket travel. Because the rocket axis is always aligned with its direction of travel, at least for stable flight, no misalignment exists.

Nosecone Pitot-static Probe Construction

Several model rocket nosecones were modified to produce Pitot-static probes. The nosecones used were part of the Blue Ninja model rocket kit manufactured by Estes Rockets. Each nosecone was nominally 41.6mm in diameter at the bottom (model rocket body size BT-60), 170mm long (exposed), and had a tip radius of about 6mm as shown in Figure 5. The tapered region can be approximated with a curvature of radius 565mm (often called a *tangent ogive*).
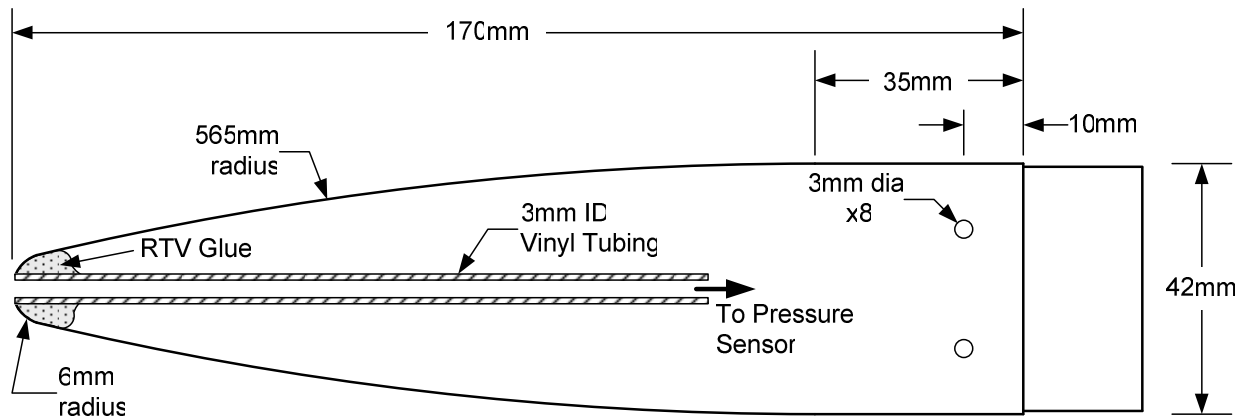

Figure 5. Modified nosecone assembly drawing.

To create the *total pressure* port, a clearance hole was drilled in the nosecone tip to accommodate the insertion of flexible vinyl tubing with an inside diameter of 3mm. Room

Temperature Vulcanizing (RTV) silicone glue was used to secure the tubing in the hole. The vinyl tubing was then connected to one port (P1) of the differential pressure sensor.

The *static pressure* port was created by drilling eight, 3mm diameter holes symmetrically spaced around the tube in the non-tapered area at a distance of 10mm from the back edge of the exposed portion of the nosecone. These holes were placed as far from the tip as possible (160mm) while still allowing room for the nosecone to be fastened to the rocket body tube with cellophane tape. Because the differential pressure sensor was housed inside the nosecone, the air pressure at the remaining port of the sensor was the static pressure. The distance of the static port holes from the tip of the probe is approximately 4 times the diameter of the probe ($x_h/D = 4$). From Figure 4, this hole placement produces about a -1% error in the static pressure measurement due to leading edge effects.

Pressure Sensor Calibration

Each differential pressure sensor was mounted on a printed circuit board (PCB). The PCB also contained the manufacturer recommended power supply decoupling capacitance and reverse connection protection diode, output signal filtering, and terminal block. Figure 6 shows a schematic of the pressure sensor PCB.
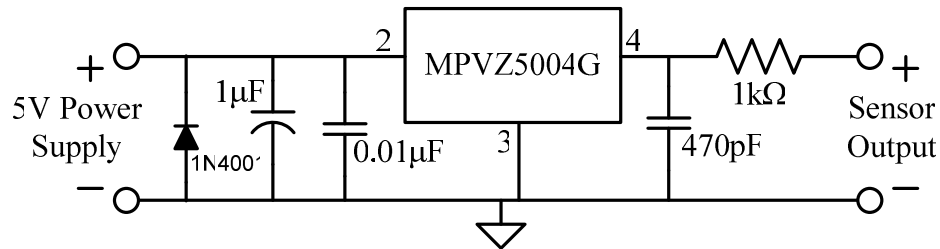

Figure 6. Differential pressure sensor PCB schematic diagram.

The sensors were then tested by the rocket teams in the laboratory using a column of water as the pressure reference. Figure 7 shows the apparatus diagram for testing the sensors.

The sensitivity of the pressure sensor is ratiometric with the supply voltage (for $V_S = 5.0V \pm 0.25Vdc$). The output voltage to supply voltage ratio is given by the following transfer function:[6]

$$\frac{V_{out}}{V_{supply}} = (0.2P + 0.2) \pm 0.0625 \qquad \text{(P is pressure in kPa)} \qquad (4)$$
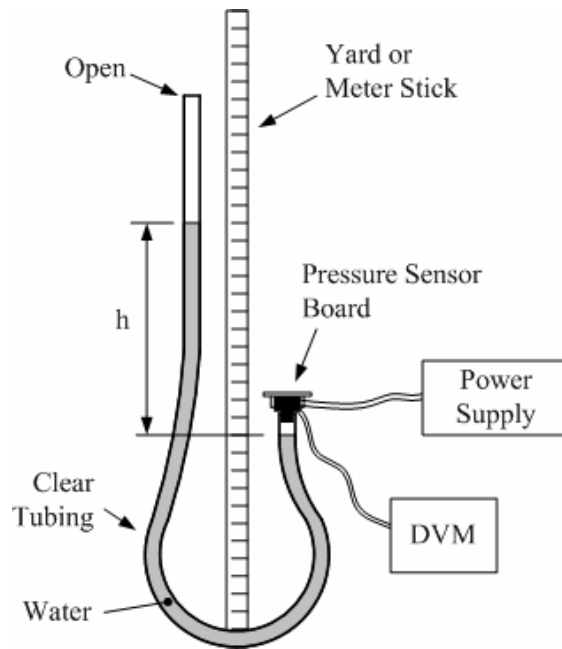
Figure 7. Pressure sensor laboratory test setup.
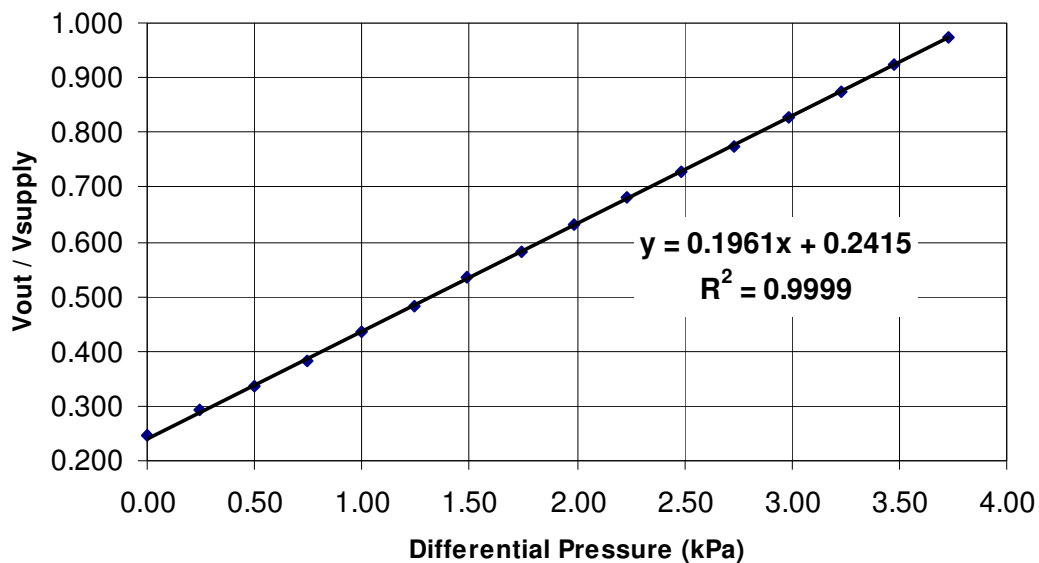

$$y = 0.1961x + 0.2415$$
$$R^2 = 0.9999$$

Figure 8. Typical differential pressure sensor calibration data.

Therefore, a calibration table of ratiometric measurements as a function of differential pressure (due to the water column) was created for each sensor. Figure 8 shows a plot of this calibration data for one example sensor. It was observed that the data for all of the MPVZ5004G pressure sensors indicated that the ratio of output voltage to supply voltage with zero pressure differential and the scale factor relating differential pressure to the voltage ratio were very near or actually

above the maximum specified by the manufacturer. This may have been due to the parts being obtained as samples from the manufacturer that were not guaranteed to conform to the published specifications.

Nosecone Pitot-static Probe System

Each nosecone was mated with a pressure sensor to form a Pitot-static measurement system. These nosecone-sensor pairs remained together throughout the wind tunnel testing and actual rocket flights. Figure 9 shows a photograph of an assembled nosecone-sensor pair. The wiring harness shown in Figure 9 is used to provide the +5V supply voltage to and measure the output voltage from the pressure sensor.

The +5V supply voltage for the sensor is provided by a fixed +5V voltage regulator located on the main PCB of the rocket data acquisition system. The main PCB also contains the microcontroller with the analog to digital converter (ADC) that is used to measure the output voltage of the pressure sensor.

Figure 9. Nosecone Pitot-static probe system.

The microcontroller's ADC has a resolution of 10 bits and was configured via software to use the regulated +5V supply voltage as its measurement reference. With this reference configuration, the ADC digital output was ratiometric with respect to the +5V supply voltage. Because the pressure sensor output voltage was also ratiometric with respect to the +5V supply voltage, the measurements were insensitive to supply voltage changes.

Wind Tunnel Instrumentation

Each nosecone Pitot-static probe system was tested and calibrated in the wind tunnel facility at Lehigh University. This wind tunnel can produce a maximum air speed of 40 m/s. The maximum anticipated airspeed of the rockets in flight is approximately 45 m/s so the wind tunnel provided nearly full range coverage.

Each nosecone was mounted to a stationary rocket body in the center of the air flow cross section as shown in Figures 1 and 2. The stationary rocket body also housed the main PCB containing the microcontroller with the ADC. The same microcontroller PCB was used for the wind tunnel testing as for the actual rocket flight. During wind tunnel testing however, the microcontroller was programmed to send the pressure sensor output voltage measurements to a laptop computer rather than storing the data in EEPROM as was done during the rocket flight. The measurement data was sent to the laptop via RS232 serial cable (twisted pair) connection.

For the wind tunnel testing, the microcontroller was programmed to sample and average the pressure sensor output voltage. The sensor output was sampled at 20Hz and the average of the last 20 readings (1 second) was transmitted to the laptop computer via serial connection. The raw ADC register value (0 – 1023) was used here because it is already ratiometric with respect to the max value (Vin = Vref) of 1023. The wind tunnel airspeed was allowed to stabilize for several seconds before each reading was recorded.
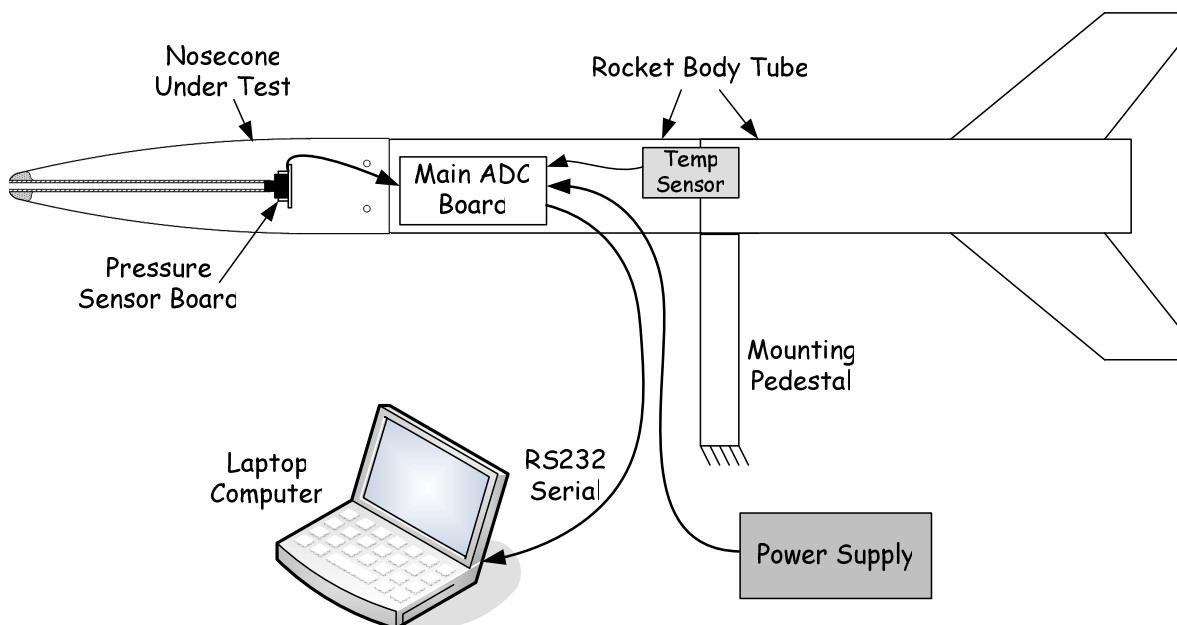

Figure 10. Apparatus diagram for nosecone Pitot-static probe wind tunnel testing.

An integrated circuit temperature sensor (LM34CZ) was also placed inside the main body tube to measure the air temperature inside the wind tunnel. The LM34CZ output voltage was also sampled and averaged with the microcontroller ADC and transmitted to the laptop computer. Figure 10 shows an apparatus diagram for the wind tunnel instrumentation.

LabVIEW software was developed to process and display the pressure sensor voltage and wind tunnel air temperature. The serial data from the microcontroller inside the main body tube was converted and displayed on the laptop computer from which the students recorded the data for their particular nosecone Pitot-static probe.

Wind Tunnel Test Results

Seven nosecone Pitot-static probe systems were tested in the wind tunnel facility. Figure 11 shows the ADC digital output value as a function of wind tunnel air speed for each probe system. Several discrete air speeds were used as shown in Figure 11. Figure 11 also shows the values that would be produced by an ideal Pitot-static probe (as predicted by Bernoulli's equation and an air density of 1.204 kg/m^3) and a pressure sensor with the calibration data shown in Figure 8 (Pitot serial number 001). (Recall that during laboratory calibration, all of the MPVZ5004G pressure sensors were found to exhibit offset and sensitivity values that were near or above the maximum specified on the datasheet.) Also, note that the zero-pressure offset voltage imposed by the pressure sensor required that equation (3) be modified to include this offset.
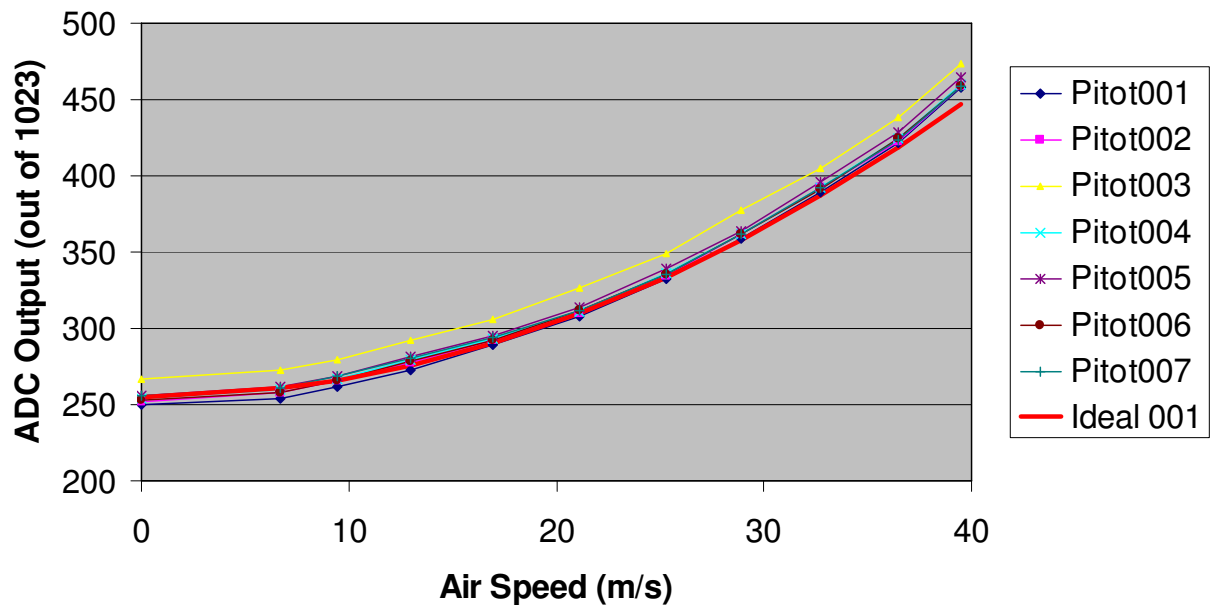

Figure 11. Nosecone Pitot-static probe wind tunnel testing data.

The nonlinear data shown in Figure 11 was expected to follow a parabolic relationship with respect to air speed. Therefore, if the data is plotted as a function of the square of the air speed, a linear relationship is expected. By doing this, a linear regression can be employed to find a best-fit calibration line.

Figure 12 shows an example of the best-fit calibration line for Pitot-static system number 001. For this particular system, the calibrated input-output (input = velocity, output = digital word) relationship becomes:

$$\text{digital word} = \text{int}[0.1314(\text{velocity})^2 + 249.63] \tag{5}$$

The inverse of (5) was used by the students to find the rocket velocity from the measured ADC digital output word:

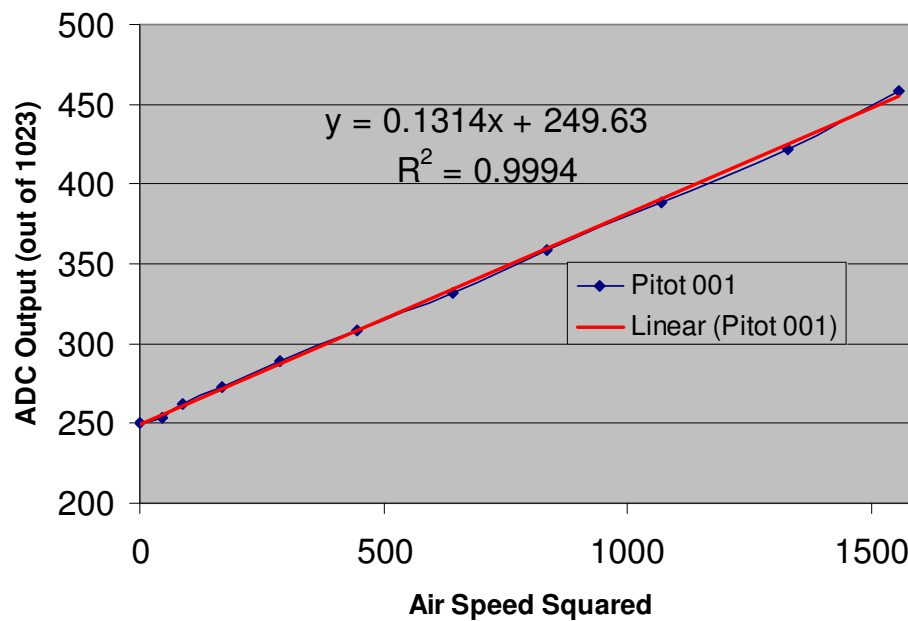$$\text{velocity} = \sqrt{\frac{(\text{digital word}) - 249.63}{0.1314}} \tag{6}$$

Figure 12. Example calibration plot of ADC output versus the square of the air speed
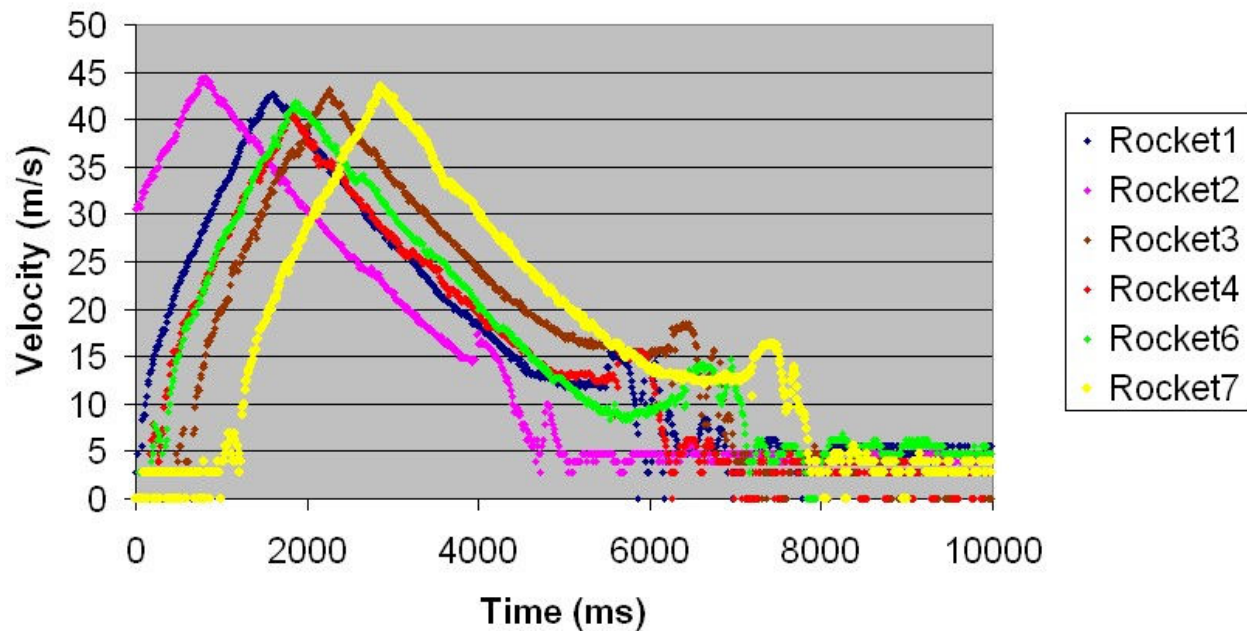
Rocket Flight Data

Figure 13. Actual rocket velocity data for the nosecone Pitot-static probe systems.

Figure 13 shows the actual velocity profiles derived from the data retrieved from the flight of six different rocket nosecone Pitot-static probes (one Pitot-static probe (serial number 005) did not fly due to technical difficulties unrelated to the nosecone). Each plot is staggered horizontally due to the varied timing between hitting the launch button and actual rocket liftoff. The velocity profiles were found to correlate very well with the measured acceleration and altitude displacement via numerical integration and differentiation respectively.

Conclusions

The calibration data indicates that the simple Pitot-static probes constructed by modifying model rocket nosecones produced very acceptable results. The nosecone of a model rocket lends itself very well for this application. The shape of a nosecone is desirable for forming the probe and the velocity of a rocket is often a desired quantity to measure.

The range and resolution of differential pressure sensor required to measure the pressures present in a nosecone Pitot-static probe are readily available and affordable. The construction techniques required to modify the model rocket nosecones is also well within the capability of engineering technology students. No special tools or materials are needed.

This research also indicates that very acceptable results for rocket speed can be obtained by using the ideal predictions once the pressure sensor itself has been calibrated. The calibration of the pressure sensor is also easily performed using very simple apparatus and procedures.

Acknowledgments

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