

Airflow Measurement Accuracy

Energy Cost Savings

Buildings annually consume more than 30% of the total energy and more than 60% of the electricity used in the United States.¹ The energy required to run the heating ventilation and air conditioning (HVAC) system constitutes about half of a buildings' energy cost.² Therefore, reducing energy consumption often means paying closer attention to the equipment running the HVAC system.

Indoor Air Quality

The potential annual savings and productivity gains from improved indoor air quality (IAQ) in the United States are estimated as high as \$14 billion from reduced respiratory disease, \$4 billion from reduced allergies and asthma, \$30 billion from reduced sick building syndrome, and \$160 billion from direct improvements in worker performance that are unrelated to health.¹ Therefore, modest investments toward improved IAQ would generate substantial returns.²



Issues

- Transducer Accuracy
- Transducer Span Selection
- Analog to Digital Signal Conversion
- Combining Errors
- Additional Sources of Error

How Much Could You Be Saving?

Accurately measuring and controlling the outdoor air intake flow rate and building pressure are options that should be considered for reducing HVAC energy consumption and improving IAQ.

Using high accuracy outdoor airflow measurement systems minimizes energy costs associated with conditioning ventilation air. Ventilation air is used to dilute and remove common sources of indoor contaminants, and strategies to improve IAQ have been proven to reduce costs associated with sick leave, health care, and loss of productivity; reduce liability associated with sick building syndrome; and increase the building resale value.

Control strategies such as volumetric (fan) tracking that utilize high accuracy supply and return airflow measurement systems to maintain a slightly positive building pressure minimizes energy costs associated with negative building pressure problems such as added perimeter heating loads that must be compensated for using energy from a boiler or electric reheat system and reduced return fan energy consumption since the return fan moves less air. Costs associated with poor IAQ due to infiltration of common sources of outdoor contaminants and moisture buildup causing mold growth inside buildings arising from condensation due to infiltration of water vapor (humidity) can also be reduced. Overly pressurized buildings can also waste energy if an excessive amount of conditioned air is exfiltrated; cause building security issues by not allowing exterior doors to close properly; and exert excessive force on building seals leading to premature sealant failures.

Airflow measurement systems used for ventilation rate control or volumetric tracking to control building pressure require a primary element to measure the flow and a transducer to convert the raw signal to velocity. The preferred method of measuring airflow is the Pitot-tube; the primary standard which most other technologies are tested against.³ Pitot-tube arrays have an accuracy of $\pm 2\%$.⁴ However, the overall airflow measurement accuracy is only as good as the transducer being used to interpret the differential between the total and static pressures measured by the Pitot-tube array. Transducer accuracies must be examined to insure that adequate tolerances are maintained. Most transducers accuracies are rated as a percent of full scale (F.S) span; the larger the span, the greater the inaccuracy. Therefore, transducers should be ranged based on the design maximum velocity plus 10% to allow for field adjustment. To reduce error, the square root function of converting the measured velocity pressure into velocity should also be done prior to analog-to-digital signal conversion. Additional sources of error include transducer drift for low velocity applications, changes in air density associated with ventilation rate control in climates with large temperature variances, and signal noise. The following is a detailed look at each of these potential sources of error.

Transducer Accuracy

Transducer accuracy is the conformity of an indicated value to an accepted standard value and is expressed as a percentage of the transducers F.S. span. However, what we should be concerned with is what the accuracy will be when expressed as a percentage of reading.

Many engineers specify ±1% F.S. accuracy transducers. However a ±1% F.S. accuracy transducer provided for low velocity or variable air volume (VAV) applications can introduce significant error. The following example shows how to calculate error as a percent of reading in terms of velocity. Figure 1 on the following page shows the potential error associated with turndown.

Example 1

At standard conditions the velocity pressure at a velocity of 500 fpm equals 0.0156 inches of water column (in. wc). For an application with a F.S. velocity of 2,000 fpm using a transducer with a ±1% F.S. accuracy and a 0.25 in. wc F.S. span, the percent error of reading at a velocity of 500 fpm (4:1 turndown) would equal:

$$Error_{P_v} = \frac{F.S. Accuracy \times F.S. Span}{P_v} \times 100\% = \frac{0.01 \times 0.25}{0.0156} \times 100 \approx 16\% Error$$

This error is in terms of velocity pressure. To calculate error as a percent of reading in terms of velocity, the velocity pressure needs to be converted to velocity. At standard conditions the equation for converting velocity pressure to velocity is:

$$V = 4005 \times \sqrt{P_v}$$

To calculate the actual velocity based on the velocity pressure error the above equation becomes:

$$V_{actual} = 4005 \times \sqrt{P_v \pm P_v \times Error_{P_v}} = 4005 \times \sqrt{0.0156 \pm 0.0156 \times 0.16}$$

For a positive error the actual velocity equals 539 fpm and for a negative error the actual velocity equals 458 fpm. The error as a percent of reading in terms of velocity is:

$$Positive Error_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(539 - 500)}{500} \times 100 \approx 7.8\% Error$$

$$Negative Error_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(458 - 500)}{500} \times 100 \approx -8.4\% Error$$

When the accuracy is stated in terms of F.S. span, it is impossible to state a single value for the transducer accuracy in terms of reading.

Paragon Controls Inc. (PCI) developed the MicroTrans Airflow Signal Processor using current state-of-the-art digital microprocessor technology with an unequaled 20-bit (1,048,576 steps) analog-to-digital converter (ADC) capable of producing overall ±0.1% accuracy. The high degree of accuracy even under very low turndowns is achieved by using a 20 bit ADC (0.000005vdc/step), selecting an extremely stable and repeatable pressure sensor, and performing calibration utilizing multi point linearization of the pressure sensor.

The following example shows how to calculate error as a percent of reading in terms of velocity using the MicroTrans. Figure 2 shows the potential error associated with turndown.

Example 2

For an application with a F.S. velocity of 2,000 fpm using the MicroTrans with a ±0.1% F.S. accuracy and a 0.25 in. wc F.S. span, the percent error of reading at a velocity of 500 fpm (4:1 turndown) would equal:

$$V_{actual} = V_{theoretical} \pm V_{F.S.} \times F.S. Accuracy = 500 \pm 2,000 \times 0.001$$

For a positive error the actual velocity equals 502 fpm and for a negative error the actual velocity equals 498 fpm. The error as a percent of reading in terms of velocity is:

$$Positive Error_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(502 - 500)}{500} \times 100 \approx 0.4\% Error$$

$$Negative Error_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(498 - 500)}{500} \times 100 \approx -0.4\% Error$$

FIGURE 1

Figure 1

Utilization of differential pressure transducers with ±1% full scale accuracies has been the weakness of Pitot-tube airflow measurement and is why statements were made that velocities below 600 fpm should be avoided. Using a differential pressure transducer with ±1% F.S. accuracy may result in over ±7.8% error when operating the system at 500 fpm (4:1 turndown) and over ±42% error when operating the system at 200 fpm (10:1 turndown).

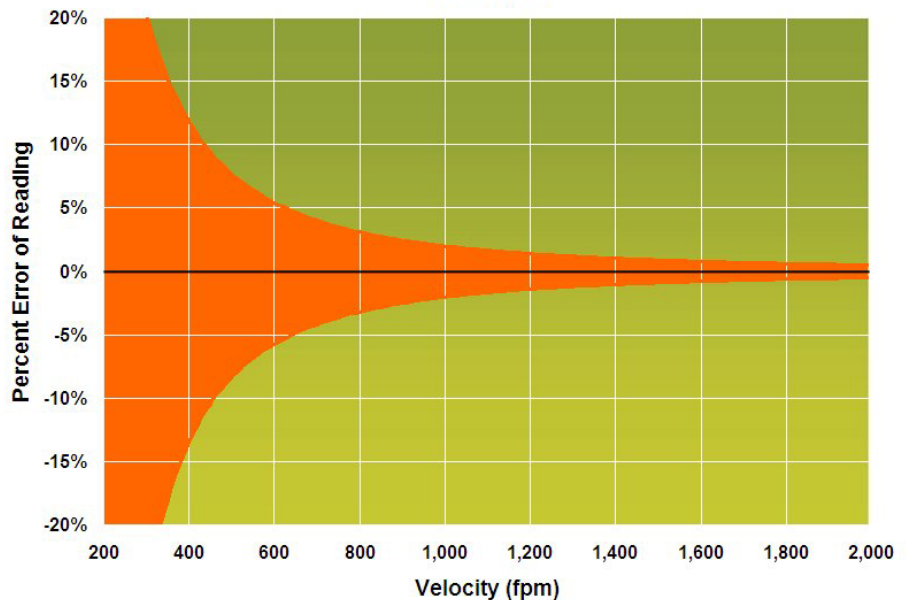
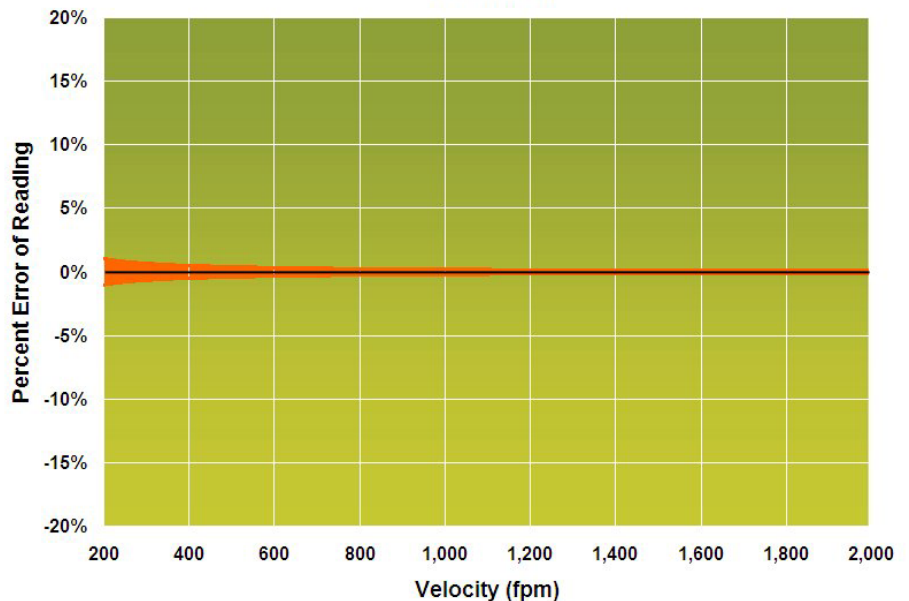


FIGURE 2

Figure 2

Today's highly accurate differential pressure sensing cells coupled microprocessor technologies has made it possible to provide accurate low velocity airflow measurement utilizing Pitot-tube arrays and to apply this type of measurement for the continuous monitoring and controlling of low velocity applications such as minimum outdoor air ventilation rates and for VAV control. The potential error is only ±0.4% when operating the system at 500 fpm (4:1 turndown) and only ±1% when operating the system at 200 fpm (10:1 turndown).



Transducer Span Selection

Transducer span is the algebraic difference between the upper and lower range values. For differential pressure transducers this value is expressed in terms of in. wc, which represents the measured velocity pressure. It is very common in our industry to find incorrect transducer spans being applied to a given measurement application. Figures 3 and 4 illustrate the control signal error resulting from the incorrect transducer span selection of 0.5 and 1.0 in. wc, respectively for an application having a F.S. velocity of 2,000 fpm. Both figures are based on $\pm 1\%$ transducer accuracy. The equations used in Example 1 can be used to calculate the error as a percent of reading in terms of velocity by changing the value for the F.S. span from 0.25 to 0.5 and 1.0 in. wc. As illustrated, the potential error is significantly increased from the error shown in Figure 1 which was for a correct transducer span selection of 0.25 in. wc.

FIGURE 3

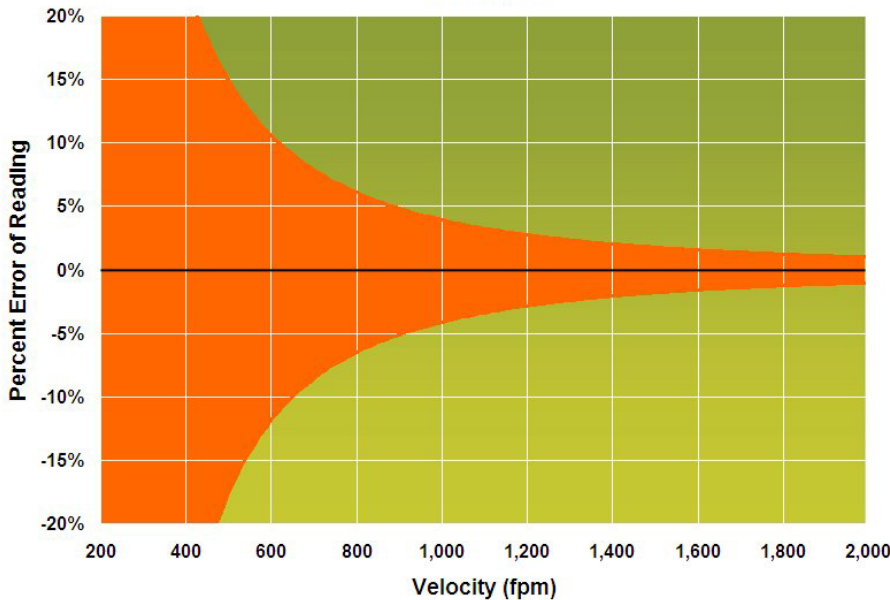


Figure 3

Using a transducer with $\pm 1\%$ F.S. accuracy and incorrectly selecting a transducer span of 0.5 in. wc may result in over $\pm 15\%$ error when operating the system at 500 fpm (4:1 turndown) and over $\pm 73\%$ error when operating the system at 200 fpm (10:1 turndown).

FIGURE 4

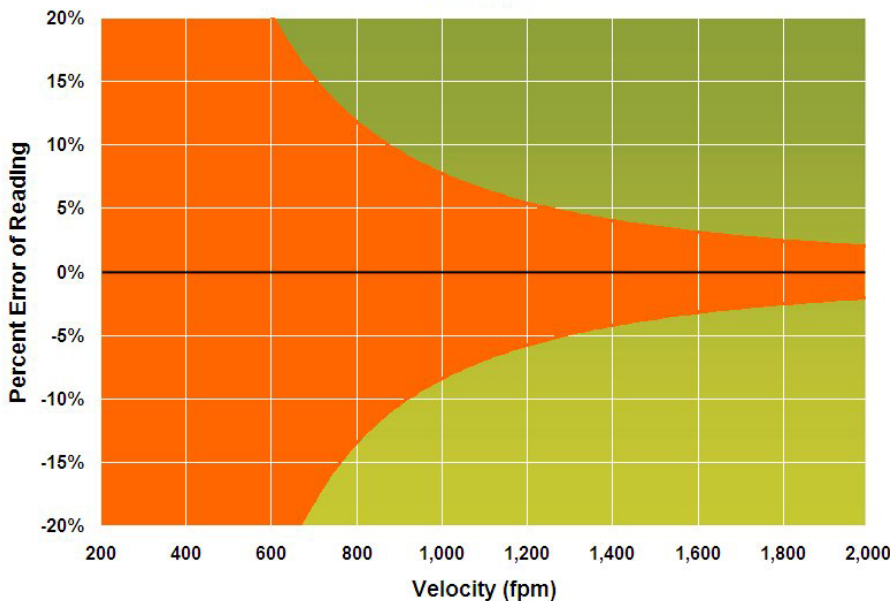


Figure 4

Using a transducer with $\pm 1\%$ F.S. accuracy and incorrectly selecting a transducer span of 1.0 in. wc may result in over $\pm 28\%$ error when operating the system at 500 fpm (4:1 turndown) and over $\pm 124\%$ error when operating the system at 200 fpm (10:1 turndown).

Analog to Digital Signal Conversion

An ADC is used to transform the analog voltage or current output of the transducer to the digital language of computers (a series of 1's and 0's called binary numbers). The number of binary digits (bits) that represents the digital number determines the ADC resolution. However, the digital number is only an approximation of the true value of the transducers analog output at a particular instant because the voltage or current can only be represented (digitally) in discrete steps. For example, a 10-bit ADC has a resolution of one part in 1,024 steps, where $2^{10} = 1,024$. Thus, a 10-bit ADC with a maximum input of 10 VDC can resolve the measurement into 10 VDC/1,024 steps= 0.00977 VDC/step. The resolution is usually specified with respect to the full-range reading of the ADC, not with respect to the measured value at any particular instant.⁵ The following example shows how to calculate error as a percent of reading in terms of velocity for a 10-bit ADC resolving a 0-10 VDC output from a differential pressure transducer. Figure 5 shows the potential error associated with turndown.

Example 3

In this example we assume that the accuracy of the ADC equals its specified resolution. However, most ADCs are not as accurate as their specified resolution because other errors contribute to the overall error such as gain, linearity, missing codes, and offset. Nonetheless, the accuracy of a good ADC should approach its specified resolution.⁵ At standard conditions the velocity pressure at a velocity of 500 fpm equals 0.0156 in. wc. For an application with a F.S. velocity of 2,000 fpm using a differential pressure transducer with a 0.25 in. wc F.S. span, the percent error of reading for a 10-bit ADC resolving the 0-10 VDC analog output of the transducer at a velocity of 500 fpm (4:1 turndown) would equal:

$$Error_{P_v} = \frac{ADC \text{ Resolution} \times F.S. \text{ Span}}{ADC \text{ Max Input} \times P_v} \times 100\% = \frac{0.00977 \times 0.25}{10 \times 0.0156} \times 100 \approx 1.6\% \text{ Error}$$

This error is in terms of velocity pressure. To calculate error as a percent of reading in terms of velocity, the velocity pressure needs to be converted to velocity. At standard conditions the equation for converting velocity pressure to velocity is:

$$V = 4005 \times \sqrt{P_v}$$

To calculate the actual velocity based on the velocity pressure error the above equation becomes:

$$V_{actual} = 4005 \times \sqrt{P_v \pm P_v \times Error_{P_v}} = 4005 \times \sqrt{0.0156 \pm 0.0156 \times 0.0157}$$

For a positive error the actual velocity equals 504 fpm and for a negative error the actual velocity equals 496 fpm. The error as a percent of reading in terms of velocity is:

$$Positive \ Error_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(504 - 500)}{500} \times 100 \approx 0.8\% \text{ Error}$$

$$Negative \ Error_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(496 - 500)}{500} \times 100 \approx -0.8\% \text{ Error}$$

The error associated with 4:1 turndown for a 10-bit ADC resolving the 0-10 VDC analog output of the differential pressure transducer does not seem significant. However, for systems operating at 200 fpm (10:1 turndown) the error may be over $\pm 4.8\%$.

Additionally, if the differential pressure transducer is spanned incorrectly the error associated with the ADC at 500 fpm (4:1 turndown) becomes significant. For example, the error as a percent of reading in terms of velocity that results from a 10-bit ADC resolving a 0-10 VDC output from a differential pressure transducer having an incorrect full scale span of 1.0 in. wc. at a velocity of 500 fpm may be over $\pm 3\%$. Figure 6 shows the potential error associated with turndown for this application

FIGURE 5

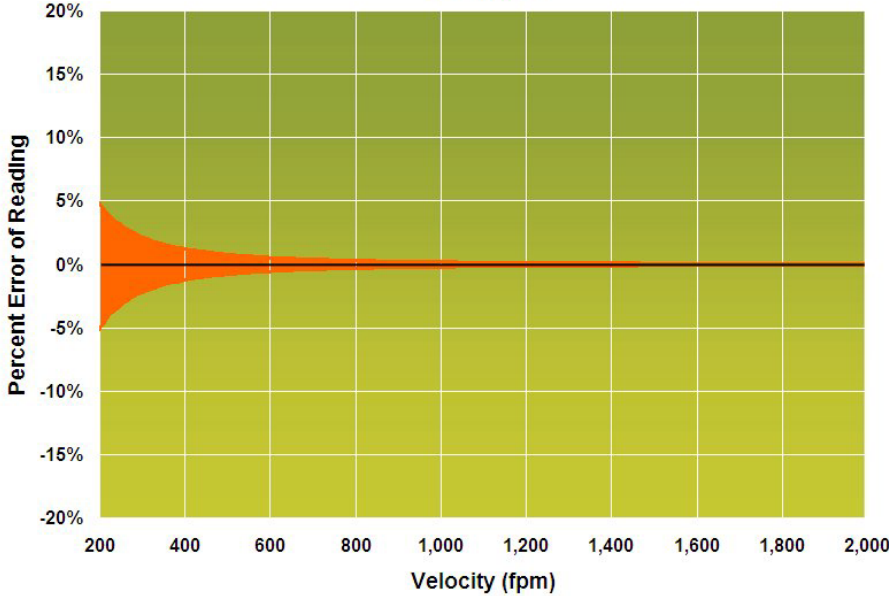


Figure 5

Using a 10-bit ADC to resolve the 0-10 VDC analog output of a differential pressure transducer having a F.S. span of 0.25 in. wc may result in over $\pm 0.8\%$ error when operating the system at 500 fpm (4:1 turndown) and over $\pm 4.8\%$ error when operating the system at 200 fpm (10:1 turndown).

FIGURE 6

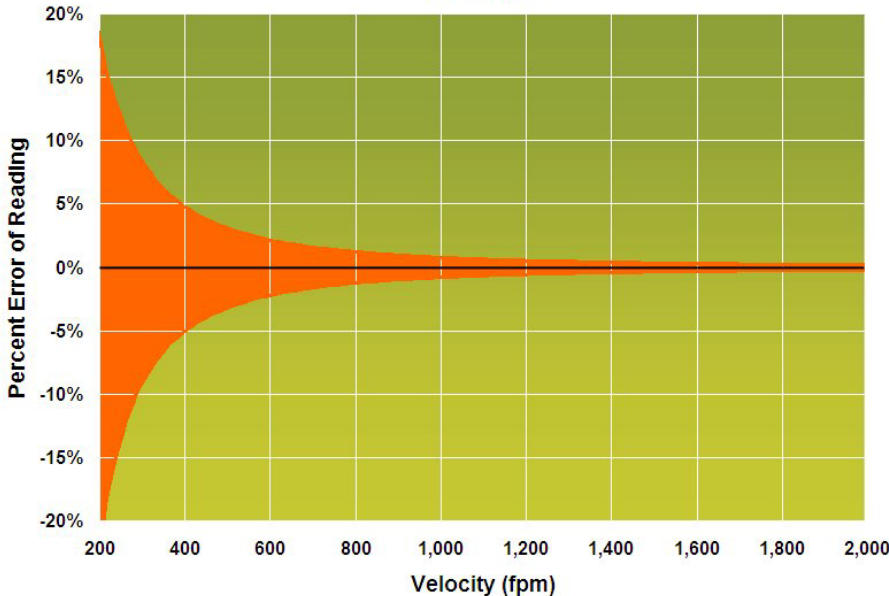


Figure 6

Using a 10-bit ADC to resolve the 0-10 VDC analog output of a differential pressure transducer having an incorrect span of 1.0 in. wc may result in over $\pm 3\%$ error when operating the system at 500 fpm (4:1 turndown) and over $\pm 18\%$ error when operating the system at 200 fpm (10:1 turndown).

Another important fact is that the percent error of reading associated with an ADC transforming the signal from a differential pressure transducer is larger than the percent error of reading associated with an ADC transforming the signal from a flow transducer (such as PCI's MicroTrans or FT Series) because the output of a differential pressure transducer is linear to velocity pressure whereas the output of a flow transducer is linear to velocity. The following example shows how to calculate error as a percent of reading in terms of velocity for a 10-bit ADC resolving a 0-10 VDC output from a flow transducer. Figure 7 shows the potential error associated with turndown.

Example 4

For an application with a F.S. velocity of 2,000 fpm using a flow transducer with a 0.25 in. wc F.S. span, the percent error of reading for a 10-bit ADC resolving the 0-10 VDC analog output of the transducer at a velocity of 500 fpm (4:1 turndown) would equal:

$$V_{actual} = V_{theoretical} \pm V_{F.S.} \times ADC \text{ Resolution} = 500 \pm 2,000 \times 0.00977$$

For a positive error the actual velocity equals 502 fpm and for a negative error the actual velocity equals 498 fpm. The error as a percent of reading in terms of velocity is:

$$Positive \text{ Error}_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(502 - 500)}{500} \times 100 \approx 0.4\% \text{ Error}$$

$$Negative \text{ Error}_V = \frac{(V_{actual} - V_{theoretical})}{V_{theoretical}} \times 100\% = \frac{(498 - 500)}{500} \times 100 \approx -0.4\% \text{ Error}$$

FIGURE 7

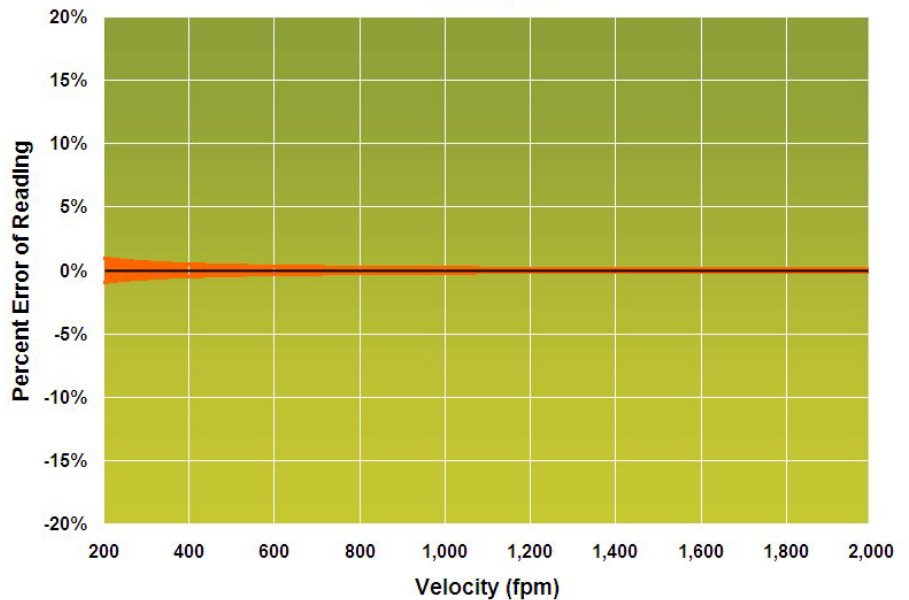


Figure 7

Using a 10-bit ADC to resolve the 0-10 VDC analog output of a flow transducer having a F.S. span of 0.25 in. wc, the potential error is only $\pm 0.4\%$ when operating the system at 500 fpm (4:1 turndown) and only $\pm 1\%$ when operating the system at 200 fpm (10:1 turndown).

Comparing Figures 5 and 7 illustrates why the square root function of converting the measured velocity pressure into velocity should be done prior to the ADC transforming the analog voltage or current output of the transducer. This is why using a flow transducer (such as PCI's MicroTrans or FT series) improves the overall airflow measurement accuracy instead of using a commercial differential pressure transducer and having the direct digital controller (DDC) or building automation system (BAS) do the square root function after the ADC has transformed the signal.

Combining Errors

A very important fact is that the error associated with the above issues (transducer accuracy, transducer span selection, and analog to digital signal conversion) are compounding. The root-sum-square method can be used to determine the overall airflow measurement system error:

$$Total\ Error = \sqrt{E_{Pitot}^2 + E_{Transducer}^2 + E_{ADC}^2}$$

Where:

$$E_{Pitot} = Error\ of\ the\ Pitot-tube\ Array = \pm 2\%$$

$$E_{Transducer} = Error\ From\ Transducer\ Accuracy\ \&\ Span\ Selection$$

$$E_{ADC} = Error\ From\ ADC\ Resolution$$

Many control contractors will use a $\pm 1\%$ F.S. accuracy differential pressure transducers to convert the raw signal from the Pitot-tube array to velocity pressure and have the DDC or BAS do the square root function after the ADC has transformed the signal. As stated above, it is very common in our industry to find incorrect transducer spans being applied to a given measurement application, such as a 1.0 in. wc F.S span used for an application with a F.S. velocity of 2,000 fpm. Figure 8 was created to show the possible airflow measurement error associated with this application.

FIGURE 8

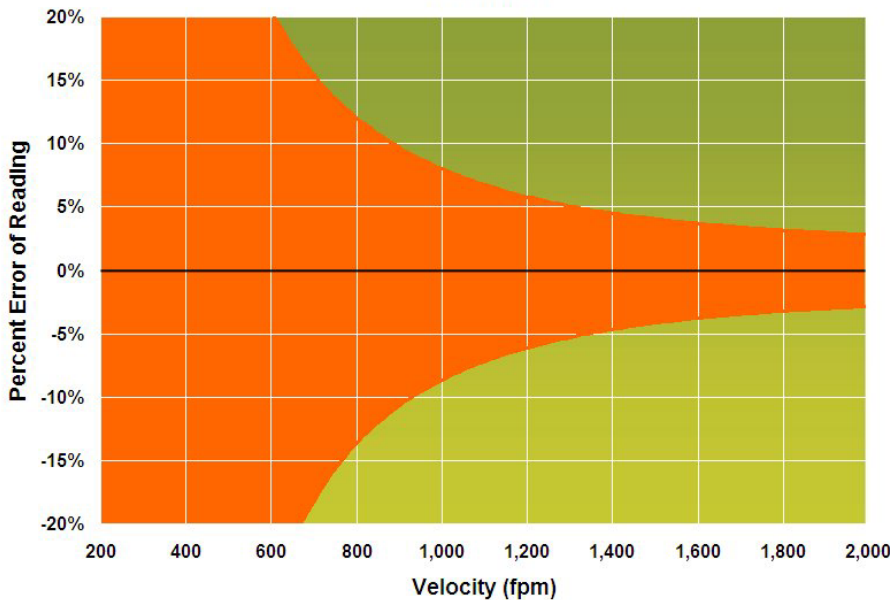


Figure 8

Figure 8 shows the total error for an airflow measurement system consisting of a duct mounted Pitot-tube array, a differential pressure transducer with a $\pm 1\%$ F.S. accuracy and 1.0 in. wc F.S. span, using a 10-bit ADC to transform the signal. This application may result in over $\pm 28\%$ error when operating the system at 500 fpm (4:1 turndown) and over $\pm 125\%$ error when operating the system at 200 fpm (10:1 turndown).

Using PCI's FT series flow transducers with a $\pm 0.5\%$ F.S. accuracy and a 0.25 in. wc F.S span can greatly reduce the error associated with turndown as shown in Figures 9; the possible error is reduced from $\pm 28\%$ to $\pm 4.5\%$ when operating the system at 500 fpm (4:1 turndown) and from $\pm 125\%$ to $\pm 23\%$ when operating the system at 200 fpm (10:1 turndown). PCI's MicroTrans with a $\pm 0.1\%$ F.S. accuracy and a 0.25 in. wc F.S span should be utilized to minimize the error associated with turndown as shown in Figure 10; the possible error is reduced from $\pm 28\%$ to only $\pm 2\%$ when operating the system at 500 fpm (4:1 turndown) and from $\pm 125\%$ to only $\pm 2.4\%$ when operating the system at 200 fpm (10:1 turndown). Using PCI's MicroTrans as part of the outdoor airflow measurement system or building pressurization control system can significantly reduce energy consumption associated with conditioning ventilation air and maintaining positive building pressure as well as improve IAQ leading to potential gains from reduced illness and liability and increased productivity.

FIGURE 9

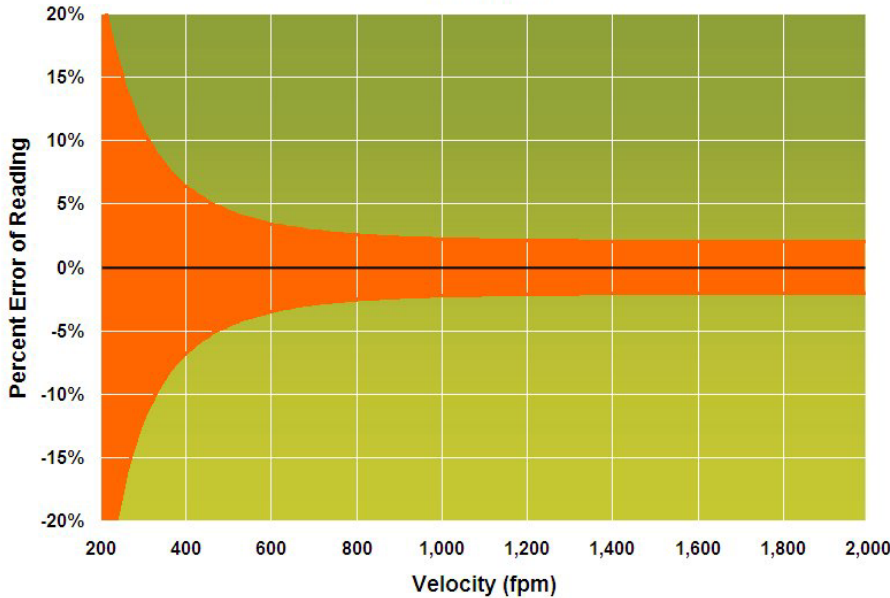


Figure 9

Figure 9 shows the total error for an airflow measurement system consisting of a duct mounted Pitot-tube array, PCI's FT Series flow transducer with a $\pm 0.5\%$ F.S. accuracy and 0.25 in. wc F.S. span, using a 10-bit ADC to transform the signal. The possible error is reduced to $\pm 4.5\%$ when operating the system at 500 fpm (4:1 turndown) and $\pm 2.3\%$ when operating the system at 200 fpm (10:1 turndown).

FIGURE 10

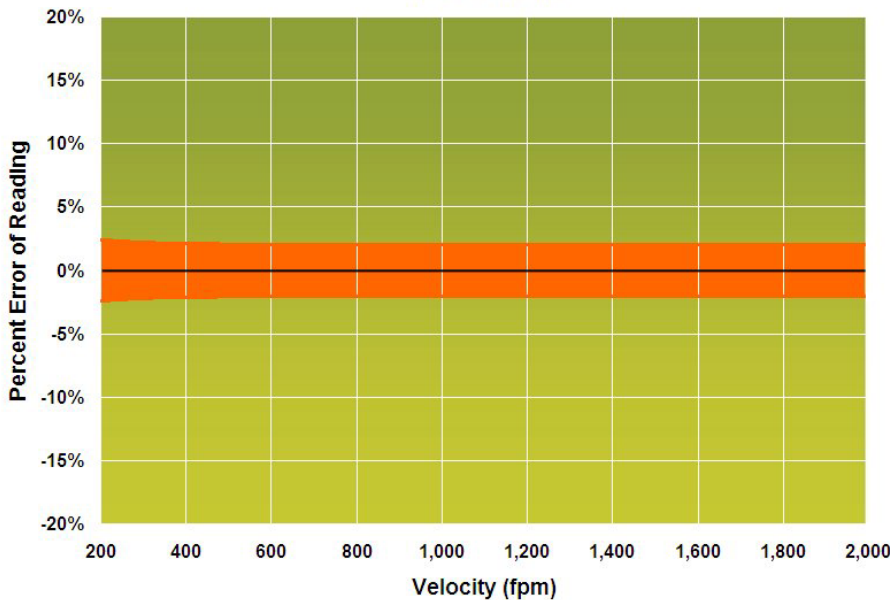


Figure 10

Figure 10 shows the total error for an airflow measurement system consisting of a duct mounted Pitot-tube array, PCI's MicroTrans airflow signal processor with a $\pm 0.1\%$ F.S. accuracy and 0.25 in. wc F.S. span, using a 10-bit ADC to transform the signal. The possible error is reduced to $\pm 2\%$ when operating the system at 500 fpm (4:1 turndown) and $\pm 2.4\%$ when operating the system at 200 fpm (10:1 turndown).

Additional Sources of Error

For VAV systems the overall airflow measurement accuracy is also affected by transducer drift. For the continuous monitoring and controlling of minimum outdoor air ventilation rates, the overall airflow measurement accuracy is also affected by air density changes from summer to winter months. Signal noise also affects the airflow measurement accuracy for all applications. Each of these is discussed below.

Transducer Drift

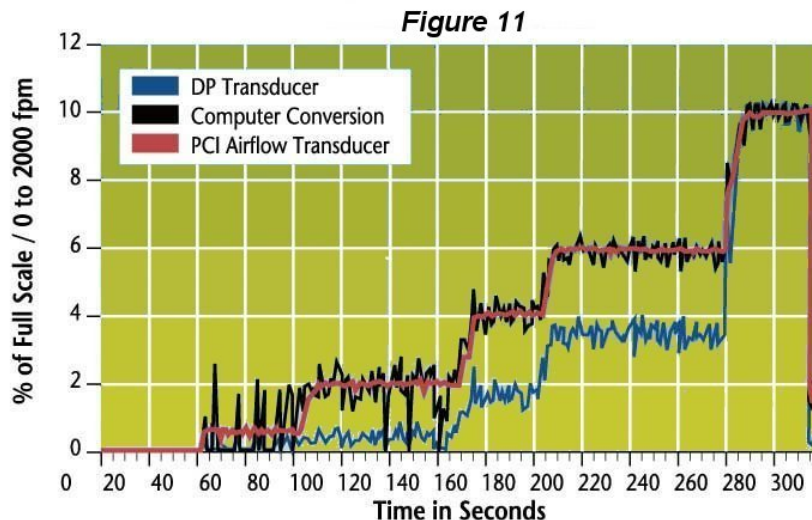
All differential pressure transducers are subject to varying degrees of mechanical, electrical and thermal zero drift. This error is further amplified due to the very high square root gain associated with high turndowns found in VAV systems. To eliminate the effects of zero drift, the MicroTrans incorporates an autozero circuit. On preselected intervals, the autozero circuit locks the output signal, common-modes the two differential pressure ports, removes any zero error, re-pressurizes the transducer and re-enables the output signal. The result is an output signal void of any zero error.

Air Density Changes

When measuring outside air, the density of the air needs to be considered if accuracy of air flow measurement is required. If air density is not considered, an error of up to 10% can occur over a temperature variation of 30 to 130 degrees. To eliminate the error due to temperature variations, the MicroTrans receives a 0-10VDC or 4-20 mA signal from a temperature transmitter and incorporates the value into the density calculation thereby compensating and correcting for temperature variations.

Signal Noise Processing

Signal noise is an unwanted component of a signal which obscures the information content. This is not an electrical issue, but rather the measurement of pneumatic shock waves generated when fans push and/or pull air or when wind loads and unloads against outdoor air intakes. Anyone that has taken airflow measurements in the field has experienced the difficulty of determining the actual velocity pressure being indicated on the differential pressure device. For a fact, noise can make it impossible to perform airflow control even when receiving an extremely accurate flow transducer signal. To eliminate control instability, due to this ever present background noise, the selected transducer should incorporate signal noise processing. This function allows for a stable feedback signal to the automatic control system. Figure 11 has been created from input data to a building management system. From this graph it is quite evident that the use of a flow transducer having signal processing capability (such as PCI's FT series shown as the red line) will significantly improve control accuracy as well as control stability.



References

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