Quantitative Self-Verification, a Breakthrough in Ultrasonic Metering Technology

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Abstract. The accuracy of ultrasonic metering technology has advanced to a level that it is now the technology of choice in many custody-transfer and fiscal applications. With meters capable of meeting the accuracy requirements of these applications when initially calibrated, end-user attention has moved to the diagnostic capability of these meters. Diagnostics are now commonly used to increase the confidence of the user that the meter is functioning accurately between calibrations, which could be a year apart or even longer. Although current ultrasonic meter diagnostics are very powerful, they are qualitative in nature, i.e. they provide an indication if something is wrong or has changed, but they have not yet been able to quantify the possible range of error, correctly termed the measurement uncertainty. This paper presents new technology that has been developed to equip ultrasonic flowmeters with additional measurement data that is used to quantify the uncertainty in the meter's output. This capability reduces the complexity of diagnostic monitoring, as the result can be monitored as an uncertainty in volumetric or percentage terms, and hence allows for quick and simplified decision making. The paper presents the fundamentals of the new self-verifying technology and the testing that has been conducted to validate the uncertainty output provided by the meter. This includes an independent Technology Qualification evaluation conducted by DNV where the meter was subjected to a variety of real-world upset conditions and the meter performance and uncertainty output compared with reference data from traceable test facilities.

Keywords: ultrasonic, flowmeter, verification, custody transfer, fiscal, metering, measurement, self-verification, uncertainty, diagnostics, multipath

1 Introduction

The first practical embodiments of ultrasonic transit time flow metering technology emerged in the 1950s, and the first multipath meters for application in large pipes with higher accuracy demands were developed in the late 1960's and early 1970's (e.g. Hastings 1968). In the mid-to-late 1980's multipath ultrasonic meters were developed for use in natural gas custody transfer applications, driven by the desire to overcome some of the technical limitations of orifice plate and turbine flow meters which predominated at that time (e.g. Nolan *et al* 1988). The attraction of ultrasonic technology was due to the following potential benefits:

1. High Accuracy
2. No moving parts
3. No obstruction of the flow
4. No pressure loss
5. No calibration required
6. No dependence on fluid properties
7. Large rangeability
8. Bi-directional measurement
9. Minimal upstream straight pipe required
10. No routine maintenance requirements
11. Long life and long-term stability

Over the past 40 years there have been numerous advances in ultrasonic flow measurement technology for custody transfer applications. Ultrasonic meters are now commonly used for natural gas custody transfer and also for crude and refined petroleum products, and liquified gasses. Some of the areas in which significant advances have been made are as follows:

- Improvements in electronics and signal processing, resulting in more robust and accurate measurement of ultrasonic transit times
- Development of extremely robust transducers with applicability to wide temperature and pressure ranges
- Introduction of improved path configurations to reduce sensitivity to fluid-dynamic installation effects and reduce reliance on flow-conditioning devices
- Development of best practices and documentary standards, e.g. ISO, API and AGA standards
- Development of advanced diagnostics capabilities

With these developments, many of the promised benefits of ultrasonic technology have now been realised, and the additional benefit of advanced diagnostic capabilities has been added to the list. However, ultrasonic meters for custody transfer are still subjected to an initial calibration in a flow calibration laboratory, as this step ensures traceability and higher accuracy, reducing the potential for measurement bias/error. Long term stability of the measurement technology is expected, and in some regulated applications intervals between calibration of up to 5 years are allowed, but faults and adverse process conditions can still lead to measurement errors in the field. With the current state of the art enabling the design, manufacture, and calibration of multipath ultrasonic meters to achieve uncertainties of the order of 0.2 to 0.3 % when installed, the main aspiration of users now is to answer the question: *how can long-term measurement performance and stability be assured?*

This aspiration can be summed up clearly by quoting from the Value to Members section of the PRCI Smart USM Diagnostics – Phase 3 project report (Zanker 2014):

"Understanding the performance of multipath gas ultrasonic flow meters has been identified by the PRCI Measurement Technical Committee as its most important measurement issue needing resolution. With smaller staffs and larger pipeline networks, operators clearly need metering systems capable of doing more to self-diagnose their performance and verify their reports."

2 Capabilities and Limitations of Previous Methods of Self-Verification

2.1 Diagnostic Analysis and Condition Based Monitoring

Multipath ultrasonic meters have arguably the largest array of diagnostic capabilities of modern flow metering techniques. The measurement process starts with the generation and reception of ultrasonic pulses, and using digital signal processing a variety of diagnostic measures can be applied to each signal that is received. With signals being sent both upstream and downstream on each measurement path several times a second, it is also possible to generate comparative and statistical diagnostics. At the lowest level are diagnostics that provide information about individual signals and paths, a partial list of which is given below:

- Amplifier gain (related to signal strength)
- Signal-to-noise ratio
- Speed of sound (SOS)
- Standard deviation of the velocity measurement (sometimes called *turbulence*, as turbulence in the flow can dominate this statistic)
- Percent of accepted pulses (sometimes called *performance*)

Once path-level information has been obtained it is then possible to use that information to construct higher level diagnostics. A partial list of such higher-level diagnostics is given below:

- Path-to-path SOS comparisons
- Relative gain comparisons
- Velocity profile metrics such as asymmetry, flatness, cross-flow and swirl
- Comparison of meter calculated SOS with a reference SOS for the fluid in question

Some of the parameters above can be monitored versus limits that are based on practical considerations (such as the maximum gain available in the electronics) or experience (such as the level of agreement that can be expected in speed of sound and the limits of velocity profile metrics such as flatness). However, most of these parameters are expected to change to some degree owing to changes in process conditions which can make it hard to define how limits should be set. For example, a velocity profile metric could change because of a transducer problem that would result in an error, but it could also change owing to a change inflow conditions without a resulting increase in uncertainty.

The availability of software packages that collect and monitor ultrasonic meter diagnostic parameters is now common-place among manufacturers of high-tier ultrasonic meters. These packages are generally referred to as Condition Based Monitoring (CBM) software and in their most advanced forms incorporate means of creating *diagnostic fingerprints* for specific meters and application conditions so that changes can be closely monitored relative to a known baseline.

The limitation of CBM is that whilst it can quickly identity and alert a user to a significant failure, such as a transducer fault, it is extremely difficult to relate changes in diagnostic parameters to estimations of measurement uncertainty. This is because the parameters that are monitored do not have a direct relationship with measurement uncertainty. In other words, a CBM package can normally alert the user to the fact that something has changed, but it cannot quantify the impact of that change on the accuracy of the flow measurement. The end result is that CBM packages can be useful in alerting users to potential problems but with evaluation of the potential error and subsequent action being based on qualitative interpretation or supposition.

2.2 Two Flow Meters in One Body

Given the limitations of qualitative diagnostics and CBM, some end-users have resorted to use of two flow meters in series as a means of verifying the primary flow measurement as well as providing redundancy. This in turn has led to development of products that incorporate two ultrasonic flow meters in one body.

As a means of self-verification, the two-meters-in-one-body approach has a number of limitations. In one of the simplest forms of this meter type, the first meter is a 4-path meter and the second meter is a simple 1-path meter. The fundamental limitation of this approach is that the 1-path meter is very sensitive to problems that may not affect the 4-path meter significantly. For example, published results show a case at 7 m/s velocity where the influence of a flow conditioner blockage on the 4-path result is a change of 0.005% and the corresponding influence on the 1-path meter is 3.5 % (van Helden *et al* 2012). This difference in sensitivity indicates that the probability of triggering a false alarm when comparing the 4-path and 1-path results is very high.

Other variations of the two-meters-in-one-body approach include having two 4-path meters in one body. A first limitation of this approach is that a flow conditioning device is required, as otherwise each 4-path meter is sensitive to transverse flow/swirl and should not be expected to agree closely. A second limitation is that both meters can be affected by common-mode error. Common-mode error is when the sign and magnitude of error is the same (or very close to the same) on both meters. So if, for example, contamination build-up on the first 4-path meter resulted in an error of +0.99% and the same condition resulted in an error of +1.01% on the second meter, then the difference between the two meters would be only 0.02% and would not trigger an alarm, but the measurement result would be in error by 1%.

Even when two *different* multipath configurations are used in one body, the potential for common-mode error exists, one example being both meters over-reading when there is liquid passing through a gas meter. A final complication with this meter type is that even when the error does not have a common-mode aspect to it, the comparison of one meter with another does not directly answer the question of which of the two meters is correct.

3 Development of Quantitative Self-Verification

3.1 Design Basis

The design basis adopted for development of quantitative self-verification was to identify and address the components that contribute to measurement uncertainty using a first-principles approach. Whilst other approaches such as machine learning combined with existing technology could potentially be applied to this problem, the complexity of design and process variables and the requirement for extensive learning and validation sets inclusive of highly accurate flow measurement reference data makes the first-principles approach more attractive for a robust solution.

The basic equation for a chordal multipath ultrasonic meter, illustrated schematically in Figure 1, can be presented in reduced form as:

$$q_V = M_F A \sum_{i=1}^{i=N} w_i v_i \quad (1)$$

where q_V is the actual volumetric flowrate, M_F is the meter factor, A is the cross-sectional area of the measurement section, N is the number of chordal measurement planes (each plane having one or more paths),

v_i is the axial velocity in chordal plane i, and w_i is the corresponding chordal weighing factor. The chordal velocity v_i is derived from geometry terms and measurements of ultrasonic transit time obtained from transducers located to form measurement paths spanning the chordal plane. For a given design, the weighting factors w_i are usually constants. The meter factor M_F is a compound factor that is normally applied based on the results of a flow calibration, and as such accounts for secondary influences of the flow velocity profile.

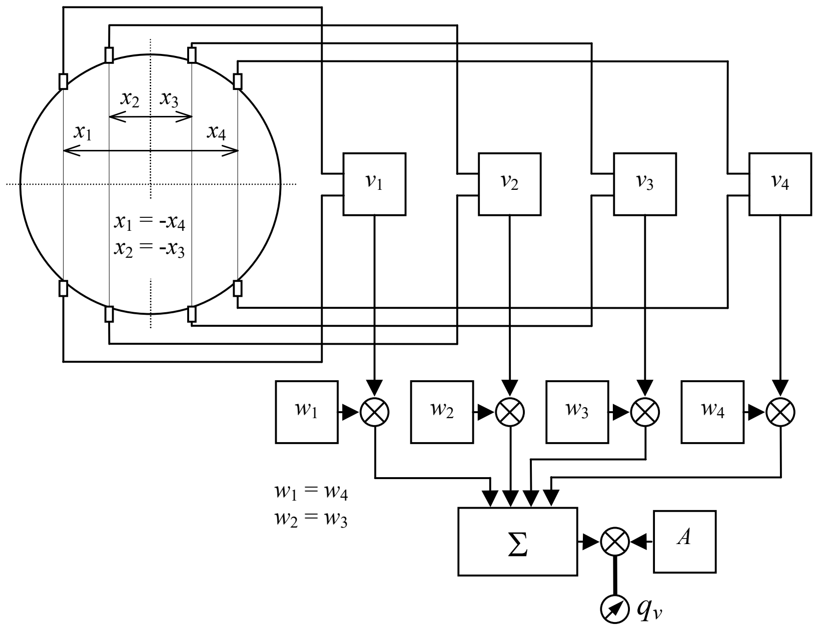


Figure. 1. Schematic illustration of chordal multipath ultrasonic flow meter

Considering equation (1) above, it is clear that if the uncertainty in the primary chordal velocity measurement inputs, the meter factor, and the cross-sectional area can be evaluated whilst the meter is in service, then the uncertainty in q_V can be obtained, providing a quantitative self-verification of the measurement result.

3.2 Primary Measurement: 4-Chord, 8-Path Foundation

The philosophy adopted for the primary measurement system of the self-verifying meter (SVM) was to take the well-established 4-chord, 8-path design used in Caldon LEFM 280Ci and LEFM 380Ci flowmeters and build the quantitative self-verification capabilities on top of that foundation. The 4-chord design is based on the mathematically robust approach of using Gaussian integration to determine the spacing and weighting of the measurement chords, first introduced to the Caldon predecessor LEFM product line by Westinghouse in the late 1960's (Hastings 1968).

The 4-chord, 8-path 280 and 380 models employ a pair of crossed paths in each of the four chordal planes to eliminate transverse flow from the solution of the velocity calculation, as described in section 3.3 below. This combination of the chordal integration method and transverse flow cancellation results in a meter design that does not require a flow conditioner and that is highly accurate even in the presence of swirling and/or distorted flow profiles. This is evidenced by the ability of the 380 model to achieve the performance required at the highest accuracy class of OIML R137 with only 5D of straight pipe and no conditioner downstream of pipe bends (Brown *et al* 2013).

The piezoceramic ultrasonic transducers used in Caldon metersare removably located in metal transducer housings that, with the meter body, form the pressure boundary containing the process fluids. As such, the transducers are completely isolated from contact with the liquid or gas, and also from pressure variations in the process, making them extremely robust.

With reference to the components of uncertainty outlined above, build-up of contamination on the transducer housings and/or alteration of the cross-sectional area of the measurement section can result in errors. Caldon meters can be supplied with a proprietary adhesion and corrosion resistant internal coating that has been demonstrated to improve measurement stability in arduous conditions (Brown and Bach 2016). This internal coating has been adopted as a standard feature of the self-verifying meter.

The features outlined above were chosen so that the primary measurement should be highly accurate and have very robust long-term performance. In other words, the aim was to design the SVM so that it would inherently have very low uncertainty with the added capability to perform a continuous quantitative verification of that low uncertainty.

3.3 Self-Verification of the Primary Chordal Velocity Inputs

The first and most important input to the flow rate result are the chordal velocity measurements themselves. With reference to Figure 2, it can be shown with certain assumptions that the transit times associated with a single chordal ultrasonic path can be represented as follows:

$$t_{up} = \frac{L}{c - v_{axial}\cos\theta - v_{transverse}\sin\theta} \quad (2a)$$

$$t_{down} = \frac{L}{c + v_{axial}\cos\theta + v_{transverse}\sin\theta} \quad (2b)$$

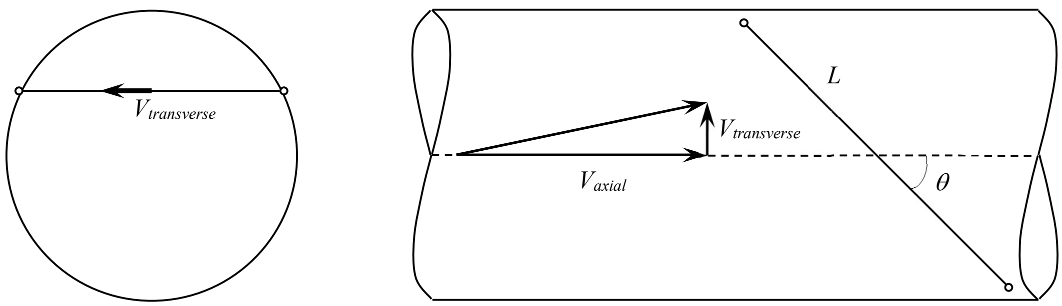


Figure 2. Illustration of the transit time measurement principle with axial and transverse velocity components shown.

Where L is the length of the path, c is the speed of sound, v_{axial} is the velocity component in the axial direction, $v_{transverse}$ is the velocity component at 90 degrees to the axial direction in the chordal measurement plane and θ is the effective path angle. Introducing a calculated path velocity term v_{path} for an individual path we can write:

$$v_{path} = \frac{L(t_{up}-t_{down})}{2co \quad _{up}t_{down}} = v_{axial} + v_{transverse} tan\theta = v_{axial} + \frac{X}{Z} v_{transverse} \tag{3}$$

where $tan\theta$ is replaced with X/Z, where X and Z are the projections of the path in the transverse and axial directions, respectively.

Equation 3, illustrates a problem for ultrasonic measurement that has endured for a long time despite the fact that the solution has also been known for a long time; *the velocity inferred from a single measurement path is sensitive to both the axial velocity and the transverse velocity.* A common way to address this issue has been to employ a flow conditioning device to try to remove the non-axial component of velocity from the flow itself. A more elegant and more effective solution is to combine two paths in the same chordal plane such that the transverse velocity cancels out of the equation. Designating two paths in a single chordal plane as A and B, it can be shown that the two paths can be combined to eliminate the transverse velocity and solve for the axial velocity as follows:

$$v_{axialAB} = \frac{\left(v_B - v_A \frac{Z_A X_B}{X_A Z_B}\right)}{\left(1 - \frac{Z_A X_B}{X_A Z_B}\right)} \tag{4}$$

If we choose, as in the case of the Caldon 8-path meter, to use a pair of paths that traverse the same chord but have equal but opposite angles to the pipe axis, such that $Z_B = Z_A$ and $X_A = -X_B$ then Equation 4 above reduces to:

$$v_{axialAB} = \frac{v_B + v_A}{2} \tag{5}$$

Whilst Equation 5 is simple and elegant for implementation, i.e. the transverse velocity is eliminated by taking the simple average of the velocity results two paths arranged in an ‘X’ at equal but opposite angles, the general form of Equation 4 is much more useful and offers the key to self-verification of the primary velocity inputs.

It is apparent from Equation 3 that any individual path is sensitive to both axial and transverse velocity, and hence, even when located in the same chordal plane they should not be expected to agree with one another. However, Equation 4 shows that a pair of paths at two different angles can be combined to eliminate the transverse velocity. Now if we add a third path (designated as path C) to a given chordal plane, we can calculate the axial velocity using any two paths from the set of three, i.e.

$$v_{axialAB} = \frac{\left(v_B - v_A \frac{z_A x_B}{x_A z_B}\right)}{\left(1 - \frac{z_A x_B}{x_A z_B}\right)} \qquad v_{axialBC} = \frac{\left(v_C - v_B \frac{z_B x_C}{x_B z_C}\right)}{\left(1 - \frac{z_B x_C}{x_B z_C}\right)} \qquad v_{axialAC} = \frac{\left(v_C - v_A \frac{z_A x_C}{x_A z_C}\right)}{\left(1 - \frac{z_A x_C}{x_A z_C}\right)} \quad (6)$$

Given that the axial velocity values calculated according to the equations above are for the same chordal plane in each case, and have had the transverse flow eliminated, when everything is working as expected these velocity values should agree within the uncertainty expected for the chordal velocity input. When they do not agree with one another, owing to an error in signal detection or a change in effective path geometry, the difference between the results is a quantitative measure that can be used to evaluate the uncertainty in the flow measurement.

Adding a third path in each chordal plane, as illustrated in Figure 3, provides the meter with the additional measurements required for continuously performing a quantitative verification of the primary measurement inputs (Brown and Augenstein 2019). The uncertainty is quantified per chord in velocity terms, and then as a component of the uncertainty in volumetric rate and relative percentage terms by applying standard methods of uncertainty analysis (e.g. JCCM 2008, ISO 2005) to the primary equations.

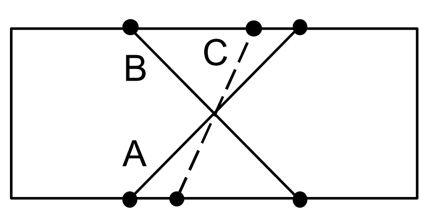


Figure 3. Illustration of the velocity self-verification principle using three paths per chordal plane

As shown in Figure 3, the additional path can be added between the existing paths of the 4-chord, 8-path design and as such make it easy to incorporate the additional transducers and resulting in a path length and path angle that is different to the others, which in turn provides a difference in sensitivity to changes such as contamination build-up on the face of the transducer housing.

3.4 *Self-Verification of the Velocity Profile Integration*

As described in section 3.2, the average velocity over the cross-sectional area is inferred by combining chordal velocities that are located and weighted according to the rules of Gaussian integration. Whilst this is a very powerful method in the 4-chord, 8-path format (with the transverse flow already eliminated from the equations), for a true quantitative self-verifying meter it is still necessary to have a means of continuously quantifying this component of uncertainty, and its response to changes in the velocity profile.

In numerous studies of velocity profile effects and of integration methods in general, it has been observed that different integration schemes produce different errors (e.g. Brown *et al* 2006), and therefore that using two different integration methods could be used as a means of evaluating the uncertainty in the integration result. It was also observed that even- and odd-numbered integrations would often produce results where the sign of the error was opposite, and furthermore that the abscissa of odd-numbered integration schemes could sometimes fall close to those of even-numbered schemes, suggesting that chordal velocity inputs could be shared between two different chordal integration schemes. This has led to the development of a method whereby an additional chordal measurement plane is added on the diameter, so that a 5-chord integration is constructed along with the 4-chord integration, with the two integration methods using separate sets of weighting factors (Brown 2019).

The benefit of this approach is that the method can be implemented without having to use much additional hardware. Three paths are added on the diametric plane, two so that the axial velocity can be determined and the transverse velocity eliminated, and the third so that the diametric velocity itself can be self-verified. In comparison to the 4-path vs 1-path configuration discussed in section 2.2 of this paper, this approach is much more robust as it firstly eliminates the transverse flow influence, and secondly compares two highly accurate (4-chord and 5-chord) integration methods. It is also more robust than comparing two multipath meters with one another, as each chordal velocity input to the integrated result is first verified by the method described in section 3.3.

3.5 *Self-Verification of the Cross-Sectional Area*

Any significant build-up of contamination or physical alteration of the internal geometry of the meter can potentially be detected by one of the two means of self-verification already described. In other words, contamination build-up effects on the primary choral velocity inputs or on the velocity profile averaging can be detected and quantified. However, it is possible that the cross-sectional area could be affected in a particular way that could go undetected by those methods. The areas outside those covered by the primary measurement paths, i.e. the very top or the very bottom of the measurement cross-section, which represent approximately 5% of the cross-sectional area, could potentially 'hide' an area blockage of one or two percent quite easily. It is an unfortunate coincidence that contamination in the form of a second phase in what should be a single-phase fluid is most likely to be present in one of those locations, i.e. liquid contamination running along the bottom of a gas meter, or gas contamination passing through the top of a liquid meter.

To ensure that any contamination in these areas is detected, the SVM design adds a reflected ultrasonic path that is oriented in a vertical 'V' or 'Λ' shape with the reflection point located at the bottom of the pipe in a gas self-verifying meter and at the top of the pipe in a liquid self-verifying meter. The measurement results from this path are not used in the flow velocity or flowrate computations, but are used, in combination with information from the chordal planes, to evaluate any increase in uncertainty of the cross-sectional area.

3.6 Self-Verifying Meter Full Configuration

Figure 4 below, illustrates the full configuration of the Self-Verifying Meter (liquid version shown):

- Four primary chordal planes each with three measurement paths per chordal plane for uncertainty evaluation of the primary velocity measurements
- Diametric plane comprising three paths used to produce a self-validated fifth chordal velocity as input to the 5-chord integration result for 4-chord vs 5-chord evaluation of the velocity profile related uncertainty
- Vertical Λ -path with reflection at the top of the pipe for use in the area uncertainty evaluation

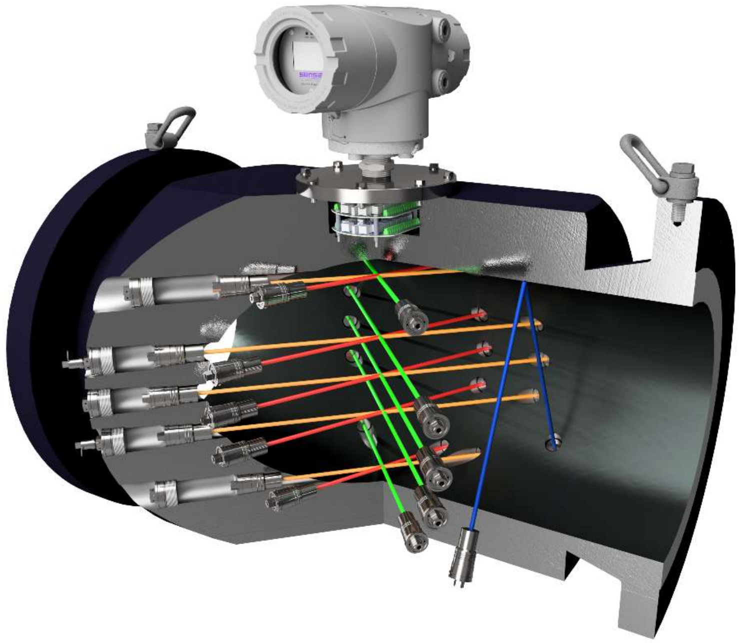


Figure 4. Illustration of the full self-verifying measurement configuration

The electronics and software that comprise the operating system of the self-verifying meter gather the signals from all 32 transducers (16 measurement paths) several times a second and process the signals to compute the measurement result and its corresponding uncertainty. The uncertainty is computed during each measurement update cycle by combining the component uncertainties according to the established methods of the GUM (JCGM 2008) and ISO 5168 (ISO 2005). The component uncertainties and the overall uncertainty in the meter's actual volumetric rate output are computed in volumetric flowrate units and can also be read/displayed as a percentage of the flowrate. The volumetric rate uncertainty is also totalised internally, so that the internal registers of the meter include the totalised volume of fluid that has passed through the meter and the corresponding uncertainty that volume.

4 Self-Verifying Meter Technology Qualification

4.1 The DNV Technology Qualification Scheme for Ultrasonic Flowmeters

As a recognised leader in testing, certification, and technical advisory services, DNV have introduced a Technology Qualification (TQ) scheme for ultrasonic flowmeters. The purpose of the TQ is to extend the evaluation of flow meters beyond the tests and standards that are routinely applied to fiscal metering and custody transfer to include a thorough evaluation of the accuracy, robustness and diagnostic ability of ultrasonic meters in real-life operational situations, such as performance in the presence of contamination.

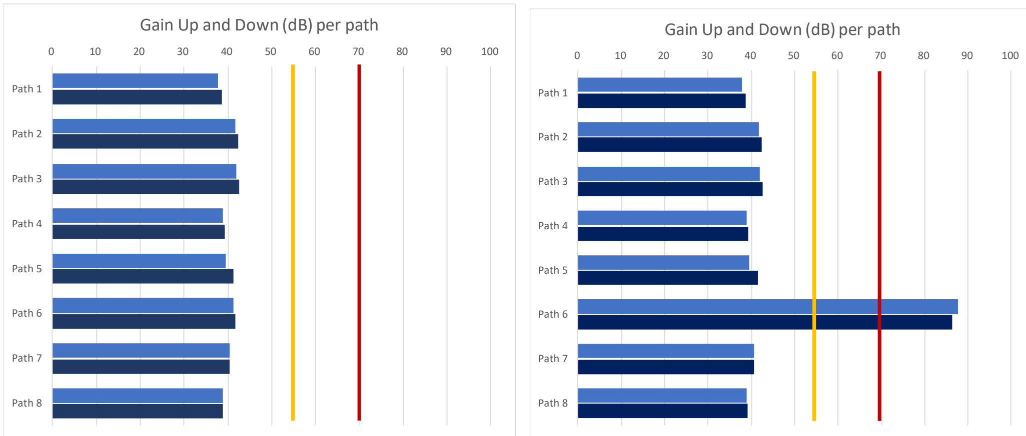
As the self-verifying meter technology is a breakthrough of significant novelty in design and capability, Sensia engaged DNV to undertake a full technology qualification for both gas and liquid custody transfer applications, including evaluation of the meter's ability to continuously evaluate its own uncertainty under changing process conditions (sometimes referred to as 'live uncertainty').

Sections 4.2 and 4.3 present two test cases taken from the full set of tests performed by DNV. The full extent of the tests conducted during the TQ evaluation is summarised below:

- Sensitivity to temperature
- Sensitivity to pressure
- Sensitivity to viscosity
- Sensitivity to transducer failure
- Sensitivity to transducer contamination
- Sensitivity to meter body contamination
- Sensitivity to flow profile / flow conditioner blockage
- Detectability of the presence of gas in liquid or liquid in gas
- Robustness in the presence of gas in liquid or liquid in gas

4.2 Example 1 – Simulation of Poor Transducer Signals

In this first example, one of two wires connecting one of the transducers on path no. 6 was severed to simulate reception of a poor-quality signal without outright failure of the measurement path. Figures 5 below, shows one of the conventional diagnostic parameters, 'gain', before (a) and after (b) the wire was severed. The gain represents the amount of amplification applied to the signal received on the measurement path and it can be observed that when the wire was severed the gain on path 6 exceeds the warning and alarm limits indicated by the vertical orange and red lines. Whilst this information is useful for indicating that a problem has occurred, it does not provide any indication of the likely magnitude of error that might be associated with the problem.



(a) (b)

Figure 5. Signal gain diagnostic prior to (a) and during (b) the simulated failure

Figures 6 and 7, show output of the SVM Uncertainty under the same conditions. In Figure 6, it can be observed that over the full range of velocities tested the meter's evaluation of its own uncertainty is within a range of +/- 0.1 % to +/- 0.15 %. Following the severing of the transducer wire, the uncertainty output from the self-verifying meter increases as shown in Figure 7.

Also shown in Figure 7, are the error/deviation results of comparing the meter in the fail condition against the reference standard in the laboratory. It is apparent that the error magnitude is similar to the SVM uncertainty evaluation, and the trend of error increasing as flowrate is reduced,. The fact that the error magnitude is smaller than the SVM uncertainty evaluation is not problematic, as the uncertainty evaluation describes the *probable range of error*, and it is to be expected that errors can be of lower magnitude than the uncertainty.

Comparing Figures 6 and 7, it is clear how the end user can utilise this quantitative output of uncertainty to drive decision making. For example, if operating only at high velocities (> 10 m/s) the user may be able to tolerate the increase in uncertainty to approximately +/- 0.2 %, but if operating at velocities of 5 m/s and below, the increase in uncertainty to +/- 0.5 % may be too large to tolerate, meaning remedial action must be taken promptly.

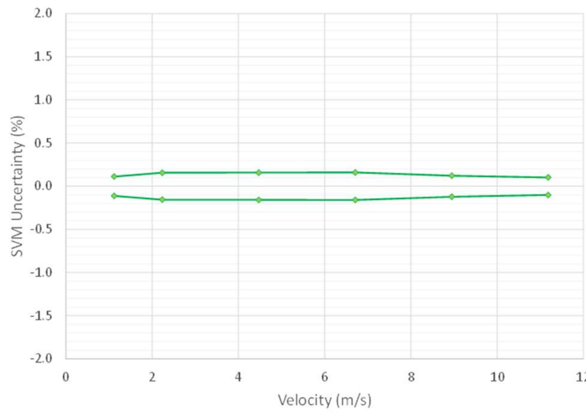


Figure 6. SVM uncertainty evaluation output under normal conditions

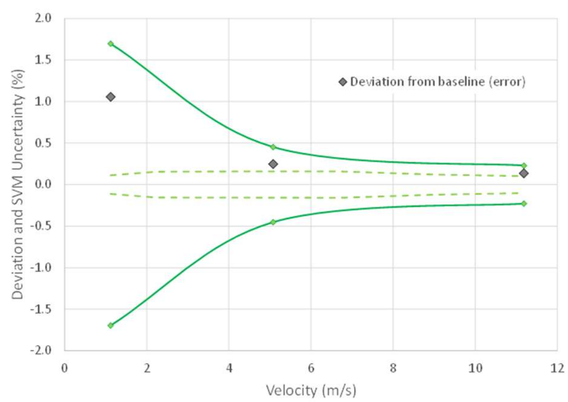


Figure 7. SVM uncertainty evaluation and error relative to the reference with simulated poor transducer signal

4.3 Example 2 – Gas SVM in Wet Gas Conditions

The second example is taken from testing the SVM gas meter in wet gas conditions. Figure 8 shows the result of testing the meter with gas flow at 7.5 m/s velocity and a pressure of 35 bar with addition of liquid up to 1.1 % by volume. It can be observed that the SVM uncertainty output increases gradually from +/- 0.19 % at a liquid volume fraction of 0.02 % to +/- 3 % at a liquid volume fraction of 1.08 %. Also shown on Figure 8, are the deviations/errors with respect to the laboratory reference dry gas rate. Again, it can be observed that there is good agreement between the SVM uncertainty evaluation and the errors relative to the reference. At the maximum liquid volume fraction, the SVM uncertainty evaluation is +/- 3 % when the deviation relative to the reference is 3.8 %. Although in the extreme case the uncertainty has been under-estimated, relative to uncertainty expectations for custody transfer the magnitude of uncertainty is large and hence the SVM uncertainty output is still deemed to be very useful is it is of similar magnitude to the error and would prompt appropriate action (as confirmed by DNV, see section 4.4 below).

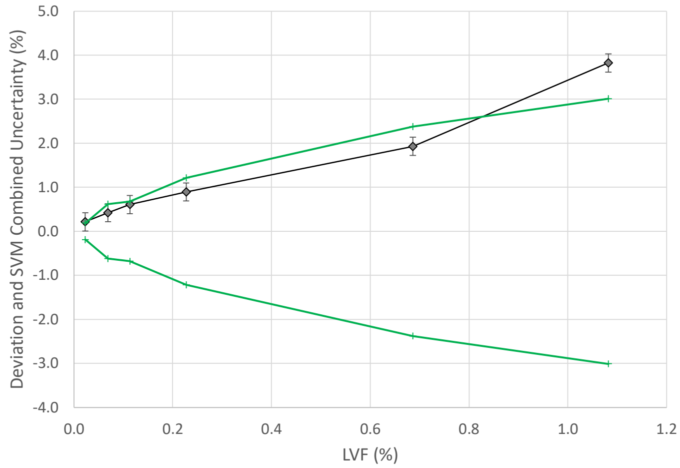


Figure 8. SVM uncertainty evaluation and error relative to the reference in wet gas conditions

Figure 9 below, shows the three main components that contribute to the uncertainty evaluation output by the SVM in the wet gas example. These are the chordal velocity, integration/profile and area uncertainty terms as discussed in sections 3.3, 3.4 and 3.5 respectively. In this example, the chordal velocity measurement uncertainty and the velocity profile averaging uncertainty do not increase noticeably until the liquid volume fraction has exceeded 0.7 %, and in all cases the largest contribution of the overall SVM uncertainty output is from the area term. This example highlights useful additional information that can be obtained from the component parts of the SVM uncertainty calculation, in this case providing a clear indication of the cause of the increased uncertainty.

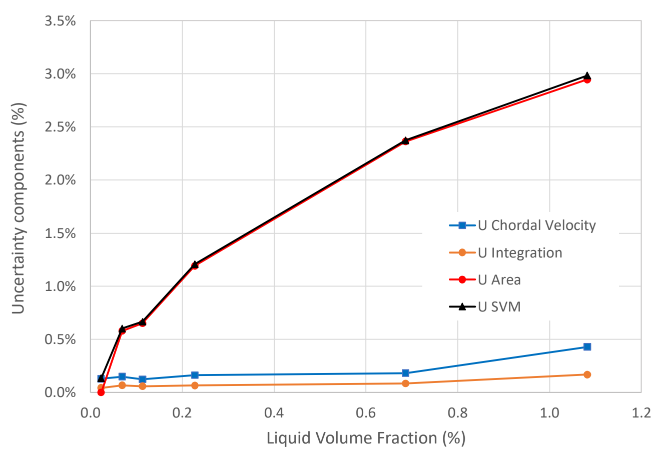


Figure 9. Components of the SVM uncertainty evaluation in wet gas conditions

4.4 Summary of the DNV TQ

The DNV technology qualification results are summarised in Technology Certificates for the gas and liquid meters respectively (DNV 2021a and DNV 2021b). The following statements are taken directly from the SVM gas certificate with the extracts corresponding to the liquid certificate added in square brackets where those differ.

- *The Caldon SVM gas [liquid] meter has undergone a technology qualification and on all aspects tested it qualified for the most stringent requirements as set for fiscal metering class I[L]-AAA [with accuracy class level of 0.25%]*
- *The Caldon SVM meter is a robust meter that is capable of handling field disturbances efficiently. In most cases the meter is able to cope very well with the field disturbances, in the sense that the meter flow output is hardly affected*
- *The SVM live uncertainty output were consistent with the deviations determined by testing in 95% [98%] of the conditions tested, meaning the deviations were equal to or smaller than expected based on the reported uncertainty values. Even in cases where the SVM uncertainties are slightly lower than the actual deviation, those deviations (>3%) are so high that they are detected rapidly. [In the one case where the SVM value was lower than the actual deviation, the deviation and U-SVM values are so high that the condition is detected rapidly.] Overall, it is concluded that the diagnostic ability of this meter, making use of the U-SVM uncertainty evaluation, is very high and provides a validated and useful tool to determine that the meter has potentially large deviations and action should be taken.*

5 Summary and Conclusions

The self-verifying meter (SVM) technology introduced in this paper is a powerful tool for continuous validation of measurement results in applications where high accuracy is critical including fiscal and custody transfer of liquid and gaseous hydrocarbons.

In contrast to pre-existing ultrasonic meter diagnostics and condition-based monitoring, SVM provides live quantitative output of measurement uncertainty derived from additional measurements that are dedicated to that purpose. The additional measurements used in the uncertainty evaluation have been carefully designed to specifically address each of the components that can contribute to the uncertainty of the ultrasonic meter. The results of the uncertainty evaluation are provided as the overall uncertainty in the flowmeter's volumetric output and can be presented in units of volumetric rate or as a relative percentage of rate, as well as being totalised internally alongside the volume throughput totals. Uncertainty components that are determined in the process of calculating the overall uncertainty are also available for analysis.

The end result is a self-verifying meter (SVM) that continuously determines flow rate and the uncertainty in that flowrate. This allows the end user to quickly detect and understand the impact of a change in the meter's performance, so that warning and alarm limits can be set in a much more meaningful way than before, and actions driven accordingly.

In addition to being based on a first-principles approach, the uncertainty quantification provided by the SVM technology has been independently qualified by DNV, providing a very high level of confidence in its use.

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Data Availability

The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest

All authors confirm there are no conflicts of interest.

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