Permanently-Installed Airflow Measuring Devices

Sources of the difference between expected and actual performance

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INTRODUCTION

The proper selection of airflow measurement devices is critical to the performance of today's state-of-the-art HVAC control systems. Comparison of nearly identical products by their published literature rarely displays all of the true differences. Subtle differences in descriptive language should set off alarm bells that all may not be as advertised. Many of the requirements and limitations of one measurement technology are often mistakenly thought to apply to every other (over-generalization), especially when the comparison involves two similar technologies. Vendor self-interest combined with buyer ignorance; make good use of the ease with which people will make undeserved assumptions.

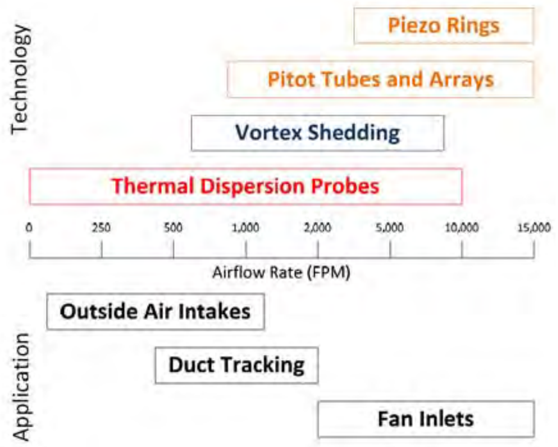
Accuracy and repeatability can vary dramatically between measurement instruments and are most significantly influenced by: the inherent advantages / disadvantages of the basic technology, the manufacturer's implementation of the technology employed, the quality and capability of basic components used, the consistency in manufacturing quality control and the field conditions available for measurement. These things should be universally understood, but many fail to search beyond their noses.

This paper offers HVAC designers and operators an overview of the sources for functional and performance differences displayed by currently available airflow measurement technologies used to improve the control of ventilation systems in buildings of all types throughout the world. If you are a fan of velocity pressure devices and have trouble hearing the truth, please stop reading now.

Our focus will be on the two most popular technologies for permanently duct-mounted commercial measurement systems:

- **Velocity Pressure devices** (which includes all Pitot arrays, Pitot probes, Piezo rings, and other ΔP methods) and
- **Thermal Dispersion devices** (microprocessor-based instruments using some form of thermistor sensors – not RTDs).

The three primary technologies with their effective operating velocity ranges can be compared to the airflow range for the three primary HVAC applications. This graphic provides us with a visual reference for the suitability of measurement types for the primary HVAC air measurement applications.



We intentionally exclude discussion of vortex shedding and thermal-type (RTD) industrial instruments from this discussion, which are not commonly used in commercial HVAC systems.

HISTORY

Velocity Pressure arrays, Pitot arrays and Self-averaging arrays are all names for the same product genus. They are generally described as a device that separately captures and equalizes total and static pressures within a length of partitioned tubing for differential measurements through very small sampling holes, positioned at a cross-sectional plane in the duct. A single differential pressure sensor measures the difference in pressure between the two compartments or equalizing manifolds. The raw output is assumed to be the "average" from numerous ports, providing a non-linear differential pressure output (velocity pressure - P_v) from which velocity can be calculated. This analog result must then be converted electronically and output to a controller or display. The raw signal is made linear either by an integrated transmitter, by a separate intermediate device (‘square-root extractor’) or by another means of calculation following transmission of the non-linear signal. The analog-to-digital (A/D) conversion normally occurs within the host controller.

The improved comfort control and energy saving promises of Variable Air Volume (VAV) air distribution designs were broken early during VAV controls development by the lack of measurement reliability at both the AHU and at the terminal units. Systems were simply too difficult to control and maintain. “Pressure independence” is essential to their function and reliable instrumentation is essential to maximize their performance and realize the original promise. The concepts have proven to be solid, but the technology needed to implement the theory took many years to find.

A more reliable measurement technology would be necessary to allow designers and building operators to avoid the inherent limitations of pressure-based devices, including the many possible sources of measurement error.

Some of the sources of P_v measurement error are:

- duct placement (resulting in variations in turbulence exposure)
- measurement sampling (averaging) error
- a field calibration reference using hand-held instruments
- uncertainties due to manual measurement techniques
- measurement corrections ignored for zero drift, non-repeatability, non-linearity and temperature effects
- air density changes (temperature or altitude) without adjustments
- effect of improper installation
- effect of improper maintenance, and
- the cost-dominated component selection criteria (transducer range and FS accuracy).

Other considerations for measurement device selection include:

- installation time and setup costs
- setup requirements
- initial and recurring instrument calibration requirements
- continuous maintenance requirements
- low velocity (turndown) limitations

PITOT-STATIC TUBES vs. VELOCITY PRESSURE ARRAYS

Pressure-based devices use a similar mathematical relationship between differential pressures and velocity to provide a non-linear velocity pressure output signal, requiring adjustment before use with controls and factored correctly so that velocity may be calculated at standard conditions. This physical principle was first identified by Bernoulli's Equation and later modified by Andre Pitot and has been in use for hundreds of years. It is very useful and potentially very accurate, but it does have limitations in usage for HVAC duct airflow measurement, related to the primary sources of measurement error: the in-duct device; the pressure sensor used and the linearization means.

The devices used for control in commercial ventilating systems are not an array of multiple Pitot-static tubes, each with a separate transducer, but a single element using assumptions for averaging with a single differential transducer. It is the "averaging" assumptions with these devices and the device sensitivity to duct disturbances (unequal distribution of pressures) that create the issues here. It is also one of the reasons these arrays are considered performance-sensitive to turbulence and placement conditions.

The term "Pitot-Tube" array as a generic term for "permanently installed instruments" tends to mislead uninformed readers and imply that Pitot arrays possess the same properties, capabilities and limitations as Pitot-static tubes referenced within the expression. A misleading association that may elevate a technology's characteristics is one reason that many manufacturers continue to take advantage of the misuse of this terminology and have extended an association with Pitot-static tubes, equating the number of holes in a collection tube to the codified minimum number of independent determinations required in a standardized traverse.

The laboratory Pitot-static tube is a 'primary' instrument. This is an instrument having physical properties that have been scientifically proven to provide a predictable level of measurement performance, albeit with known application limitations. In the alternative, a Pitot array is not a primary instrument. The Pitot-static tube and the Pitot array share only the use of the velocity pressure (P_v) relationship in the calculation of air velocity.

However, a Pitot-static tube in the hands of a skilled test and balance technician can calculate the average duct velocities using traverse measurements. This is still a highly trusted method of obtaining field test information. They are important to the initial testing and balancing of many systems. This method is also the basis of many test standards (e.g. ASHRAE Stds. 41.2, 51/AMCA 210, and 111), but is susceptible to error creeping into the process, if only due to the normal inconsistencies of human implementation. Newer ASHRAE Standards requiring more precise airflow measurements refer to these standards, but also offer information on how to improve measurement performance in testing or validating products, namely: ASHRAE Stds. 195 and 215. They embraced changes more readily as they have less vested in older methodologies or involve the testing of higher performing products and devices.

The nature of pressure measurement limits its performance in the measurement of velocity over a predetermined range. With being rated by the pressure error potential at its maximum Full Scale (FS) output, that same pressure error converts to a much larger velocity error when operating toward the low end of the velocity range. This difference highlights the square-root, non-linear relationship of pressure to velocity.

Other sources of transducer error also have significant impacts: zero drift over time, sensitivity to temperature changes, humidity changes, air density changes, fouling, maintenance, et.al. Overall, the largest sources of error for pressure devices can make the total uncertainty in measurement can easily exceed 40-50% from actual, and depending on the specific situation could be well over that. Discoveries of errors in the 100% range made the early use of these devices questionable in many situations.

Professional TAB contractors measure the cross sectional average velocity in a duct by recording individual readings at specific locations on a plane perpendicular to airflow direction. Each Pitot reading is determined by evaluating the equation V=4005*(ΔP) $^{0.5}$, where ΔP is expressed as inches of H_2O. This generalized relationship uses a constant (4005) that assumes IP units and standard conditions of altitude and temperature. The formula does not account for changes in air density due to variation in air temperature and barometric pressure (altitude). The readings are simply added together, divided by the number of measurements and a final average airflow rate is claimed.

Taking a high number of readings throughout the duct attempts to compensate for dynamic changes in the velocity profile during operation. It may reduce the uncertainty by increasing the number of samples in the average; however, it also increases the total time required to complete the determination of all the data needed for averaging (ISO 3966) and increases the uncertainty of the assumed rock-like stability of the system flow rate.

VELOCITY PRESSURE ARRAYS - AVERAGING ERROR

Manufacturers of Pitot arrays promote high ‘sensor’ densities as a product feature (referring to tiny sampling holes in pressure collector tubing) and suggest that the sensor density of other devices using independent sensing elements is inadequate. The manufacturers also associate the quantity of these perforations in collector tubing with the required quantity of velocity determinations necessary to satisfy ISO 3966, ASHRAE Standard 111, AMCA 203, or any of the TAB National Guideline duct traverse requirements.. **Sampling holes are not equivalent to independent sensing elements and the comparison is physically and mathematically invalid.**

Pitot arrays theoretically average the velocity of a profile; however, in practice, pressure equalization occurs along the length of a common collector tube before the pressure “average” is determined by a single sensing element (the pressure transducer). Thus, Pitot arrays with a single differential pressure sensor have far less sensor density (1/total area) than any device with multiple truly independent sensors. The output of a Pitot array can only represent the average reading across a duct that exhibits an equal pressure distribution at all areas; certainly difficult under controlled laboratory conditions, and extraordinarily unlikely in actual field applications. Since Pitot arrays are very sensitive to placement conditions, significant lengths of ductwork are required between disturbances to completely develop the necessary pressure profile across the array.

The differences between single-sensor and independent multi-sensor technologies is easily demonstrated and confirmed by laboratory testing. The use of a normal single point velocity pressure-to-velocity formula assumes everything averages perfectly and that there is no difference if P_v is converted to v, before or after the average is determined from multiple points. Mathematically, a significant error is introduced to the result (est. 8 – 18% of reading), when compared to any method of independent velocity measurements. The significance is dependent upon the maximum difference of the velocities in a profile in the duct.

Mathematically, the difference looks like this:

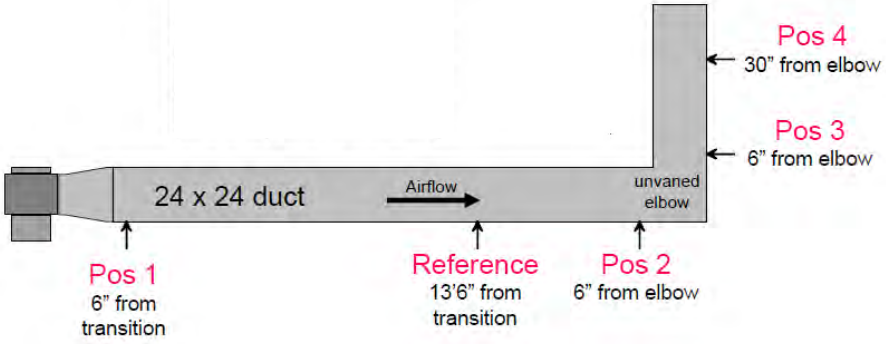
Pitot Traverse Pitot Array

$$\frac{\sqrt{Pv_1}}{n} + \frac{\sqrt{Pv_1}}{n} + \dots + \frac{\sqrt{Pv_n}}{n} \neq \sqrt{\frac{Pv_1+Pv_2+\dots+Pv_n}{n}}$$

Holes in a custom manifold or the interconnections of tubing, does not allow one to claim that an equalized pressure represents an average of the velocities that contributed to the total pressure. **[P_T - P_S = P_V** and **(P_V)$^{0.5}$ *4005 = V]**

An industry technical White Paper based on a discussion of these technologies, supported by empirical test results, compares the influence of upstream and downstream disturbances on measurement performance, as well as the effect on:

- Individual sensor accuracy (effect of "turbulence")
- Overall sampling error of the array (effect of the velocity profile)
- Placement of the sensor probe with respect to the velocity vector plane (rotation effect)
- Calibrated accuracy of the sensor(s)
- Calibrated accuracy of the transmitter/transducer
- Long-term stability



ACTUAL DEMONSTRATON TEST DATA		
% Deviation (typ.) **compared to Reference Position**		
Duct Position	Pitot* Array	Thermal Dispersion Brand X
1	25.90%	-2.3%
2	0.20%	-4.6%
3	45.30%	-5.6%
4	35.40%	-0.1%

Table 2 Effects of Placement on Performance – Advantage of Independent Determinations

*Differential pressure measurements were taken with an MKS Baratron pressure sensor, having 0.05% of Reading accuracy to eliminate transducer contributions to total measurement uncertainty and focusing only on the placement induced error effects on the instrument technology.

PITOT ARRAY PERFORMANCE VERIFICATION

It is difficult to validate the performance of velocity pressure-based, permanently mounted instruments under field conditions using field references as the comparison standard. There are too many sources of potential error, inherent variations in the methods, variations in the between the skill and training of different technicians, uncontrollable short-term variations in system flow, internal and external pressure changes that influence measured airflow.

Furthermore, even under laboratory conditions, the performance differences among applied velocity pressure-based devices cannot be easily compared. Comparison of the published performance charts of 'AMCA-certified' products confirm this issue.

Almost all Pitot arrays claim to provide an "accuracy of 2 percent". 2% 'of what?', however, is not indicated. The terminology is at best misleading and without using the standards available for communicating instrument performance, it implies that this level of measurement performance is actually achievable in the field. The claims ignore differences in the application or in the uncertainty contributed by all of the other components needed in the P_v system to produce a linear duct average velocity signal to the controller. The implication is that the stated "accuracy of 2 percent" makes the device equal to all other products with a maximum uncertainty in measurement of "±2% of reading."

This claim overstates the capability of Pitot array technology and oversells performance expectations. In ideal laboratory conditions, with professionally selected research equipment and test set up (as in AMCA Standard 610-06 R2012), Pitot arrays can produce a measurement uncertainty of ±2% from a reference. In Certified performance testing, the reference is the AMCA lab, which contributes its own uncertainty of measurement and adds to the total uncertainty in any comparison. Pitot arrays cannot consistently provide the claimed 2% level of combined total uncertainty under field conditions, against field references using unspecified quality P/E conversion equipment and unspecified linearization methods. There are too many potential sources of error. Typically, a Pitot array comparison is made only between two P_v devices. This practice mutes the contrast to the P_v reference standard and makes the comparison more favorable to the particular P_v device under test.

The accuracy of velocity pressure devices rely on the physical sampling of air through an array of many tiny sampling ports engineered to specific dimensions. Regular maintenance of these ports must be performed in order to prevent clogging of the orifices and to ensure proper performance of the measurement device. Most Pitot array suppliers offer the option of a pressurized purge system, intended to reduce the manual labor associated with regular cleaning of the sampling port orifices. The effectiveness of these purge systems has never been evaluated, however the cost of a separate instrument air system can be many times the first cost of the most expensive P_v measurement devices, not to mention the ongoing maintenance requirements for the entire system.

The accuracy of pressure based instruments with averaging/sampling cavities that have no apparent method of drainage is also concerning. Although output readings from a partially blocked collection cavity may appear to remain acceptable, the entire premise supporting the theory on averaging pressures is invalidated.

Combined moisture and airborne debris in the airstream of return fans will impact the performance potential and increase the maintenance needs of ANY instrument placed in such unsuitable locations. Pitot arrays physically sample the air and are inherently susceptible to fouling under these conditions. Vigilant attention to, and regular cleaning of sensors is necessary to prevent failure of their ability to detect variations in velocity profiles. Particulate buildup continues to be one the main worries when using Pitot array sensors.

EBTRON'S **THERMAL DISPERSION DESIGN**

EBTRON's advanced thermal dispersion airflow measurement technology was introduced in 1985. Within the scope of this paper, the type is defined to include only microprocessor-based designs. Analog electronic designs using thermistor sensors exhibit unacceptable response times and are unreliable, with major deficiencies in performance when operating over the expected normal equipment operating temperature range. Some microprocessor-based designs overcome these deficiencies, and are differentiated from all other types of thermal-based velocity measurement technologies.

Thermal dispersion technology is currently used by HVAC control systems in a wide range of office buildings, laboratories, healthcare and educational facilities to ensure healthy indoor air quality and economy of operation. Some thermal dispersion manufacturers produce instruments that feature a combination of electronic components and most are believed to provide totally independent sensing elements. *EBTRON* is the only thermal dispersion manufacturer that produces instruments whose sensing elements are individually factory calibrated to NIST-traceable velocity reference standards. When properly designed and applied with a sufficient density of sensing elements, the thermal dispersion instrument can overcome (or minimize) the placement limitations and measurement uncertainties inherent in the use of velocity-pressure instruments.

There are at least three U.S. manufacturers of commercially available thermal dispersion airflow measurement instruments that meet some or all of those qualifications. Although they may appear to be similar in form and construction, a closer comparison of their design implementation, qualitative value, historical reliability, application limitations and verifiable performance yields surprisingly large differences between them.

Enhancements to *EBTRON's* sensor design in the early 1990's allowed for turbulent condition to be created artificially and consistently under actual airflow. This design feature was further exploited during the factory calibration process. As a result, these particular thermal dispersion sensors are influenced far less by duct disturbances. The design is proven in documented full scale laboratory testing.***** With advanced thermal dispersion instruments, often 0.75 to 1.5 simple equivalent duct diameters [(width + height)/2] is sufficient for accurate measurement when higher sensor density devices of this type are applied. Independent sensors allow the ability to measure much closer to disturbances than any other measurement technology, with much smaller decreases in performance due to conditions. Contrast this to the required 3 to 10 equivalent duct diameter distances that are required of other devices as the industry minimum standard (ASHRAE, 2013 Handbook of Fundamentals 36.16 and Standards 41.2, 51, 111).

> ***** Refer to Technical White Paper *Airflow Measurement for HVAC Systems – Technology Comparison - Thermal Dispersion versus Pitot Tube Arrays* at http://www.airflowmeasurement.com/Web_Pdfs/AirflowMeasurement_Comparison.pdf

In the spring of 2000, over 350 units of this design of thermal dispersion devices were provided for installation at the Advanced Measurement Lab complex at NIST in Gaithersburg, MD (http://aml.nist.gov/). These devices have performed without the necessity of field adjustment and are reported to be functioning well, without a reported sensor failure since installation about 15 years ago.

The thermal dispersion manufacturer's selection of the type and design of the sensing elements employed will ultimately impact all of the following measurement attributes:

- base cost,
- reliability,
- sensitivity to environmental changes, including changing temperatures,
- instrument stability over time,
- to perform reliably without mechanical failure due to continuous cycling between thermistor heating and cooling,
- validity of the manufacturers' factory calibration process,
- the need for or lack of interchangeability of instrument components, and
- supplier's limitations on product placement

Although continuously soaked by water condensation from coils or carryover from exterior louvers, water alone will not damage some instruments. *EBTRON* devices are designed to withstand it. When consideration for these conditions is given during the instrument's design, the impact of liquid water immersion on thermal dispersion performance is temporary, with normal performance resuming as the sensor surface returns to ambient moisture levels.

Typically, common dust and airborne particulate found in outdoor air and conditioned air ventilating systems is not capable of accumulating and producing an insulating value sufficient to materially impact the thermal transfer characteristics of the sensor. The impact on performance from common airborne dust and dirt is negligible to bead-type glass encapsulated thermistors. This is an capability not shared by mass produced thermistors, like diode-case, epoxy coated or glass-coated thermistors. The names are close, but the products are substantially different. "Sensors shall be glass bead, hermetically sealed with coated leads" are not the same thing as "bead-in-glass type, pre-stabilized" thermistors.

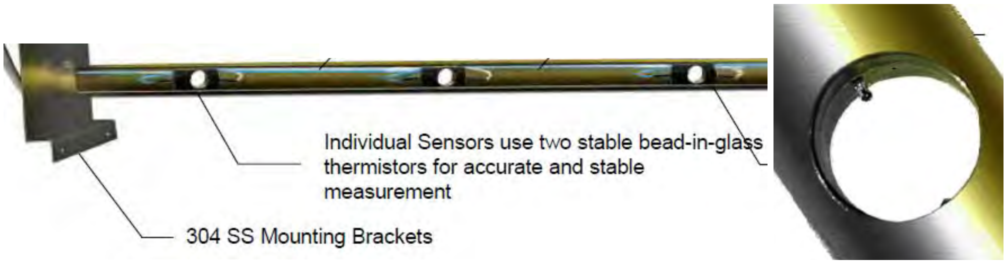
THERMAL DISPERSION ARRAYS

In contrast to velocity pressure devices, thermal dispersion sensors are arguably the best suited for HVAC applications than any other commercially produced technology. The biggest performance advantages are found in: measurement range, low flow sensitivity, accuracy, repeatability, factory calibration, low potential for drift, and minimum maintenance. Even though the thermal dispersion components are relatively inexpensive, the methods used in their production provides for a very robust product, allowing it to be very reliable. *EBTRON's* methods of calibration and testing are extremely dependable and the results are stable well beyond other products with claimed comparable performance and at much lower first and life-cycle costs. They are potentially the best in overall performance and they provide "% of reading" output, without turn-down limitations.

EBTRON's Thermal dispersion products use an array of multiple sensors or sensor assemblies that provide independent determinations of velocity and temperature for every position in the array where a node is placed. Using its high speed microcontroller, it uses the raw sensor data to calculate the air speed and temperature in almost real time. That calculation is then used to perform either a velocity-weighted average temperature or straight arithmetic average for output as a voltage or as a number on the field-selected network protocol.

They feature sensor nodes (sensor assemblies - right) with a very large portion of free area and an extremely small surface area for the individual sensing element.

Probe Cut-away and Sensor Node Up Close



With their thermal conductivity intact, this allows thermal dispersion sensors to continue to operate as designed in defiance of normal dust buildup, making them inherently immune to fouling from most common types of ventilation system dirt. The effects of some chemical compounds functioning as a binding agent, combined with the insulating properties of some airborne contaminants, can degrade the thermal conductivity of individual thermal sensors, yet require only a light cleaning to restore their original performance levels.

One of the reasons for *EBTRON* design superiority in performance is found in the nature of the thermistor sensors that were selected and used. These are "bead-in-glass" type thermistor 'probes'. No other type of thermistor sensor is pre-stabilized to resist drift and exhibits the highest potential temperature measurement capability (same part is offered as NIST-traceable ±0.001°C). Used by *EBTRON* for both "powered" and "passive" application, individually characterized and calibrated during the manufacturing process for both temperature and air velocity. These are not inexpensive components and must be individually calibrated, unlike their mass-produced cousins, used by other thermal AFMS manufacturers.

In many cases, such as with fan tracking applications, repeatability, linearity and turndown are more important than absolute accuracy. Repeatability is the most useful measurement attribute in the application of volumetric fan tracking control. Fan inlet conditions are generally unpredictable and therefore not conducive to situation-based comparison studies. Fan inlet conditions may be extreme to the point of undesirability. It is the last possible airflow measurement placement that *EBTRON* recommends. While it eliminates some design issues for the engineer, other troublesome installation issues arise (e.g. access to the reverse side of dual inlet fans in the field, etc.) as well as fan sound and fan performance issues that many P_v inlet installations generate.

EBTRON has developed a fan inlet mounting arrangement (Face Mount) that overcomes all of these issues and reduces the potential impact to more sensitive plenum fan performance to less than 1% of rated flow. Be sure to request comparative fan performance values with and without velocity pressure probes at the fan inlet. Furthermore, the design of this particular thermal dispersion instrument provides consistently repeatable control in the most challenging airflow measurement applications.


Face Mount

The difficulty in determining the true baseline volumetric calculation and the resulting impact on control accuracy is compounded by the difficulty in determining the actual area of the plane in the inlet cone where the measurement device is to be installed. This is true for any airflow measurement technology applied at fan inlets. However, when the instrument produces measurements that are repeatable, it can be set up in the field to produce reliable and repeatable results. This is especially important as accessibility for maintenance or replacement is diminished, especially with many dual inlet fan designs and air handler configurations.

VORTEX SHEDDING

Vortex Shedding is a technology historically used in fluid flow measurement which was applied to airflow about 25-30 years ago. It provides better performance potential than Pitot arrays, but they also have finite limitations on the average velocities where they may be applied (>450 fpm approx.). Below an arbitrary velocity limit determined during manufacturing, the output is forced to zero by factory settings, below which the unit was determined to be unreliable. They do provide independent sensing elements in an array configuration, but are somewhat more expensive per sensing element than are thermal dispersion arrays per sensor node. The analog circuitry includes components that are prone to drift and may require frequent field calibration using a frequency generator.

Therefore, because most outdoor air and some return air applications are at velocities lower than where vortex shedding technology can be successfully used; their review was intentionally excluded from this paper due to their diminishing and limited popularity. Although a viable technology, further development and investment is needed to make the technology more competitive.

CONCLUSIONS

Many types of velocity measurement products have been applied - successfully and not-so-successfully - from numerous sources over the past 40 - 50 years. The information provided here should help you make better decisions on equipment selection, application and instrument placement. With this additional knowledge, you will increase the probability of your next project, operating more efficiently and more reliably.