Calibration of a Low-Speed Wind Tunnel Using Pressure-Based Velocity Measurements

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The objective of this experiment was to characterize the laboratory air, calibrate a pressure transducer and Scannivalve against a micromanometer, and determine test-section velocity as a function of wind-tunnel fan setting. Atmospheric pressure and temperature were first measured and used to calculate an air density of $1.0991 \pm 0.0038\ kg/m^3$. The micromanometer was then used as the reference for pressure-transducer and Scannivalve calibration over fan settings ranging from 15 to 50 Hz. Linear least squares fits showed strong linear behavior, with R^2 values of approximately 0.999 for the pressure transducer and 0.99958 for the Scannivalve respectively. For the wind tunnel calibration, pitot tube dynamic pressure, contraction pressure drop, and static port Scannivalve measurements were used to obtain three separate velocity estimates. Test section velocity increased from 9.3 m/s at 15 Hz to 44 m/s at 50 Hz. The pitot-tube and contraction methods remained in close agreement throughout most of the range, while the Scannivalve method showed greater deviation, particularly at 25 Hz. Overall, the experiment established pressure calibration relationships and a velocity-versus-fan-setting baseline for use in future wind-tunnel measurements.

I. Nomenclature

A	= *Cross sectional area (m^2)*
AR	= *Wind Tunnel area ratio, A_2/A_1*
b	= *linear calibration intercept*
h	= *micromanometer readings (in. H_2O)*
m	= linear calibration slope (Pa/V)
N	= Number of pressure ports
P	= Pressure (Pa)
P_g	= Test section gage pressure (Pa)
q	= dynamic pressure (Pa)
R	= specific gas constant for air (J/(kg * K))
R^2	= coefficient of determination
S	= sum of squared residuals (Pa^2)
T	= Absolute air temperature (K)
V	= flow velocity (m/s)
V_{out}	= pressure instrument voltage output (V)
x_i	= independent measured variable
ΔP	= differential pressure (Pa)
ρ	= air density (kg/m^3)
σ	= measurement or propagated uncertainty
σ_f	= uncertainty om ca;ci;ated quantity f
σ_{x_i}	= uncertainty in measured variable x_i
Pmean	= mean Pressure (Pa)
Mean	= Mean Voltage (V)

II. Introduction

In order for wind tunnel experiments to be properly performed, there needs to be a known relationship between the setting of the tunnel and the flow conditions within the test section. For the lab facility in which this experiment took place, the fan is controlled by a frequency setting in hertz. This setting specifies the operation of the drive system of the wind tunnel, which is the rotational speed of a fan motor instead of the actual velocity of the airflow in the wind tunnel itself. That is, a setting of 30 Hz does not (independently) establish the airspeed of a corresponding test section. Therefore the wind tunnel must be calibrated in such a way that each operating setting can be directly associated with a physically measured freestream velocity. Moreover, this relationship needs to be established before one can relate later obtained aerodynamic quantities to known flow conditions. This experiment intends to develop this calibration, while also comparing other pressure based methods of determining airspeed.

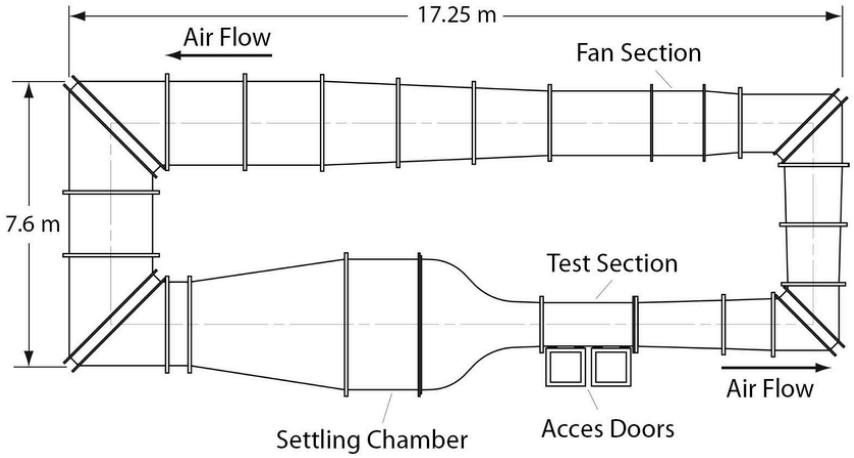


Fig. 1. General low speed wind tunnel. Adapted from Ref. [1].

If a wind tunnel has incompressible flow, velocity can be determined indirectly from measurements of pressure, as Bernoulli's principle relates changes in fluid velocity to changes in static pressure for steady, inviscid and incompressible flow along a streamline. Static pressure represents the local thermodynamic pressure of the moving fluid, whereas total pressure is the pressure that the fluid would have if it were brought to rest without losses. That is, total pressure includes both pressure already present in the moving air and the additional pressure that is associated with stopping its motion. Meaning that the difference in Total pressure and static pressure is dynamic pressure, a measurement that relies on fluid density and the square of the flow velocity. The measurement of the pressure difference (to thereby obtain dynamic pressure) allows one to infer the local velocity (when air density is known). Therefore, it's a prerequisite to measure atmospheric pressure and temperature to determine the tunnel air density and thereby infer and/or calculate the velocity. Pressure based approaches such as this are particularly useful because the instruments do not directly measure the translational speed of individual air particles but instead measurable pressure quantities are converted into velocity through the governing fluid mechanics relationship. [3]

A second way to determine the velocity of the test section is obtained through the change in pressure as it moves through the wind tunnel contraction. Conservation of mass requires the mass flow rate through the settling chamber and test section to remain constant for particles in steady flow. And, because the air is incompressible, a reduction in the cross sectional area of the wind tunnel must therefore lead to an increase in the flow velocity. The wind tunnel used in this experiment had a 6.25:1 ratio between the cross section of the settling chamber to the test section. Meaning that the test section is one sixth and one quarter the cross section of the area upstream. Under the assumption that the flow is incompressible, the test section velocity would be much greater than the velocity upstream. Moreover, Bernoulli's principle requires the increase in velocity through the contraction to reduce the static pressure, (or vice versa) and by measuring this static pressure difference across the contraction and combining the conservation of mass with Bernoulli's principle, the velocity of the test section can be determined without inserting a velocity probe directly into the test section. Further, unlike the pitot method (which characterizes the flow near a particular location in the test section), the contraction method gives a velocity estimate based on the overall flow through the tunnel cross section

In the experiment, several instruments were used to obtain the pressure measurements required for calibration. An absolute pressure transducer and digital thermometer provide the atmospheric pressure and temperature measurements used to determine air density, a micromanometer measures small differences in pressures and is used as the reference instrument when calibrating the pressure measurement devices. The pressure transducer directly

converts a differential pressure into a voltage output, and the scannivalve also produces an electric output that directly corresponds to the pressure supplied through its connected pressure lines [5]. During the instrument calibration, the micromanometer, pressure transducer and scannivalve are all connected to the pitot tube pressure system so that their responses can be compared over a range of fan settings. Then, calibration curves are used to relate the voltage outputs of the pressure transducer and scannivalve to the measured pressure [4]. During the wind tunnel calibration the instruments are used in separate configurations, that is: the pressure transducer measures the dynamic pressure of the pitot tube near the center, the micromanometer measures the static pressure drop across the contraction area and the scannivalve measures static gage pressure from multiple pressure ports along the floor of the test section.

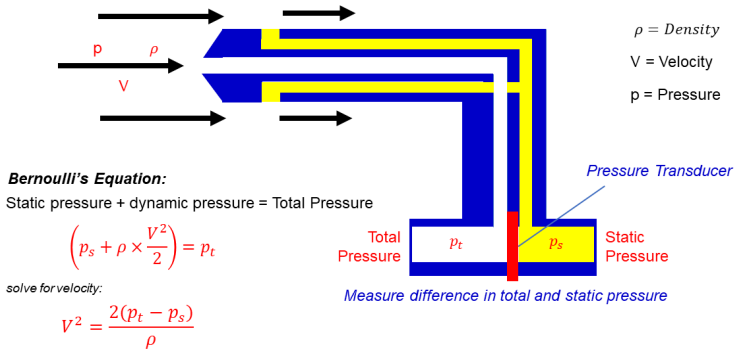


Fig. 2. Pitot static tube anatomical diagram. Adapted from Ref. [2].

The objective of this experiment is to determine the pressure and density of the laboratory air, calibrate the pressure transducer and scannivalve and determine the test section speed as a function of the wind tunnel fan setting. Three pressure based methods are used to be able to determine the test section velocity, those are: the dynamic pressure measured using the pitot tube and pressure transducer, the static pressure drop measured across the contraction using the micromanometer and finally the static gage pressure measured from the test section floor ports using the scannivalve. Then the resulting velocity vs. fan setting relationship provides us with calibration curves for the wind tunnel. Comparing the three methods gives us a way to evaluate the consistency of the measurements and identifying the effects of instrument uncertainty, calibration error and the assumptions used in converting measured pressure into flow velocity.

III. Experimental Procedure

A. Atmospheric Pressure and Density

First, laboratory atmospheric conditions are measured to determine the air density required for further pressure to velocity calculations. The laboratory absolute pressure is recorded along with the air temperature and the uncertainty of our manometer is recorded, further, the uncertainty of all other measurement devices is given in our lab files on canvas, this is also necessary for all future calculations. The measured temperature is converted to absolute temperature (Kelvin) and the atmospheric pressure is converted to pascals. Operating under the assumption that air behaves as an ideal gas, the density is calculated from

$$\rho = (P/RT) \quad (1)$$

Where P is absolute pressure, T is absolute temperature and R is the specific gas constant for air. A value of R = 287.05 is used throughout the procedure.

The uncertainties of the measurement instruments were taken from the supplied machine error data. For quantities calculated from multiple measured variables, these specified instrument uncertainties were propagated through the governing equations using the root sum square method

$$\sigma_f = \sqrt{\sum_{i=1}^{n} \left(\frac{\delta f}{\delta x_i}\sigma x_i\right)^2} \quad (2)$$

where f is a calculated quantity, x_i is an independent variable, and σx_i is the uncertainty associated with that variable. Equation 2 is applied to the density calculation using the uncertainties in absolute pressure and temperature. This

general method is also used for pressure and velocity uncertainties throughout the experiment. (Note: the underlying machine uncertainties are supplied values, not values estimated.)

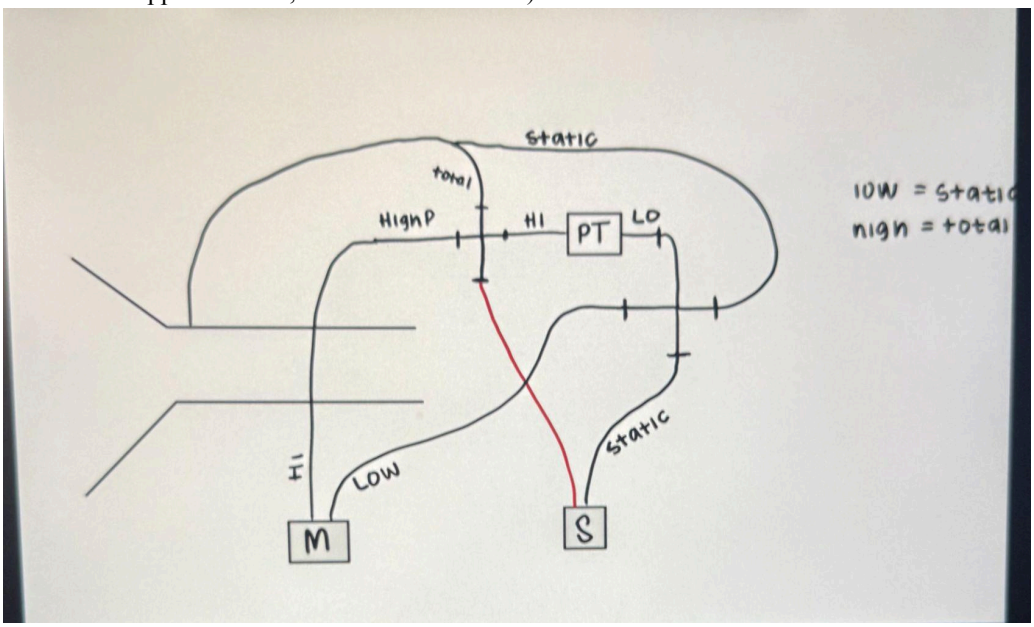


Fig. 3. Provided wind tunnel equipment layout diagram

B. Pressure Transducer and Scannivalve Calibration

The pressure transducer and scannivalve are first calibrated against the micromanometer in Part II, the resulting calibration relationships are then used in Part III to convert their electrical outputs into pressure measurements for the wind tunnel velocity calculations. The micromanometer, pressure transducer, and scannivalve are connected to the pitot tube pressure system so that their response can be compared under the same wind tunnel operating condition. The wind tunnel is operated at fan settings from 15 to 50 Hz going up by increments of 5 Hz each measurement, and the micromanometer reading, pressure transducer voltage and scannivalve voltage are recorded at each setting. The micromanometer serves as the reference pressure measurement because its reading can be converted directly into differential pressure, compared to the electronic instruments that require a relationship between their voltage output and applied pressure.

Before the manometer measurements are used for calibration, the measured zero bias is removed according to

$$h_{corr} = h_{raw} - h_{bias} \tag{3}$$

where h_{raw} is the indicated manometer reading and h_{bias} is its measured zero offset. The corrected reading is then converted from inches of water to pascals using

$$P_{man} = h_{corr}\left(249.09\frac{Pa}{in, H_2O}\right). \tag{4}$$

Because the bias is itself a measured quantity, its uncertainty is included along with the uncertainty of the manometer reading. For equal uncertainties in the raw reading and bias, the corrected manometer uncertainty is

$$\sigma_{h,corr} = \sqrt{\sigma_h^{\,2} + \sigma_{bias}^{\,2}} = \sqrt{2}\sigma_h. \tag{5}$$

Then, a linear relationship between electrical output and pressure is determined for both electronic instruments, the calibration model is

$$P = mV_{out} + b \tag{6}$$

where V is the measured instrument voltage, P is the corresponding corrected manometer pressure, m is the calibration slope and b is the intercept. The calibration coefficients are obtained through using a least squares regression that minimizes the residual sum.

$$S = \sum_{i=1}^{n} [P_i - (mV_i + b)]^2. \tag{7}$$

The corresponding working expressions for the slope and intercept are

$$m = \frac{\sum_{i=1}^{n} (V_i - Vmean)(P_i - Pmean)}{\sum_{i=1}^{n} (V_i - Vmean)^2} \quad (8)$$

and

$$b = Pmean - mV_{mean}. \quad (9)$$

One transducer/manometer pair is retained for each fan setting on the pressure transducer calibration because these values are repeated in the data file for the individual scannivalve port measurements. This should prevent repeated measurements of the same transducer value from artificially affecting the calculated regression statistics. For the scannivalve calibration, all individual scannivalve readings are retained and each is paired with the corrected manometer pressure corresponding to its fan setting.

MatLab then performs a first order polynomial regression for each calibration and calculates the coefficient of determination using

$$R^2 = 1 - \frac{\Sigma(P_i - P^{hat}_i)^2}{\Sigma(P_i - P)^2} \quad (10)$$

The residual variance from each regression is then also used to determine the uncertainties within the fitted slope and intercept. A second calibration constrained to pass through the origin is generated for comparison; but the unconstrained linear relationship of Eq. (6) is used for all subsequent pressure calculations.

The uncertainty associated with a pressure calculated from the electronic calibration is determined by propagating the voltage, slope, and intercept uncertainties through Eq. (6) which gives

$$\sigma_p = \sqrt{((m\sigma_V)^2 + (V\sigma_m)^2 + \sigma_b^2}. \quad (11)$$

This procedure is then applied separately to the pressure transducer and scannivalve using their respective instrument and regression uncertainties.

C. Wind Tunnel Velocity Calibration

Following the calibration procedure of the electric pressure instruments, the pressure connections are reconfigured for determination of the test section velocity. The micromanometer is connected across the contraction of the wind tunnel to measure the static pressure decrease between the upstream section and the test section. The (calibrated) pressure transducer is connected across the pitot tube system to determine dynamic pressure at the test section. Multiple static pressure ports on the floor of the test section are connected to the scannivalve top measure test section gauge pressure. As stated earlier the measurements are obtained at fan settings of 15 to 50 Hz in 5 Hz increments. At each setting the test section air temperature and outputs of the three pressure measurement systems are recorded.

The air density is recalculated independently at every fan setting for data processing instead of assuming a single constant density for the entire calibration. Further, the temperature and ambient pressure measurements associated with each operating condition are each converted to SI units and put into Eq. (1). Then the corresponding density uncertainty is recalculated at each setting using Eq. (2).

1. Pitot Tube Method

For the pitot tube method, the recorded values of the pressure transducer at each fan setting is converted to dynamic pressure using the pressure transducer calibration from Eq. (6). The uncertainty in this pressure is then calculated from Eq. (11). Dynamic pressure is related to the velocity at the test section by

$$q = \frac{1}{2}\rho V^2. \quad (12)$$

And solving Eq. (12) for velocity gives

$$V_{pitot} = \sqrt{\frac{2q}{\rho}}. \quad (13)$$

Because the transducer measurement is repeated in the data file for each associated scannivalve port at a given fan setting,; a single repeated transducer value is used for the pitot calculation at each operating condition. Equation (13)

is then evaluated using the dynamic pressure and the density corresponding to that setting. Moreover, the application of Eq. (2) to Eq. (13) gives the velocity uncertainty as

$$\sigma_V = \sqrt{\left(\frac{\sigma_q}{\rho V}\right)^2 + \left(\frac{V\sigma_\rho}{2\rho}\right)^2}. \quad (14)$$

2. Contraction Method

The second velocity estimate is obtained through using the static pressure drop across the wind tunnel contraction. Bernoulli's equation is applied between the settling chamber (the area right before the contraction, denoted as station 1) , and the test section, denoted as station 2:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 \quad (15)$$

Then, for steady and incompressible flow the conservation of mass requires

$$A_1 V_1 = A_2 V_2 \quad (16)$$

Solving Eq. (16) for the upstream velocity gives

$$V_1 = \frac{A_2}{A_1} V_2. \quad (17)$$

The area ratio used in the analysis is then defined as

$$AR = \frac{A_2}{A_1}. \quad (18)$$

For the wind tunnel, $\frac{A_1}{A_2} = 6.25$, giving AR = 0.16, further substitution of Eq. (17) into Eq. (15) and definition of the measured pressure difference as

$$\Delta P = P_1 - P_2 \quad (19)$$

gives

$$\Delta P = \frac{1}{2}\rho V_2^2 (1 - AR^2). \quad (20)$$

So therefore, the working expression for the mean test section velocity becomes,

$$V_{contr} = \sqrt{\frac{2\Delta P}{\rho(1-AR^2)}}. \quad (21)$$

At each fan setting, the raw manometer measurement is corrected for the zero bias using Eq. (3), converted to pascals using Eq. (4), and then substituted into Eq. (21). As with the pressure transducer data, the contraction manometer value is repeated for the individual scannivalve port rows within each setting, meaning one repeated value is used for the contraction calculation.

3. Scannivalve Method

For the third method the scannivalve voltage measured at each test section floor port is converted to static gage pressure using its calibration relationship from Eq. (6). Unlike the pitot and contraction measurements, all the individual scannivalve port measurements are retained. The calibrated pressures at a given fan setting are averaged according to

$$P_g = \frac{1}{N}\sum_{i=1}^{N} P_{g,i}, \quad (22)$$

where N is the number of connected floor pressure ports.

Two contributions are included in the uncertainty of the averaged scannivalve pressure, the first being the instrument calibration uncertainty calculated from the scannivalve voltage, calibration slope and calibration intercept. The second is the observed variation among the individual floor port pressures, this is represented by their standard deviation. Then these contributions are combined as

$$\sigma_{P_g} = \sqrt{\sigma_{inst}^2 + \sigma_{spatial}^2}. \quad (23)$$

For the processing used in this experiment, the magnitude of the average test section gage pressure is used in the same pressure to velocity relationship as in Eq. (13)

$$V_{scanni} = \sqrt{\frac{2\left|P_g\right|}{\rho}}. \quad (24)$$

The measured sign of the gauge pressure is then retained separately in the tabulated results, while only its magnitude is used to calculate the velocity. The velocity uncertainty is obtained from Eq. (14) with $\left|P_g\right|$ and its uncertainty substituted for dynamic pressure.

After all three velocity estimates are calculated at each fan setting, the test section velocity is plotted as a function of fan frequency for the pitot tube, contraction, and scannivalve methods. A first order linear fit is then generated for each velocity calibration curve and the propagated uncertainty thats associated with each velocity point is displayed using error bars. Separate uncertainty plots are generated for the three measurement methods. These curves provide the final calibration between wind tunnel fan setting and test section velocity

IV. Results

A. Atmospheric Density

The measured laboratory atmospheric pressure and temperature are used to determine the density of the air required for the pressure based velocity calculations. The resulting laboratory air density is $1.0991 \pm 0.0038\ kg/m^3$, corresponding to an uncertainty of approximately 0.34%. This density value establishes the initial atmospheric condition for the experiment. Note that during the wind tunnel calibration the density is recalculated at each fan setting using the corresponding measured temperature and ambient pressure. The calculated test section density decreases from approximately $1.1140\ kg/m^3$ at 15 Hz all the way to $1.1024\ kg/m^3$ at 50 Hz as the recorded test section temperature increases.

B. Pressure Transducer and Scannivalve Calibration

Figure 4 presents the calibration of the pressure transducer against the micromanometer reference. The measured data points follow a roughly linear relationship over the complete pressure range. The pressure obtained from the unconstrained least-squared calibration remains within approximately 1.9 Pa of the corresponding manometer measurements over a reference range of roughly 41 to 1066 Pa. The close agreement suggests that a linear voltage to pressure relationship adequately represents the pressure transducer response over the operating range of the experiment. The zero intercept and unconstrained fits become almost coincident at larger pressure values but separate more noticeably at the low pressure end of the figure. This behavior suggests that forcing calibration through the origin has a larger effect at low tunnel settings, supporting the use of the unconstrained linear fit for subsequent calculations.

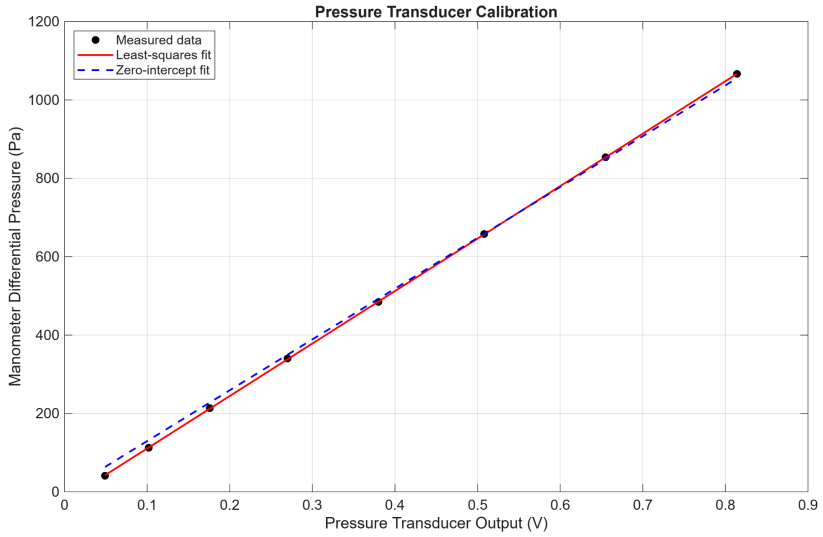


Fig. 4. Pressure transducer calibration against the micromanometer reference, including the measured data, leased-squared calibration and zero intercept comparison.

Figure 5 shows the corresponding scannivalve calibration. The Scannivalve also seems to exhibit a mostly linear relationship between output voltage and the reference pressure. The averaged calibrated scannivalve pressures closely reproduce the manometer measurements through most of the calibration range, although the deviations are larger than the ones observed for the pressure transducer. The largest difference occurs at the 15 Hz calibration condition, where the manometer measures approximately 41.10 Pa and the calibrated scannivalve pressure is approximately 54.88 Pa. Similar to the pressure transducer, the zero intercept fit departs most strongly from the unconstrained least squares fit at the lower pressure measurements. The calibration data supports the use of a linear voltage to pressure relationship while also showing that the scannivalve measurements contain a greater variation than the pressure transducer measurements.

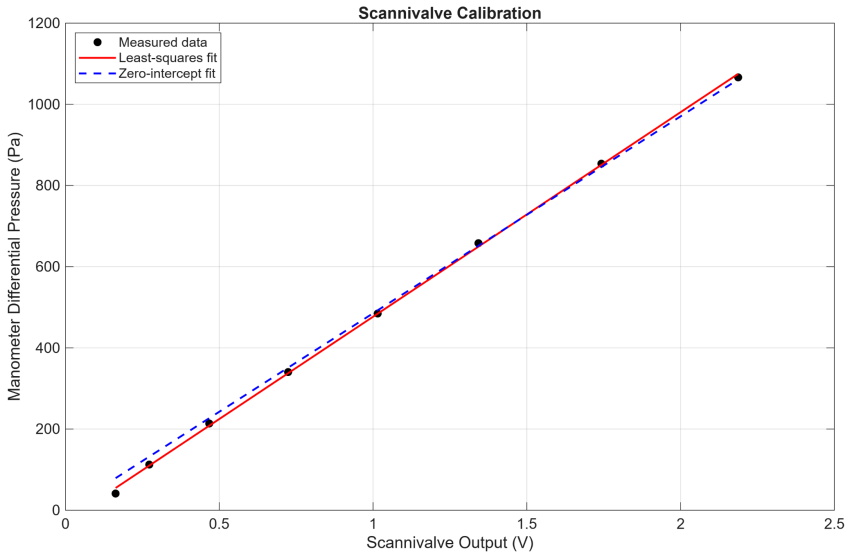


Fig. 5. Scannivalve Calibration against the micromanometer reference, including the measured data, least squares calibration and zero intercept comparison

C. Empty Test Section Velocity Calibration.

The test section velocities that were obtained from the pitot tube, contraction and scannivalve methods are compared as functions of fan setting in Hz within Fig. 6. All three methods show the expected increase in the test section velocity with increasing fan frequency. Linear regression of the calculated velocities gives approximate slopes of 0.9870 $m/s\,Hz^{-1}$ for the pitot tube method, 0.9679 $m/s\,Hz^{-1}$ for the contraction method, and 0.8870 $m/s\,Hz^{-1}$ for the scannivalve method. Therefore, the pitot and contraction methods predict nearly identical changes in velocity with respect to fan setting, while the scannivalve method predicts a smaller increase.

The pitot tube and contraction results remain in close agreement throughout the operating range. At 15 Hz, the two methods produce velocities of 9.40 and 9.26 ./s, respectively, and at 50 Hz they produce values of 44.02 and 43.51 m/s. Their difference is shown to remain below 1.5% at six of the eight fan settings. The largest disagreement notably occurs at 25 Hz, where the pitot and contraction methods produce 19.67 and 20.17 m/s respectively which corresponds to a difference of roughly 5.1% relative to their mean value. Although the strong agreement over the remainder of the range indicates that the two physically different pressure measurement approaches produce a consistent tunnel calibration.

The scannivalve method also agrees closely with the other methods at the two lowest settings except for a notable difference at 25 Hz. At this setting the scannivalve method produces a velocity of 13.43 m/s compared to 19.67 and 20.71 m/s from the pitot tube and contraction method respectively. This means the scannivalve method is roughly 33.5% lower than the mean of the pitot and contraction values. Moreover, the scannivalve method also remains consistently lower than the pitot tube and contraction method from 30 through 50 Hz,with the disagreement ranging from approximately 5% to 12%. The 25 Hz point represents the largest individual discrepancy however the higher frequency results are also indicative of a larger scale difference between the scannivalve derived calibration and the other two methods. The available measurements establish this discrepancy but do not identify the physical cause of this anomaly. Without an independent truth standard, it's not possible to establish certainty to wether the anomaly with the scannivalve method is necessarily bad nor incorrect, all that can be ascertained is that the scannivalve method produced divergent results from the pitot and contraction method.

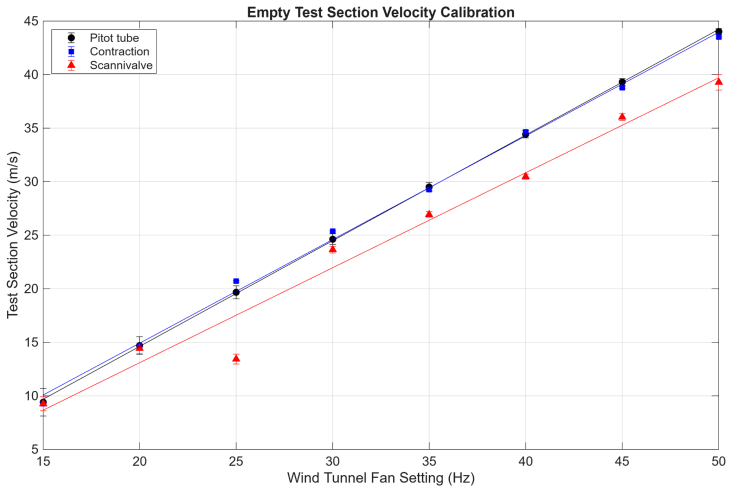


Fig. 6. Empty Test Section Velocity Calibration as a function of fan setting for the pitot tube, contraction and scannivalve methods. Error bars represent the propagated measurement uncertainties.

D. Velocity Uncertainty

Figures 7 through 9 present the propagated velocity uncertainty for the three measurement methods. The contraction method exhibits the smallest uncertainty throughout the tested range. Its absolute uncertainty decreases from $\pm$ 0.176 m/s at 15 Hz to a minimum of $\pm$ 0.075 m/s at 35 Hz and continues to remain below $\pm$ 0.084 m/s at 50 Hz. Meaning in relative terms, this shows an uncertainty of approximately 1.9% at 15 Hz to only 0.19% at 50 Hz.

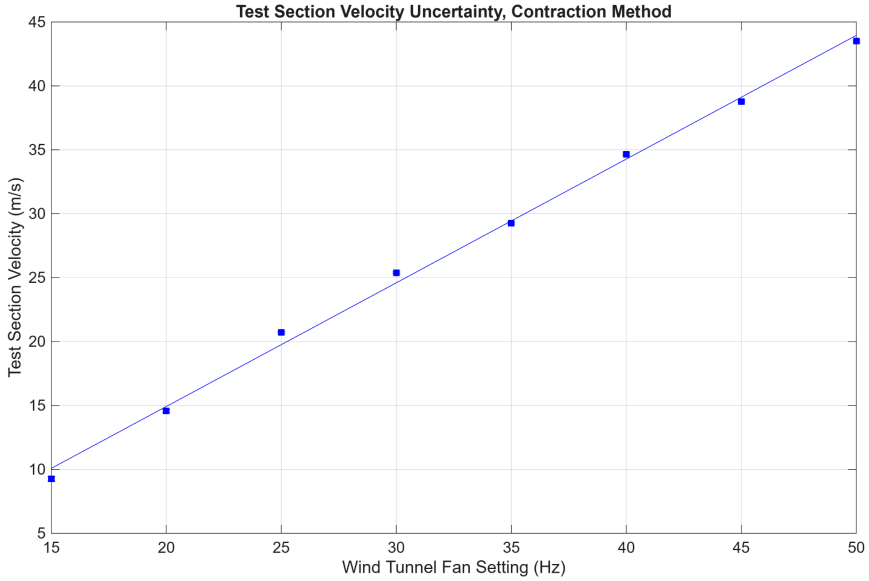


Fig. 7. Propagated test section velocity uncertainty for the contraction method as a function of fan setting. Upper and lower bars represent propagated uncertainty values, although they are visibly obscure due to the low value.

The pitot tube method exhibits a substantially greater uncertainty value at the lowest tunnel settings. At 15 Hz, the calculated velocity is 9.40 $\pm$ 1.28 m/s, corresponding to a relative uncertainty of approximately 13.6%. As fan setting increases, the relative effect of the pressure uncertainty decreases and as a result, the pitot uncertainty falls to approximately $\pm$ 0.29 m/s, or 0.65% at 50 Hz. Moreover, this trend is consistent with the pressure to velocity relationship, because a nearly fixed absolute pressure uncertainty represents a much larger fraction of the overall measured dynamic pressure at low speeds.

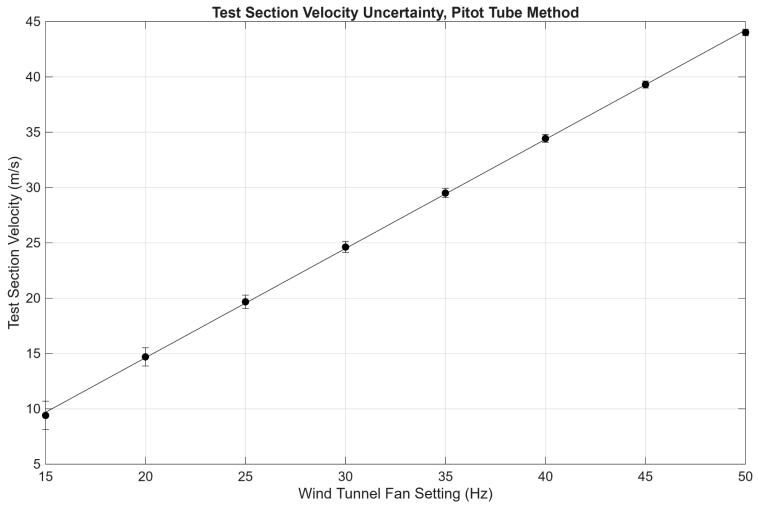


Fig. 8. Propagated test section velocity for the pitot tube method as a function of fan setting. Upper and lower bars represent propagated uncertainty values.

The scannivalve method shows an intermediate uncertainty over most of the operating range. The velocity uncertainty decreases from roughly $\pm$ 0.656 m/s at 15 Hz to $\pm$ 0.2839 m/s at 40 Hz before increasing to $\pm$ 0.721 m/s at 50 Hz. And unlike the pitot tube and contraction methods, the scannivalve pressure uncertainty includes both the instrument/calibration contribution and the variation among each individual floor port measurement. The increase at the highest setting can therefore be attributed to or association with increased disagreement among the floor port pressure measurements in addition to the electronic measurement uncertainty.

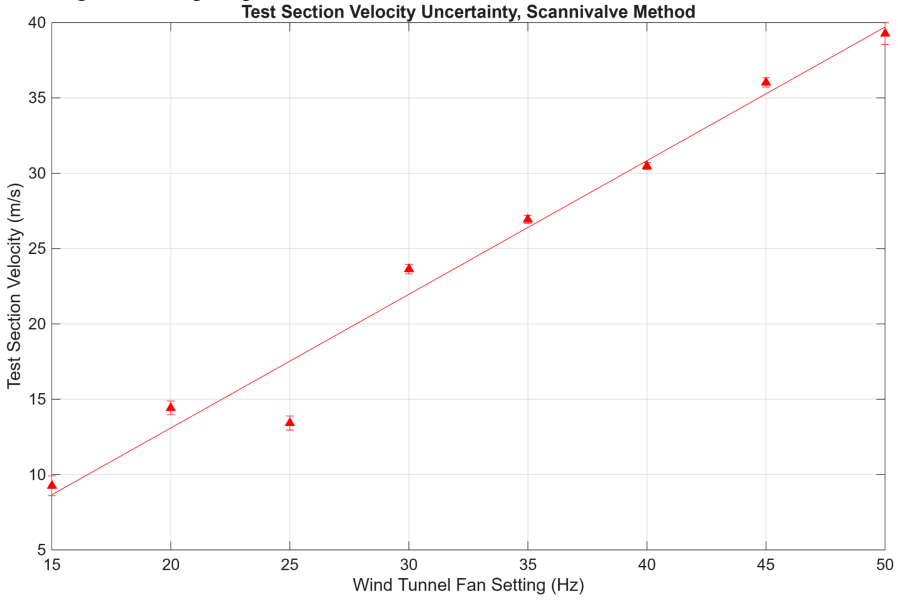


Fig. 9. Propagated test section velocity uncertainty for the scannivalve method as a function of fan setting. Upper and lower bars represent the propagated uncertainty values.

Overall, the results show that the pitot tube and contraction methods provide highly consistent results within the velocity calibrations. With the contraction method producing the smallest propagated uncertainty. The scannivalve method follows the general increase in velocity with fan setting but displays a larger disagreement with the two other methods, particularly so at 25 Hz and higher overall fan settings. These differences are considered further in evaluating the experimental errors and reliability of the three calibration methods.

V. Conclusion

The wind tunnel calibration produced a linear relationship between fan setting and test section velocity over the tested range of 15 to 50 Hz. The pitot tube and contraction methods showed a strong agreement, increasing from roughly 9.4 m/s at 15 Hz to roughly 44 m/s at 50 Hz. Furthermore, their calculated velocities remained consistently close throughout most of the operating range. This indicates that the two independent pressure based approaches were generally consistent with the expected wind tunnel behavior. Additionally, the contraction method also produced the smallest propagated uncertainty, while the pitot tube uncertainty was largest at the lowest fan settings, then decreasing as dynamic pressure increased. The scannivalve method followed the overall increase in velocity with fan setting but had larger anomalies and disagreements with the other two methods. Most notably at 25 Hz, where it predicted 13.43 m/s compared with 19.67 m/s from the pitot tube and 20.71 m/s from the contraction method. The scannivalve also remained notably lower than the other two methods at higher fan settings.

It's worth noting that the velocity calculations rely on the assumption that the airflow is steady, incompressible, inviscid and approximately uniform, and departures from these assumptions, specifically with nonuniform velocity or static pressure distributions within the test section can contribute to differences between the three measurement methods. Additional experimental error can arise from the specified instrument uncertainties**,** the measured manometer zero bias and uncertainty associated with the pressure transducer and scannivalve calibration fits. The supplied machine uncertainties are used in the MatLab analysis, while the manometer reading is corrected using the measured bias before the calculations are performed. The fitted calibration slope and intercept also carry uncertainty which is propagated into the calculated electronic pressure measurements. Variation among the indian test section floor ports provides an additional source of uncertainty in the scannivalve method and is explicitly included in the analysis through port to port standard deviation.

The Resulting calibration provides the relationship required to convert the wind tunnel fan frequency into a meaningful test section velocity for any future experiments held with this wind tunnel. Moreover, because fan frequency alone does not specify the airflow speed, this calibration method is necessary before any aerodynamic quantities and measurements can be associated with known flow conditions. Agreement between the pitot tube method and contraction method increases confidence in the resulting velocity calibration, while the disagreement observed in the scannivalve methods data shows the value of using multiple measurement methods instead of relying on a single instrument. The experiment therefore establishes both a practical operating calibration for the wind tunnel and an understanding of the measurement uncertainty and possible limitations that must be considered in any further aerodynamic testing.

Appendix A: Tabular Results

Table A-1 contains the Part II calibration data used to generate the pressure-transducer and scannivalve calibration plots. Note the micromanometer pressures include the measured 0.066 in. H_2O zero bias correction used in the MatLab analysis. Raw voltage outputs are retained because they are the independent variables in the calibration relationships

Table A-1. Part II calibration data and pressure uncertainties.

Fan setting (Hz)	Micromanometer pressure (Pa)	Micromanometer uncertainty (Pa)	Pressure Transducer output (V)	Pressure Transducer pressure (Pa)	Pressure Transducer uncertainty (Pa)	Scannivalve output (V)	Scannivalve pressure (Pa)	Scannivalve uncertainty (Pa)
15	41.10	1.761	0.049	42.52	13.412	0.163	54.88	5.692
20	112.84	1.761	0.102	113.47	13.413	0.272	109.81	5.766
25	213.97	1.761	0.176	212.53	13.416	0.467	208.08	5.984
30	340.26	1.761	0.270	338.36	13.421	0.724	337.60	6.423

35	484.23	1.761	0.380	485.61	13.430	1.015	484.26	7.090
40	657.60	1.761	0.508	656.95	13.445	1.343	649.56	8.002
45	853.63	1.761	0.655	853.73	13.466	1.742	850.64	9.271
50	1066.11	1.761	0.814	1066.57	13.496	2.187	1074.90	10.820

Table A-2 contains the Part III contraction and pitot tube measurements together with the processed velocities used in the test-section calibration plot. The contraction pressure difference shown is the bias corrected micromanometer reading that is used by the MatLab analysis, and the listed velocity uncertainties correspond to the overall plotted error bars.

Table A-2 Part III contraction and pitot-tube measurements with processed velocities and uncertainties.

Fan setting (Hz)	Temperature used (°C)	Corrected contraction ΔP (in. H_2O)	Pitot signal (V)	Contraction V (m/s)	Pitot V (m/s)	Contraction δV (m/s)	Pitot δV (m/s)
15	28.624	0.187	0.054	9.26	9.40	0.176	1.281
20	28.818	0.462	0.107	14.57	14.69	0.114	0.820
25	29.087	0.933	0.178	20.71	19.67	0.086	0.614
30	29.437	1.400	0.269	25.38	24.63	0.078	0.492
35	29.794	1.859	0.378	29.27	29.50	0.075	0.413
40	30.284	2.603	0.508	34.66	34.44	0.076	0.357
45	30.964	3.252	0.655	38.78	39.30	0.079	0.317
50	31.810	4.081	0.815	43.51	44.02	0.084	0.288

Table A-3 contains the Part III static-port scannivalve measurements used to evaluate the test-section gage pressure. The three port voltages are retained as measured quantities, while the average calibrated gage pressure, propagated pressure uncertainty, velocity, and velocity uncertainty are the processed quantities used in the scannivalve results.

Table A-3 Part III scannivalve static-port measurements, processed gage pressure, velocity, and uncertainties.

Fan setting (Hz)	Port 0 output (V)	Port 1 output (V)	Port 2 output (V)	Average gage pressure (Pa)	Pressure uncertainty (Pa)	Scannivalve V (m/s)	Velocity uncertainty (m/s)
15	-0.035	-0.038	-0.049	-47.76	6.764	9.26	0.656
20	0.292	0.285	0.275	115.86	7.204	14.43	0.449

25	0.260	0.254	0.245	100.24	6.895	13.43	0.462
30	0.680	0.672	0.659	310.56	8.274	23.64	0.318
35	0.859	0.855	0.845	402.61	7.621	26.94	0.259
40	1.080	1.076	1.068	514.33	7.872	30.47	0.239
45	1.470	1.465	1.498	717.42	12.294	36.03	0.315
50	1.706	1.708	1.809	850.13	31.096	39.27	0.721

Appendix B: Sample Calculations

The following sample calculations use the measurements obtained at the wind tunnel fan setting of 30 Hz. The same calculation procedure was applied to the remaining fan settings.

Test Section Air Density.

At 30 Hz, the measured test section pressure and ambient pressure are

$$T = 29.437\ C \text{ and } P = 96.5\ kPa$$

The temperature was first converted to kelvin,

$$T = 29.437 + 273.15 = 302.587\ K$$

The ambient pressure was then converted to pascals,

$$P = (96.5)(1000) = 96{,}500\ Pa$$

Then, using the ideal gas relation $\rho = \frac{P}{RT}$, with R = 287.05 J/(Kg*K)

We obtain $\rho = \frac{96500}{(287.05)(302.587)} = 1.1110\ kg/m^3$

The density uncertainty was obtained using the pressure and temperature uncertainties of $\sigma_P = 100Pa$ and $\sigma_T = 1.0\ K$

So then, $$\sigma_P = \sqrt{\left(\frac{1}{RT}\sigma_P\right)^2 + \left(-\frac{P}{RT^2}\sigma_T\right)^2}$$

Substituting gives $$\sigma_P = \sqrt{\left(\frac{100}{(287.05)(302.587)}\right)^2 + \left(-\frac{96{,}500(1)}{287.05(302.587^2)}\right)^2} = 0.00385\ kg/m^3$$

Meaning that therefore, $\rho = 1.1110 \pm 0.0038\ kg/m^3$ at 30 Hz.

Appendix C: Code

```
%% AEE 360 Lab 1 - Wind Tunnel Calibration
% Part I: get lab air conditions and calculate density
% Part II: calibrate the pressure transducer and scannivalve with the manometer
% Part III: calculate test-section speed three different ways
%
% instrument uncertainties and tunnel contraction ratio came from
% the canvas chart

clear; clc; close all;

%% SECTION 0: constants, recorded values, and instrument info
```

```
R_specific  = 287.05;              % dry-air specific gas constant, J/(kg*K)
inH2O_to_Pa = 249.09;              % conversion from in. H2O to Pa
DPI         = 300;                 % save all figures at 300 dpi

% Part I values recorded during the lab
P_abs_kPa      = 96.17;            % kPa, absolute pressure reading
T_F            = 89;               % deg F, wind tunnel thermocouple reading
manometer_bias = 0.066;            % in. H2O, measured manometer zero offset

% Given instrument uncertainties from the machine error chart
% I typed these values in directly from the lab sheet.
% bcos hard coding the numbers here was more reliable than trying to parse them, i
%presume this is the correct method.
% These are the same supplied uncertainties used in the report.
sigma_P_abs_kPa   = 0.1;           % kPa, absolute pressure transducer
sigma_T_C         = 1.0;           % deg C, digital thermometer
sigma_V_trans     = 0.01;          % V, pressure transducer
sigma_manom_inH2O = 0.005;         % in. H2O, micromanometer
sigma_V_scanni    = 0.005;         % V, scannivalve

% Tunnel geometry from the machine error chart
% For the Blue tunnel, A1/A2 = 6.25.
% A1 is the larger settling chamber and A2 is the test section.
% The velocity equation later uses the opposite ratio,
% AR = A_test/A_settling, so AR = 1/6.25.
contraction_ratio = 6.25;                  % A_settling / A_test
AR                = 1/contraction_ratio;   % A_test / A_settling = 0.16

% The manometer reading and its zero bias measurement both have uncertainty,
% so both have to be included after the bias correction.
sigma_manom_corr_inH2O = sqrt(2) * sigma_manom_inH2O;
sigma_P_manom_Pa       = sigma_manom_corr_inH2O * inH2O_to_Pa;

%% SECTION 1: Part I - atmospheric pressure and density
T_C      = (T_F - 32) * 5/9;
T_K      = T_C + 273.15;
P_abs_Pa = P_abs_kPa * 1000;

rho = P_abs_Pa / (R_specific * T_K);

% Propagate the pressure and temperature uncertainty into rho
```

```
sigma_T_K  = sigma_T_C;                    % a 1 degC change is the same size as a 1 K
change
sigma_P_Pa = sigma_P_abs_kPa * 1000;

dRho_dP   = 1 / (R_specific * T_K);
dRho_dT   = -P_abs_Pa / (R_specific * T_K^2);
sigma_rho = sqrt( (dRho_dP*sigma_P_Pa)^2 + (dRho_dT*sigma_T_K)^2 );

fprintf('Part I, Atmospheric density\n');
fprintf('T   = %.2f K  +/- %.2f K\n', T_K, sigma_T_K);
fprintf('P   = %.0f Pa +/- %.0f Pa\n', P_abs_Pa, sigma_P_Pa);
fprintf('rho = %.4f +/- %.4f kg/m^3  (%.2f%%)\n\n', rho, sigma_rho,
100*sigma_rho/rho);

%% SECTION 2: Part II - pressure transducer and scannivalve calibration
T2 = readtable('Tue_A_600_Part_2.txt', 'FileType','text', 'Delimiter','\t');
assert(width(T2) == 8, 'Part 2 file has %d columns, expected 8.', width(T2));
hdr2 = T2.Properties.VariableDescriptions;      % keep the original headers for
Appendix A
T2.Properties.VariableNames = {'Hz','TempC','Manometer_inH2O','Transducer_V', ...
                               'Scanni_V','Port','Velocity_ref','P_amb_kPa'};

% For the transducer fit I only need one row per fan setting.
% The file repeats the transducer/manometer values for each scannivalve port,
% and counting those repeats as new points would make the fit statistics
% look better than they actually are.
[settings2, ia] = unique(T2.Hz, 'stable');
T2_trans = T2(ia,:);

manom_corr_inH2O = T2_trans.Manometer_inH2O - manometer_bias;
P_manom_Pa       = manom_corr_inH2O * inH2O_to_Pa;

% Fit 1: transducer voltage vs. manometer pressure
[m1, b1, R2_1, sigma_m1, sigma_b1] = linfit_with_unc(T2_trans.Transducer_V,
P_manom_Pa);

% Fit 2: scannivalve voltage vs. manometer pressure
manom_all_Pa = zeros(height(T2),1);
for k = 1:numel(settings2)
   manom_all_Pa(T2.Hz == settings2(k)) = P_manom_Pa(k);
end
[m2, b2, R2_2, sigma_m2, sigma_b2] = linfit_with_unc(T2.Scanni_V, manom_all_Pa);
```

```
fprintf('Part II: Calibration fits\n');
fprintf('Transducer : P = %.2f*V %+.2f   (R^2 = %.5f)\n', m1, b1, R2_1);
fprintf('Scannivalve: P = %.2f*V %+.2f   (R^2 = %.5f)\n', m2, b2, R2_2);

% Also check what the fits look like if they are forced through zero.
% I still use the normal fit later because the intercept represents a real zero offset
% and that offset matters a lot more at the lowpressure settings
[m1_op, sigma_m1_op] = linfit_zero_intercept(T2_trans.Transducer_V, P_manom_Pa);
[m2_op, sigma_m2_op] = linfit_zero_intercept(T2.Scanni_V, manom_all_Pa);
fprintf('Zero-intercept: transducer P = %.2f*V, scannivalve P = %.2f*V\n', m1_op,
m2_op);
fprintf('Intercepts as %% of max reading: transducer %.2f%%, scannivalve %.2f%%\n\n',
...
       100*abs(b1)/max(abs(P_manom_Pa)), 100*abs(b2)/max(abs(manom_all_Pa)));

USE_ZERO_INTERCEPT = false;
if USE_ZERO_INTERCEPT
   m1_use = m1_op; b1_use = 0; sigma_m1_use = sigma_m1_op; sigma_b1_use = 0;
   m2_use = m2_op; b2_use = 0; sigma_m2_use = sigma_m2_op; sigma_b2_use = 0;
else
   m1_use = m1; b1_use = b1; sigma_m1_use = sigma_m1; sigma_b1_use = sigma_b1;
   m2_use = m2; b2_use = b2; sigma_m2_use = sigma_m2; sigma_b2_use = sigma_b2;
end

% plot the pressure transducer calibration
figure('Color','w','Theme','light');
plot(T2_trans.Transducer_V, P_manom_Pa, 'ko', 'MarkerFaceColor','k'); hold on;
xf = linspace(min(T2_trans.Transducer_V), max(T2_trans.Transducer_V), 100);
plot(xf, m1*xf + b1, 'r-',  'LineWidth', 1.5);
plot(xf, m1_op*xf,   'b--', 'LineWidth', 1.5);
grid on; set(gca,'FontSize',12);
xlabel('Pressure Transducer Output (V)');
ylabel('Manometer Differential Pressure (Pa)');
title('Pressure Transducer Calibration');
legend('Measured data','Least-squares fit','Zero-intercept
fit','Location','northwest');
exportgraphics(gcf, 'Fig_TransducerCalibration.png', 'Resolution', DPI,
'BackgroundColor','white');

% plot the scanivalve calibration
figure('Color','w','Theme','light');
```

```
plot(T2.Scanni_V, manom_all_Pa, 'ko', 'MarkerFaceColor','k'); hold on;
xf2 = linspace(min(T2.Scanni_V), max(T2.Scanni_V), 100);
plot(xf2, m2*xf2 + b2, 'r-',  'LineWidth', 1.5);
plot(xf2, m2_op*xf2,   'b--', 'LineWidth', 1.5);
grid on; set(gca,'FontSize',12);
xlabel('Scannivalve Output (V)');
ylabel('Manometer Differential Pressure (Pa)');
title('Scannivalve Calibration');
legend('Measured data','Least-squares fit','Zero-intercept
fit','Location','northwest');
exportgraphics(gcf, 'Fig_ScannivalveCalibration.png', 'Resolution', DPI,
'BackgroundColor','white');

% Put the Part II results into Appendix Table A-1
sigma_P_trans_col = sqrt( (m1_use*sigma_V_trans).^2 +
(T2_trans.Transducer_V*sigma_m1_use).^2 + sigma_b1_use^2 );
scanni_by_set       = zeros(numel(settings2),1);
sigma_scanni_by_set = zeros(numel(settings2),1);
for k = 1:numel(settings2)
   v = T2.Scanni_V(T2.Hz == settings2(k));
   scanni_by_set(k) = mean(m2_use*v + b2_use);
   sigma_scanni_by_set(k) = sqrt( (m2_use*sigma_V_scanni)^2 + (mean(v)*sigma_m2_use)^2
+ sigma_b2_use^2 );
end

TableA1 = table(settings2, P_manom_Pa, sigma_P_manom_Pa*ones(size(P_manom_Pa)), ...
               m1_use*T2_trans.Transducer_V + b1_use, sigma_P_trans_col, ...
               scanni_by_set, sigma_scanni_by_set, ...
   'VariableNames', {'Hz','P_manometer_Pa','sigma_manometer_Pa', ...
                     'P_transducer_Pa','sigma_transducer_Pa', ...
                     'P_scannivalve_Pa','sigma_scannivalve_Pa'});
disp('Table A-1: Part II pressure readings and uncertainties');
disp(TableA1);
writetable(TableA1, 'TableA1_Part2_Pressures.csv');

%% SECTION 3: Part III empty test section speed calibration
T3 = readtable('Tue_A_600_Part_3.txt', 'FileType','text', 'Delimiter','\t');
assert(width(T3) == 8, 'Part 3 file has %d columns, expected 8.', width(T3));
hdr3 = T3.Properties.VariableDescriptions;      % keep the original headers for
Appendix A
T3.Properties.VariableNames = {'Hz','TempC','Manometer_inH2O','Transducer_V', ...
                               'Scanni_V','Port','Velocity_ref','P_amb_kPa'};
```

```
settings = unique(T3.Hz);
nSet     = numel(settings);

% Print the raw scannivalve voltage from each floor port for Appendix A
fprintf('Raw scannivalve voltages by port\n');
for i = 1:nSet
   sub = T3(T3.Hz == settings(i), :);
   fprintf('%5.1f Hz:', settings(i));
   for k = 1:height(sub)
       fprintf('   port %s = %8.4f V', string(sub.Port(k)), sub.Scanni_V(k));
   end
   fprintf('\n');
end
fprintf('\n');

[V_pitot, sigma_V_pitot, V_contraction, sigma_V_contraction, ...
V_scannivalve, sigma_V_scannivalve, P_gage_avg, sigma_P_gage_avg, ...
dP_contraction, sigma_dP_contraction, q_pitot, sigma_q_pitot, ...
rho_set, sigma_rho_set, T_set] = deal(zeros(nSet,1));

for i = 1:nSet
   sub = T3(T3.Hz == settings(i), :);

   % Recalculate air density for this fan setting
   T_local_K  = sub.TempC(1) + 273.15;
   P_local_Pa = sub.P_amb_kPa(1) * 1000;
   rho_local  = P_local_Pa / (R_specific * T_local_K);

   dr_dP = 1/(R_specific*T_local_K);
   dr_dT = -P_local_Pa/(R_specific*T_local_K^2);
   sigma_rho_local = sqrt( (dr_dP*sigma_P_Pa)^2 + (dr_dT*sigma_T_C)^2 );

   rho_set(i) = rho_local; sigma_rho_set(i) = sigma_rho_local; T_set(i) = T_local_K;

   % Method 1: pitot tube using the pressure transducer
   Vt = sub.Transducer_V(1);
   q  = m1_use*Vt + b1_use;
   sigma_q = sqrt( (m1_use*sigma_V_trans)^2 + (Vt*sigma_m1_use)^2 + sigma_b1_use^2 );
   [Vp, sVp] = velocity_from_q(q, sigma_q, rho_local, sigma_rho_local);
   q_pitot(i) = q; sigma_q_pitot(i) = sigma_q;
   V_pitot(i) = Vp; sigma_V_pitot(i) = sVp;
```

```
   % Method 2: static-pressure drop across the contraction
   dP = (sub.Manometer_inH2O(1) - manometer_bias) * inH2O_to_Pa;
   dP_contraction(i) = dP; sigma_dP_contraction(i) = sigma_P_manom_Pa;
   [Vc, sVc] = velocity_from_contraction(dP, sigma_P_manom_Pa, rho_local,
sigma_rho_local, AR);
   V_contraction(i) = Vc; sigma_V_contraction(i) = sVc;

   % Method 3: test-section floor static ports using the scannivalve
   % Include the port-to-port spread in the uncertainty along with instrument error.
   % I cannot really prove what causes the spread from this data alone.
   % Ports 0 > 1 > 2 from 15-40 Hz, but that order flips at 45 and 50 Hz,
   % so it does not look like a simple streamwise pressure gradient.
   p_gage = m2_use*sub.Scanni_V + b2_use;
   p_avg  = mean(p_gage);
   sigma_inst = sqrt( (m2_use*sigma_V_scanni)^2 + (mean(sub.Scanni_V)*sigma_m2_use)^2
+ sigma_b2_use^2 );
   if numel(p_gage) > 1
       sigma_spatial = std(p_gage);
   else
       sigma_spatial = 0;
   end
   sigma_p_avg = sqrt(sigma_inst^2 + sigma_spatial^2);

   % Use the magnitude of the average test-section gage pressure for the velocity
calculation.
   % That gives |p_gage| = 0.5*rho*V^2, while the actual measured sign is still saved
   % in Table A-3. The tunnel fan setup would need to be confirmed before making
   % any physical interpretation of the pressure sign.
   [Vs, sVs] = velocity_from_q(abs(p_avg), sigma_p_avg, rho_local, sigma_rho_local);
   P_gage_avg(i) = p_avg; sigma_P_gage_avg(i) = sigma_p_avg;
   V_scannivalve(i) = Vs; sigma_V_scannivalve(i) = sVs;
end

fprintf('Part III: Test-section velocity, three methods\n');
fprintf('%6s %16s %16s %16s %10s\n','Hz','V_pitot [m/s]','V_contr [m/s]','V_scanni
[m/s]','max %diff');
for i = 1:nSet
   v = [V_pitot(i) V_contraction(i) V_scannivalve(i)];
   spread = 100*(max(v)-min(v))/mean(v);
   fprintf('%6.1f  %7.3f+/-%-6.3f %7.3f+/-%-6.3f %7.3f+/-%-6.3f %9.2f\n', settings(i),
...
```

```
       V_pitot(i), sigma_V_pitot(i), V_contraction(i), sigma_V_contraction(i), ...
       V_scannivalve(i), sigma_V_scannivalve(i), spread);
end
fprintf('\n');

% Plot all three velocity calibration methods together
figure('Color','w','Theme','light');
errorbar(settings, V_pitot,       sigma_V_pitot,       'ko', 'MarkerFaceColor','k',
'LineStyle','none'); hold on;
errorbar(settings, V_contraction, sigma_V_contraction, 'bs', 'MarkerFaceColor','b',
'LineStyle','none');
errorbar(settings, V_scannivalve, sigma_V_scannivalve, 'r^', 'MarkerFaceColor','r',
'LineStyle','none');
xf3 = linspace(min(settings), max(settings), 100);
p_p = polyfit(settings, V_pitot, 1);
p_c = polyfit(settings, V_contraction, 1);
p_s = polyfit(settings, V_scannivalve, 1);
plot(xf3, polyval(p_p,xf3), 'k-', xf3, polyval(p_c,xf3), 'b-', xf3, polyval(p_s,xf3),
'r-');
grid on; set(gca,'FontSize',12);
xlabel('Wind Tunnel Fan Setting (Hz)');
ylabel('Test Section Velocity (m/s)');
title('Empty Test Section Velocity Calibration');
legend('Pitot tube','Contraction','Scannivalve','Location','northwest');
exportgraphics(gcf, 'Fig_VelocityCalibration.png', 'Resolution', DPI,
'BackgroundColor','white');
fprintf('Velocity-vs-setting slopes [m/s per Hz]: pitot %.4f, contraction %.4f,
scannivalve %.4f\n\n', ...
       p_p(1), p_c(1), p_s(1));

% separate uncertainty plot for each velocity method (from rubric 4d)
make_error_plot(settings, V_pitot,       sigma_V_pitot,       'k','o', ...
   'Test Section Velocity Uncertainty, Pitot Tube Method', 'Fig_Error_Pitot.png',
DPI);
make_error_plot(settings, V_scannivalve, sigma_V_scannivalve, 'r','^', ...
   'Test Section Velocity Uncertainty, Scannivalve Method',
'Fig_Error_Scannivalve.png', DPI);
make_error_plot(settings, V_contraction, sigma_V_contraction, 'b','s', ...
   'Test Section Velocity Uncertainty, Contraction Method', 'Fig_Error_Manometer.png',
DPI);

% Write out the Appendix A tables
```

```
TableA2 = table(settings, T_set, rho_set, sigma_rho_set, ...
               dP_contraction, sigma_dP_contraction, q_pitot, sigma_q_pitot, ...
               V_pitot, sigma_V_pitot, V_contraction, sigma_V_contraction, ...
   'VariableNames', {'Hz','T_K','rho_kgm3','sigma_rho_kgm3', ...
                     'dP_contraction_Pa','sigma_dP_contraction_Pa', ...
                     'q_pitot_Pa','sigma_q_pitot_Pa', ...
                     'V_pitot_ms','sigma_V_pitot_ms', ...
                     'V_contraction_ms','sigma_V_contraction_ms'});
disp('Table A-2: Contraction and pitot tube measurements with uncertainties');
disp(TableA2);
writetable(TableA2, 'TableA2_Part3_ContractionPitot.csv');

TableA3 = table(settings, P_gage_avg, sigma_P_gage_avg, V_scannivalve,
sigma_V_scannivalve, ...
   'VariableNames', {'Hz','P_gage_avg_Pa','sigma_P_gage_avg_Pa', ...
                     'V_scannivalve_ms','sigma_V_scannivalve_ms'});
disp('Table A-3: Test section static gage pressure from scannivalve floor ports');
disp(TableA3);
writetable(TableA3, 'TableA3_Part3_Scannivalve.csv');

fprintf('\nDone. Figures exported at %d dpi, tables written to .csv.\n', DPI);

%% Helper functions
function [m, b, R2, sigma_m, sigma_b] = linfit_with_unc(x, y)
   % Regular least-squares line fit y = m*x + b, including slope/intercept uncertainty
   % (MAE 384 actually coming in handy here)
   x = x(:); y = y(:);
   n = length(x);
   p = polyfit(x, y, 1);
   m = p(1); b = p(2);
   resid   = y - (m*x + b);
   SSresid = sum(resid.^2);
   SStotal = sum((y - mean(y)).^2);
   R2 = 1 - SSresid/SStotal;
   s2  = SSresid / (n - 2);              % residual variance with 2 fitted parameters
   Sxx = sum((x - mean(x)).^2);
   sigma_m = sqrt(s2 / Sxx);
   sigma_b = sqrt(s2 * (1/n + mean(x)^2/Sxx));
end

function [m, sigma_m] = linfit_zero_intercept(x, y)
   % Same least-squares idea, except this fit is forced through the origin
```

```
    x = x(:); y = y(:);
    n = length(x);
    m = sum(x.*y) / sum(x.^2);
    resid = y - m*x;
    s2 = sum(resid.^2) / (n - 1);          % only 1 fitted parameter here
    sigma_m = sqrt(s2 / sum(x.^2));
end

function [V, sigma_V] = velocity_from_q(q, sigma_q, rho, sigma_rho)
    % Convert dynamic pressure to velocity and carry the uncertainty through
    V = sqrt(2*q/rho);
    dV_dq   = 1/(rho*V);
    dV_drho = -V/(2*rho);
    sigma_V = sqrt( (dV_dq*sigma_q)^2 + (dV_drho*sigma_rho)^2 );
end

function [V, sigma_V] = velocity_from_contraction(dP, sigma_dP, rho, sigma_rho, AR)
    % Bernoulli + continuity across the contraction gives
    % dP = 0.5*rho*V_test^2*(1 - AR^2), with AR = A_test/A_settling,
    % so solve that for V_test here.
    k = 1 - AR^2;
    V = sqrt(2*dP/(rho*k));
    dV_ddP  = 1/(rho*k*V);
    dV_drho = -V/(2*rho);
    sigma_V = sqrt( (dV_ddP*sigma_dP)^2 + (dV_drho*sigma_rho)^2 );
end

function make_error_plot(x, y, err, col, mkr, ttl, fname, dpi)
    figure('Color','w','Theme','light');
    errorbar(x, y, err, [col mkr], 'MarkerFaceColor', col, 'LineStyle','none'); hold
on;
    xf = linspace(min(x), max(x), 100);
    plot(xf, polyval(polyfit(x, y, 1), xf), [col '-']);
    grid on; set(gca,'FontSize',12);
    xlabel('Wind Tunnel Fan Setting (Hz)');
    ylabel('Test Section Velocity (m/s)');
    title(ttl);
    exportgraphics(gcf, fname, 'Resolution', dpi, 'BackgroundColor','white');
end
```

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