VERIFICATION OF CORIOLIS FLOW METER CALIBRATION: THEORY AND PRACTICE, INCLUDING LAB AND FIELD RESULTS

Paper # 2015-0164 CsHm 2015

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INTRODUCTION

Coriolis flowmeters precisely measure mass flow. Separately and independently from the mass flow measurement, Coriolis meters also measure liquid density. Coriolis mass flowmeters use these two measurements to calculate volumetric flow. Because of their inherent accuracy, minimal maintenance, and absence of moving parts to wear out, Coriolis flowmeters have become widely used in a range of applications. This paper will discuss how verification techniques, in conjunction with this inherent robustness, can be used to confirm mass flow calibration.

Many flow measurement applications require that the flowmeter be proven or verified. Coriolis flowmeters can be proven like any other type of flowmeter using fixed or portable provers [1, 2]. However, proving can be costly and difficult in some processes. Because of this, several techniques to verify the measurement of the Coriolis meter have been developed. This paper will give a brief overview of a subset of meter verification techniques.

Alberta Energy Regulator's Directive 17 allows verification techniques to be used to extend proving intervals in some applications [3, 4]. AER recognized that the inherent reliability of Coriolis flowmeters, their long history of maintenance free use, and the development of advanced verification technologies by vendors provide measurement confidence. Coriolis verification is also recognized by AGA-11/API MPMS Ch 14.9. This recognition can reduce cost of ownership of Coriolis technology.

To give users a framework to make informed decisions around meter verification, statistical hypothesis testing will be discussed. Hypothesis testing uses a 2 x 2 matrix to present the four possible outcomes relating meter condition and verification results.

Flow and verification data from third-party testing of one manufacturer's meters will be presented to illustrate hypothesis testing with actual flowmeters. This data shows the validity of using meter verification to confirm meter accuracy.

Case studies will be presented to show how meter verification can detect the rare condition under which meters actually fail.

To better understand Coriolis flowmeter verification techniques, Coriolis theory is first presented to provide background understanding.

CORIOLIS FLOWMETER THEORY

A Coriolis mass flowmeter directly measures the mass flow rate of a fluid by vibrating (driving) a fluid-conveying tube at resonance. A common geometry for high-performance Coriolis flowmeters is the dual "U" tube shown in Figure 1. Flow enters from the pipeline and is split by the inlet manifold into the two U-shaped flow tubes. The flow is then rejoined at an outlet manifold and continues down the pipeline.

The meter is driven in a balanced, out-of-phase fundamental bending mode, similar to a tuning fork. The Coriolis forces are generated by the cross product of the mass flow and the tube motion. These forces act on the tubes to perturb the vibrational motion, giving rise to a spatially varying time delay along the tube as shown in the top view of Figure 1. The difference in time delay between two locations is called δt, and is used to calculate mass flow rate.

The amount of perturbation of the flow tube motion, and therefore the δt, is dependent on the magnitude of the Coriolis forces and the stiffness of the flow tubes. For a given tube shape and mass flow rate, the Coriolis forces are constant. The δt therefore depends on the stiffness of the flow tubes. Tube stiffness is an important factor in verification techniques and is discussed in that context in a later section.

The mass flow rate measurement is related to the δt by the flow calibration factor which is discussed in the next section

MASS FLOWRATE MEASUREMENT

The mass flow rate $\dot{m}$ through a Coriolis sensor is related to the time delay δt by a proportionality constant called the flow calibration factor (FCF) [5].

Presented at Canadian School of Hydrocarbon Measurement March 17-18, 2015
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Expressed algebraically, mass flow rate through a sensor $\dot{m}$, is given by

$$\dot{m} = FCF \cdot \delta t \qquad (1)$$

The FCF, the mass flow calibration factor, is defined in units of mass flow rate/time delay. Typical units for the FCF is (gm/sec)/μsec.

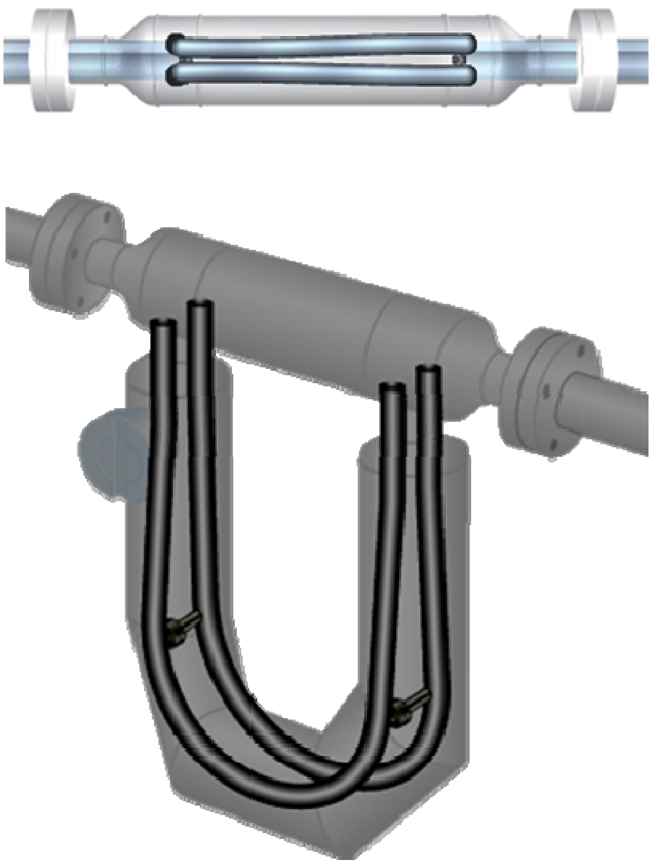


Figure 1. Typical Coriolis Meter

Since the discussion above said that the magnitude of the δt is proportional to the tube stiffness, the FCF should also be related to tube stiffness. This relationship can be shown by laborious derivations from first principles [6, 7]. However, a much simpler dimensional analysis, which uses the fundamental physical units of length, mass, and time, shows that indeed the FCF has units of stiffness.

The dimensional analysis starts by rearranging Equation (1) to isolate the FCF term.

$$FCF = \frac{\dot{m}}{\delta t} \qquad (2)$$

Equation (2) shows that the derived units of the FCF are mass flow rate/time delay, e.g. (gm/sec)/μsec.

This is shown dimensionally using fundamental physical units as

$$FCF \approx \frac{\left(\frac{Mass}{Time}\right)}{Time} \qquad (3)$$

(The $\approx$ can be read as “has units of”.) In a consistent system of units, mass can be represented by force/acceleration, taking advantage of Newton’s Second Law. Substituting this into Equation (3) shows that the flow calibration factor has units of stiffness (Force/Length).

$$FCF \approx \frac{\left(\frac{Mass}{Time}\right)}{Time} = \frac{\left(\frac{Force / acceleration}{Time}\right)}{Time} = \frac{\left(\frac{Force / (Length / Time^2)}{Time}\right)}{Time} \approx \frac{Force}{Length} \qquad (4)$$

So the FCF, which relates the δt to the mass flowrate, is simply a scalar multiple of the stiffness. Mass flow rate is the fundamental measurement made by Coriolis flowmeters.

DENSITY MEASUREMENT

Coriolis flowmeters also independently measure the density of liquid process fluids by very accurately measuring the resonant frequency of the drive mode. The resonant frequency is a function of the stiffness of the flow tubes and the mass of the flow tubes which includes the mass of the steel of the flow tubes plus the mass of the fluid within the tubes.

$$Freq \propto \sqrt{\frac{Stiffness}{(mass_{tube} + mass_{fluid})}} \qquad (5)$$

The stiffness of the flow tubes and the mass of the steel in the flow tubes is constant; so the resonant frequency depends on the mass of the fluid in the tubes. Since the tubes contain a fixed volume of fluid, the resonant frequency is dependent on the density of the fluid within the flow tubes (density=mass/volume).

While Coriolis meter can measure density of liquids very accurately, the density signal is not adequate for accurate gas density measurement. Other vibrating element technologies are optimized for gas density measurement.

CORIOLIS METERS & VOLUMETRIC FLOW RATE

Coriolis flowmeters can calculate volumetric flow rate from the independently measured mass flow rate and density using Equation (6),

$$Q = \dot{m} / \rho \qquad (6)$$

where Q is the volumetric flow rate, and ρ is the fluid density. Most other flowmeter technologies produce volumetric flow as the raw output, which is typically converted into a standard volume. Note that standard volume is closely related to total mass. Coriolis meters can also produce a standard volume output using either the instantaneous density as measured by the Coriolis meter, a standard or sampled density, or a calculated density based on process conditions.

PROVING

Proving is recognized by Directive 17 as the validation technique for flowmeters. Flowmeters are proven by comparing the indicated flow measurement (volume or mass) to a reference flow volume or mass. Proving techniques generate a Meter Factor, a number near 1.000 that adjusts the Flow Calibration Factor (FCF) so that the unit under test matches the reference. Meter Factors are adjusted until they reach a threshold value, at which point the meter is replaced or repaired and recalibrated. Typical proving intervals are monthly, quarterly, or annually.

Other flowmeter types, e.g. turbines, positive displacement (PD) meters, orifice plates, can show wear in bearings, changes in clearances, or damage due to fluid impingement. As a result, the flow accuracy of these meters can change over time. The goal of proving these non-Coriolis flowmeters is to track wear in meters that are changing and adjust the calibration.

Coriolis meters can be proven like any other flowmeter, although due to their fundamentally different nature, care must be taken to insure that they are configured properly for proving and that appropriate proving techniques are used [1, 2].

PROVING AND CORIOLIS FCF STABILITY

Coriolis meters are commonly proven in the field by comparing the calculated volumetric flow total from the Coriolis meter to the standard volume of a prover. Figure 2 shows a plot of the meter factors from six Coriolis meters used in a cavern storage application. Some of these meters have been in use for as long as 13 years. The meter factors show random variation and some bias in the meter factor. However, the provings generate a meter factor that is essentially constant over the lifetime of the meter, again showing the stability of the Coriolis flowmeter calibration.

A conservative estimate of the cost of the ~375 provings in Figure 2 is ~$200,000 (assuming ~$500 per proving). Provings may be required by legal requirements, regulations, or standard procedures. However, the data shows that these provings added nothing to the measurement accuracy of the Coriolis flow measurement [8].

Recognizing the stability of Coriolis flowmeters, users have asked Coriolis vendors to develop techniques to use the meter's onboard electronics to verify the accuracy of the flow measurement.

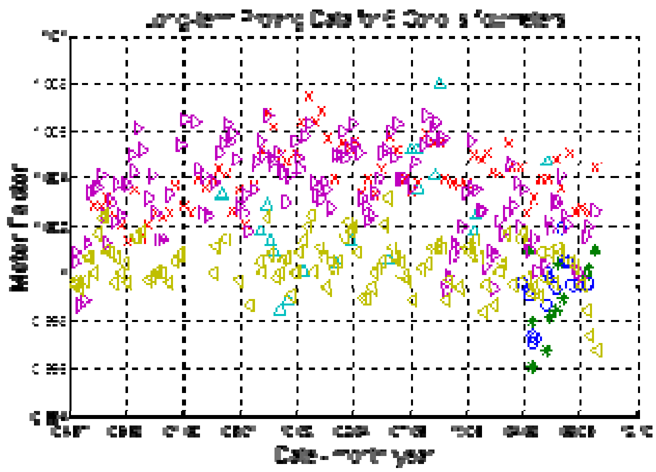


Figure 2. Long Term Coriolis Proving Data

Vendors have responded by developing several different verification technologies. Keeping pace with these developments and acknowledging the stability of Coriolis meters, Directive 17 allows the use of Coriolis verification techniques to extend proving intervals [3, 4].

Several different verification technologies are discussed next to give users a background in these methodologies. Then hypothesis testing will be presented so that these technologies can be evaluated in a formal way.

VERIFICATION METHODOLOGIES

Many different verification methodologies are available. Some are vendor independent, others are proprietary to particular vendors. Some require stopping the flow or stopping the process measurement to perform the verification. Others can be done *in situ* without stopping flow or the flow measurement. These verification methodologies can include measuring and trending process measurements, looking at internal parameters such as drive gain and pickoff amplitude, and using additional hardware internal or external to the transmitter to verify flow measurement. Some of these techniques can be done by the user and others require a service technician visit by the vendor. An overview of these methodologies was been presented previously at the Canadian

School [9] and at the International School of Hydrocarbon Measurement [10].

These papers also compared verification to proving and pointed out the need for verification techniques to check electromechanical and electronic hardware changes, transmitter configuration changes, digital or analog output hardware and configuration, and zero changes. Some of the verification techniques can do some or all of these checks. The previously mentioned papers pointed out the need for dialogue between users and vendors to understand the fine points of the verification methodologies and how they might or might not work in particular applications.

STIFFNESS-BASED VERIFICATIONS

Rather than rehashing these other papers this paper will give a brief overview of four different "stiffness based" verification techniques and compare and contrast their similarities and differences. This focus on stiffness based techniques is because of the previously described relationship between the mass flow calibration factor and stiffness.

A Coriolis flowmeter can be characterized by its mass, its damping, and its stiffness [11]. A common way to express this characterization is by the mathematical concept known as a Frequency Response Function (FRF). An FRF quantifies the response of the flowmeter to forces at specific frequencies. FRFs are discussed in detail in reference [12].

Measuring damping, mass, and stiffness simultaneously and independently requires solving at least three equations for the three unknowns. The fields of Experimental Modal Analysis and Structural Dynamics use very robust theory to develop many techniques to solve these equations from experimental data or finite element analysis based results. Coriolis vendors have adapted these techniques to develop various verification methodologies.

It can be quite challenging to calculate FRFs and solve equations in an embedded transmitter. As digital signal processing (DSP) power has advanced vendors have developed various methods to solve for the Coriolis stiffness to provide a verification metric. These different verification techniques start by recognizing that stiffness is the verification variable of interest. The various verification techniques manipulate the form of the FRF equations to solve for different representations of the stiffness, mass, and damping. Additionally some assumptions might be made to eliminate one or more equations.

It is important to recognize that these stiffness based techniques are not generating an absolute stiffness number that can be traceable to national standards. Instead these techniques focus on presenting a change in stiffness relative to a factory or calibrated value. While it is technically possible to generate an absolute stiffness number, the calibration rigor required to do so would not be cost-effective. Presenting stiffness results as a percent change from a baseline is much simpler, cheaper and provides the needed information in a format easily understood by the user.

The first stiffness-based technique discussed makes two assumptions resulting in one equation and one unknown.

STIFFNESS VERIFICATION 1. KNOWN DENSITY VERIFICATION

Known density is a legacy Coriolis verification technique that can still be used successfully today. It can be used on any model of Coriolis flowmeter that provides a density output.

The known density method rearranges the FRF equations using Equation (5) to represent the drive frequency in terms of stiffness and mass. Additionally, the known density technique makes two assumptions to eliminate two equations. First, the damping is assumed to be very small, generally a good assumption. Second, it assumes that the mass, that is the density of the fluid, is very well known. With these assumptions the stiffness can be verified.

The known density method compares the natural frequency of the meter on the controlled fluid to a factory value. If the natural frequency is the same as the factory calibration value then the ratio of the tube stiffness to the tube and fluid mass is unchanged from the factory ratio. The tube mass is assumed to be unchanged since the fluid mass is very accurately known. Therefore the tube stiffness is verified to be the same as it was when it left the factory. Since the tube stiffness is unchanged, the FCF will be the same as the factory value.

Known density verification by definition verifies that the density measurement is correct. Since both the mass flow and density measurements have been verified, then the volumetric flow measurement is also correct.

The known density technique gives information about the stiffness of the meter assuming a known mass. The next technique tries to eliminate the mass effects from the verification by using a ratio of two resonant frequencies, eliminating an assumption and providing a second equation.

STIFFNESS VERIFICATION 2. VERIFICATION OF DRIVE AND CORIOLIS MODE FREQUENCIES

This method of stiffness verification uses the ratio of two different natural frequencies of the flowmeter. To perform this verification the flowmeter is taken off-line, the meter is driven in the "Coriolis" mode, and the electronics measures the natural frequency of this mode. The natural frequencies of the normal drive and the Coriolis modes are ratioed and compared to a factory baseline. Ratioing the two natural frequencies in this manner practically eliminates the effect of process fluid density on the natural frequencies.

Any change in this ratio is due to differential changes in the modal masses or stiffnesses along the length of the tube. Again, since the Coriolis flowmeter is not expected to change, the ratio of the frequencies is expected to be constant over the life of the meter. If there is a change in the ratio of the frequencies, damage to the meter might have occurred or coating may be present.

This technique shows that additional information can be extracted from the flowmeter by driving it at a different frequency in addition to the drive mode frequency. In this case the different frequency is a resonance frequency other than the drive mode. This additional frequency gives information about any changes to the structure of the flowmeter.

The third verification technique discussed uses a single off resonance frequency (called a test tone) in addition to the drive mode to generate a second equation.

STIFFNESS VERIFICATION 3. CONFIRMING WALL THICKNESS WITH A SINGLE TEST TONE

The FRF equations can be rearranged so that wall thickness shows up as the verification variable [13]. For small changes in wall thickness, wall thickness can be related to meter stiffness. Again damping is assumed to be very small. During this verification process the meter is excited at a single additional frequency higher than the normal drive mode frequency, typically 10 to 20%. The response at this single additional test tone gives a second equation. With some reasonable assumptions about the dynamics of the flowmeter, the second equation can be solved to verify that the wall thickness is unchanged.

To solve for the damping, mass, and stiffness independently with no assumptions requires at least three equations. Direct stiffness measurement uses this approach

STIFFNESS VERIFICATION 4. DIRECT STIFFNESS MEASUREMENT

Direct stiffness measurement uses four additional test tones to measure the damping, mass, and stiffness independently with no assumptions. Two of the test tones are at frequencies below the drive mode frequency and two are at frequencies above the drive mode frequency. This results in an overdetermined set of five equations that reduce the effect of noise while solving for the three measurement variables [12].

This technique directly verifies the flow tube stiffness. Since it also uses the onboard electronics and the pickoff and drive transducers it also confirms the integrity of the transducers, wiring and the transmitter hardware and software.

The stiffness is normalized to a factory baseline and presented as a percent change. There is of course some variation in each measurement but an unchanging mean value of the stiffness verifies that the mass flow calibration is correct.

Figure 3 shows some typical direct stiffness measurement meter verification results, again from a cavern storage meter. Stiffness verification was run without controlling the process in any way. Flowrate, density, and temperature were varying considerably over the six month time span of the data. The data shows some random variation, but the mean stiffness change value is 0%. This meter has passed every verification run since all of the data is within the specification limits.

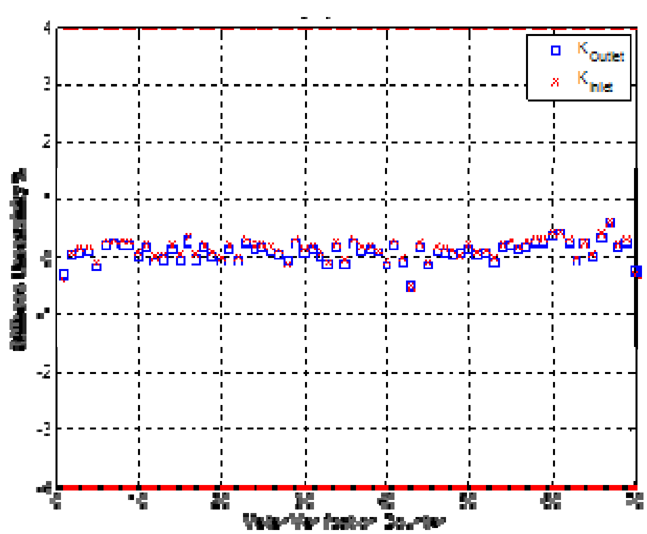


Figure 3. Direct Stiffness Measurement Verification Results

Verification results are not to be confused with proving results or any sort of meter factor. The next sections discuss a useful way with which to view meter verification.

STATISTICAL HYPOTHESIS TESTING

Statistical hypothesis testing provides a framework with which to view verification results in general. It also provides a tool with which to compare different verification methodologies. Contrasting proving with verification will show the value of the hypothesis testing framework.

PROVING METROLOGY

Proving can be presented as a specialized subcase of generalized hypothesis testing to highlight some important requirements associated with proving. Then those requirements will be re-examined when verification is discussed.

Table 1 shows this specialized subcase. There are two rows, corresponding to the meter condition. The top row is the condition where the meter is good and the bottom row is a condition where the meter is bad. The single column refers to the proving results.

Provers are treated as a traceable standard. This means that they are calibrated at regular intervals against a known standard which is ultimately traceable to a national reference. That is common knowledge.

A required condition for provers is that their variability, accuracy, and reproducibility on flow measurement is 3 to 10 times better than the flowmeter that is being proven. This requirement allows the generalized 2 x 2 statistical hypothesis testing matrix to be reduced to the 2 x 1 vector in table 1. This condition allows the prover to be treated as a reference standard against the Coriolis meter. Whatever the prover says is treated as the "accurate" result. No interpretation is required. The meter is adjusted to match the prover. The meter condition is determined based on whether or not it matches the prover.

Table 1. Proving Metrology Table

		Prover
		Correct by Definition
Meter Condition	Meter matches prover	Pass Do nothing
	Meter doesn't match prover	Fail Adjust meter factor

To drive this point about the required condition home further, Table 1 shows that there are only two possible outcomes from the proving. The meter matches the prover, cell 1, in which case nothing is needed to be done. Or the meter doesn't match the prover, cell 2, in which case the meter factor is adjusted so that its flow reading matches the prover. The meter condition, its accuracy, is determined based on whether or not it matches the prover.

The situation is somewhat different with verification techniques.

VERIFICATION METROLOGY

Verification tracks a secondary variable that is highly correlated to the flow measurement. Verification results are not traceable to a known standard. The variability, accuracy, and reproducibility of verification results are not 3 to 10 times better than the flow measurement. Typically the variability of verification results under lab conditions are on a par with the variability of the flow measurement. The variability of verification results may increase greatly over the entire range of process conditions that the meter might experience, flow, pressure, density, mounting, temperature.

A methodology known as hypothesis testing can account for the larger variability of verification, as compared to a prover. Hypothesis testing allows verification results to be used with confidence to confirm meter accuracy, as specified by Directive 17. Hypothesis testing is used in fields as diverse as medicine, pharmacology, radar, and target recognition.

Table 2. Verification Hypothesis Testing Matrix

		Verification Result	
		Pass	Fail
Meter Condition	Meter is accurate	True Positive	False Alarm
	Meter is inaccurate	Covert Failure	True Negative

Table 2 shows a generalized 2x2 hypothesis testing matrix as applied to flowmeter verification. This table can be transposed and/or the rows and columns interchanged without affecting the underlying information. Additionally the conditions can be defined in a way that makes sense for the application. For example a positive test result in medicine means that the test indicates that the patient has the disease. A doctor would consider a patient that actually has the disease to have a positive condition. It seems that medicine could use better marketing to define their nomenclature.

Table 2 is presented with the rows of the matrix corresponding to the meter condition, i.e. Is the meter actually measuring within specification or not. Similarly to Table 1, the first row corresponds to a meter condition where the meter is reading flow accurately. The second row corresponds to a meter condition where the meter is reading outside the flow accuracy specification. But the difference here is that the actual condition of the meter will not be known if there are no proving results.

Table 2 has an additional column compared to Table 1. These columns correspond to the verification result, pass or fail. The individual cells of the matrix represent the correlation between the condition of the meter and verification results The point of presenting the hypothesis testing matrix is to show that the condition/accuracy of the meter can be determined probabilistically from only the meter verification result.

AER's Directive 17 allows the use of internal meter verification diagnostics to extend proving intervals for many Coriolis applications [3,4]. Directive 17 allows the user to extend proving intervals based upon a passing verification. Directive 17 also requires additional actions to be taken, e.g. proving, if a verification fails.

This "green light/red light" approach suggested by Directive 17 may be all that is needed for many application. Relying solely on the pass or fail results of the verification makes sense for many users. The interpretation of the results are left up to the software that is provided by the Coriolis manufacturer. Users should ask their Coriolis vendor(s) to discuss their verification technology, their test results, their experience with their product in similar applications, and third party test results correlating accuracy and verification.

If these discussions show that the pass/fail approach is suitable, and this indeed can be a very good way to approach verification, the statistical discussion in the following section may not be as relevant for those users.

For users that want or need to know more, the next section provides some statistical background on meter verification. The approach presented is useful for evaluating different verification technologies. The next section also provides criteria for evaluating applications for the best approach to verification.

Example meter verification results from third party testing and vendor evaluation of returned meters are presented after the statistical discussion.

FOUR POSSIBLE OUTCOMES FROM METER VERIFICATION

Unlike proving, verification results must be interpreted in the context of the statistics associated with each cell of the hypothesis testing matrix. Most of the questions and concerns around meter verification revolve around trying to interpret the meter verification results as if they were proving results.

Note that while running meter verification by itself the user does not know the true condition of the meter, i.e. in which row is the meter. Is it accurate or not? Proving has a clear pass/fail condition for the meter because the prover is treated as a standard. Using meter verification, users will generally not get independent confirmation of whether the meter is reading accurately or not because there will be no proving results.

Table 2 shows that there are actually four possible outcomes from a verification run. The methodologies discussed here on how to interpret the results can be applied to all verification technologies and indeed all flow measurement techniques, not just Coriolis flowmeters. The statistics associated with each outcome should be discussed with vendors when evaluating verification methodologies.

One of the first things to understand about interpreting meter verification results starts with understanding the statistics around the rows in this table. The meter is good or bad independently of whether or not meter verification has been run. Vendors can provide statistics on failure rates and expected lifetimes for their Coriolis meter. That forms the basis of the statistics associated with the rows, the condition of the meter. These statistics will show that there is an extremely high probability that the Coriolis flowmeter is measuring accurately, whether or not a verification technique is used.

The columns of the hypothesis testing matrix correspond to the statistics around verification passes and failures. In the general case these the statistics would be collected over a random population of meters and the incidences of passes and fails would be tabulated. But that turns out to be not particularly useful. A more useful approach is to directly calculate the statistics, or probabilities, associated each individual outcome as discussed below. This approach requires an understanding of how the verification results correlate to the meter condition.

For a flowmeter, a condition where the meter is measuring mass flow accurately will be considered positive. For a verification result a passing result will be considered positive. The first possible outcome in cell 1, the top left, is called a true positive. For Coriolis flowmeters the vast majority of results will be true positives, accurately reading mass flow and passing verification.

The second possible outcome in cell 2, the top right, is called a false positive or perhaps preferably a false alarm. The meter is still good but verification indicates a failure. False alarms can result in needless expenditures to confirm that the meter is indeed working correctly

The third possible outcome in cell 3, the bottom left, is called a false negative, or to give it an appropriately concerning label, a covert failure. Verification has indicated that the meter is okay but the meter is actually not measuring flow to specification. Covert failures are the worst outcome for verification as safety and/or accuracy may be compromised.

The fourth possible outcome in cell 4, bottom right, is a true negative or true failure. The meter is no longer measuring flow accurately and the verification result flags it. A true negative is bad news in that the meter is no longer measuring accurately but good news because verification has detected the failure.

If meter verification results were deterministic, i.e. there were never any false alarms or covert failures and only true positives and true negatives, this hypothesis testing matrix can be thought of as the single column matrix used for proving as shown in Table 1. As much as vendors would like to provide a deterministic meter verification result about the condition of the meter, verification actually provides probabilities as to whether the meter is reading accurately or not. This is not as much of a problem as it might seem because of the inherent robustness of Coriolis flowmeters.

That robustness forms, in part, the basis for the confidence in verification technologies and the pass/fail approach endorsed by Directive 17.

One possible conservative approach to adopting verification to extend proving intervals is to continue proving and start to collect verification results. For most conditions and most Coriolis flowmeter applications the proving will pass and so will the meter verification. Good statistics for cell 1, true positives, will be collected. True positive results from third-party testing are presented below.

EXAMPLE VERIFICATION RESULTS – TRUE POSITIVE, CELL 1

The verification results presented in Figure 3 are a good example of what will be seen in a typical application. These results are definitely true positive results, first because the verifications all passed and second because there were provings done at regular interval that confirmed the meter was accurate.

Following the letter of Directive 17, since all of the verification results in Figure 3 were within the manufacturer's specification, this meter's proving interval could be extended.

Of course, a statistical analysis could be performed on those verification results. However, as mentioned above, don't make the mistake of treating the verification statistics as proving results. Going back to one of the original assumptions in the hypothesis testing matrix, the variation of the verification result can be different than the flow measurement variation. This variation can be affected by flow noise, temperature gradients, process conditions, and other field effects. The statistical analysis should be focused on showing that there is no change in the mean value of the verification results. Again, Directive 17 does not require this analysis. Only users in applications where the meter is expected to fail need to concern themselves with the statistics, as discussed below in the section on cells 2 and 3.

In another round of third-party testing of direct stiffness measurement verification, NMi in the Netherlands conducted testing on two Micro Motion Coriolis meters, a 1 inch meter and a 2 inch meter. Flow accuracy results and meter verification results were recorded. The goal of the testing was to get an understanding of the variability of meter verification results over a realistic range of process conditions.

NMi conducted tests at NEL in Scotland on gas oil over a range of flow rates and elevated temperatures. To further evaluate temperature effects, the meters were tested in both insulated and uninsulated conditions

NMi conducted further tests at Pigsar in Germany on natural gas at two pressures over a range of flow rates. Flow accuracy and verification results are presented for all of these tests for the 1 inch meter are shown in Figure 4 and for the 2 inch meter in Figure 5. Data for each condition is averaged to simplify the graph. The flow accuracy of these meters is well within specification and all of the verification results passed. Therefore these are true positive results.

These figures show the mass flow accuracy on the Y axis and the direct stiffness verification results on the X axis. All of the process conditions are plotted on the graph. The mass flow accuracy is well within the corresponding accuracy specifications for liquid and gas. The direct stiffness verification results are well below the 4% specification limit. Indeed under this range of process conditions the verification variation is within ±0.6 %.

These true positive results show that verification can confirm that a Coriolis flowmeter is good. But it is important to also understand a verification technology's detectability. Some examples of direct stiffness verification technology detecting failures follow.

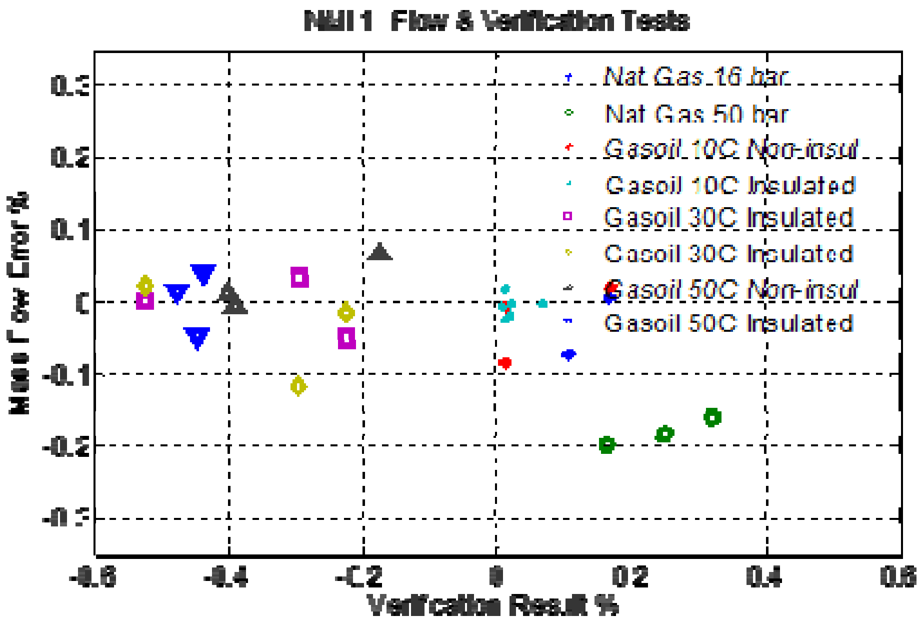


Figure 4. NMI Testing Mass Flow Accuracy vs Verification Results 1" meter

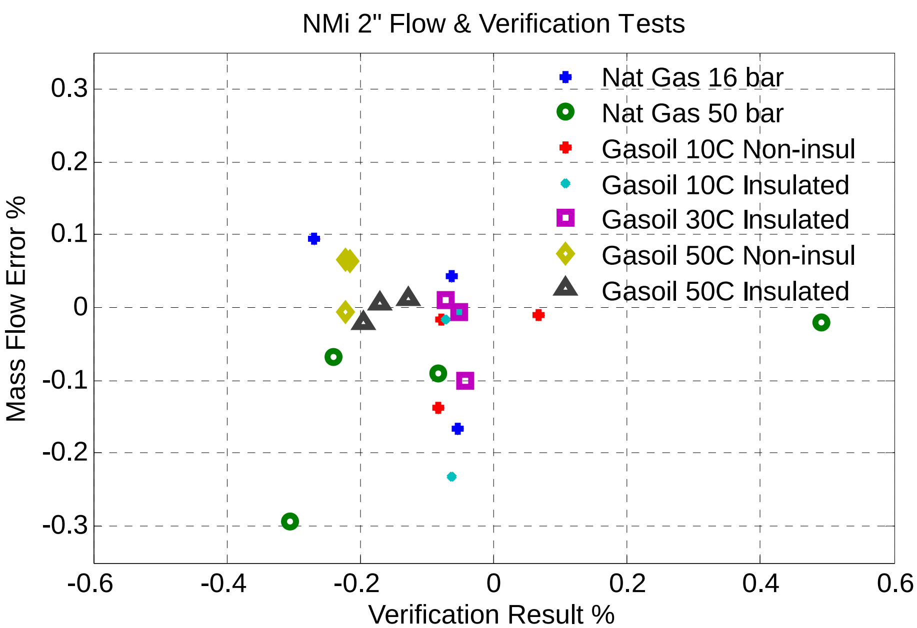


Figure 5. NMI Testing Mass Flow Accuracy vs Verification Results 2" meter

EXAMPLE VERIFICATION RESULTS – TRUE NEGATIVE, CELL 4

There is a problem with trying to analyze true negative results from Coriolis verifications. There are so few failures that it's hard to get enough data. Of the hundreds of thousands of Coriolis meters actively in service by one Coriolis vendor, two failure cases have been identified and are presented below.

The first example shows a 2 inch low-profile Coriolis meter used in an erosive slurry application. The calibration on this meter was suspect and indeed verification reported a reduction in stiffness outside the failure limit and flagged it as a failure. This meter was returned to the vendor for a quality inspection. Initial visual inspection showed clear erosion in the inlet manifold as shown in Figure 6.

This meter was flow tested using the as-found calibration values. The density was reading almost 0.25 gm/cm^3 high with a mass flow error of over +10%.

This meter was deconstructed and wall thickness was measured on both tubes along the path length and around the circumference of the tubes as shown in Figure 7. The measurements show that one side of the inlet tube is eroded such that the thickness is reduced around 6%. Much of the meter appears to have experienced no thinning whatsoever.

Figure 8 shows that the normalized stiffness for the inlet pickoff has decreased almost 10% while the outlet pickoff has decreased 8%, in line with the shift in the mass flow calibration factor. While the FCF is expected to decrease with a decrease in stiffness, the change in stiffness is not expected to equal the change in FCF, i.e. a meter factor cannot be derived from the verification results. The meter had decreased in stiffness because of the wall reduction, overreporting flow resulting in a positive mass flow error. This decrease in stiffness reduces the drive frequency causing the high density reading. All the data is consistent. The meter was scrapped.

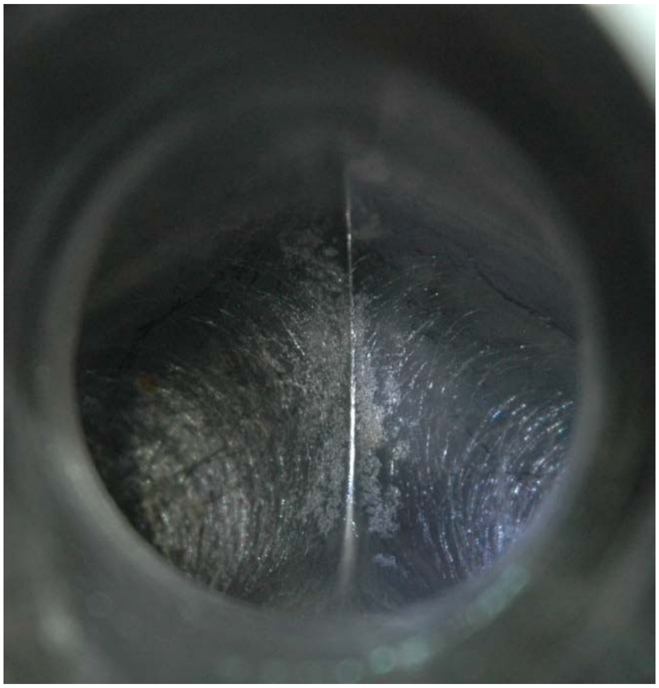


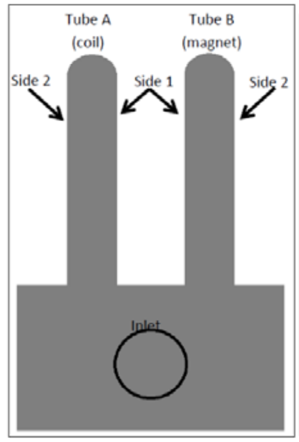
Figure 6. Eroded Inlet Manifold

The second failed meter is another 2 inch meter of a different model type, a dual U-tube. This meter was built into a skid and the entire skid was hydro-tested during the factory acceptance test. The meter then failed the initial prove. The meter was returned for quality inspection. The user had not purchased meter verification.

The quality team performed a meter verification and immediately suspected a problem. As shown in Figure 9 the stiffness had increased over 10%. An as-found calibration was done with the density reading almost 0.2 gm/cm^3 low and a mass flow error of almost -4% (low). Just as the prior data was consistent with a decrease in stiffness this data was consistent with an increase in stiffness. Experience with similar failures let the team to expect that this meter had been over pressurized.

The case was removed from the meter and immediately the over pressurization was obvious as shown in Figure 10. The ballooning in the tubes around the brace bar shows that the tubes had well exceeded their yield point. This meter had been subjected to over 150 bar pressure, even though it only had Class 150 flanges. It was never resolved how this over pressurization could have actually happened.

This meter was damaged beyond repair and scrapped.



A side 1	A side 2	B side 1	B side 2
92.8%	103.9%	103.8%	99.5%
94.4%	105.2%	103.3%	102.3%
92.6%	108.6%	104.5%	102.4%
93.1%	109.2%	102.9%	103.5%
95.4%	110.9%	104.1%	105.1%
96.2%	N/A	103.4%	N/A
99.3%	110.6%	104.8%	106.9%
N/A	N/A	106.7%	105.0%
100.9%	113.8%	104.6%	104.4%
99.3%	N/A	105.1%	N/A
101.1%	108.5%	104.5%	103.8%
101.3%	108.5%	104.9%	105.1%
100.6%	107.5%	106.1%	103.8%
102.2%	106.6%	106.9%	103.2%
103.4%	106.9%	107.5%	103.5%

Figure 7. Tube Thinning Measurements

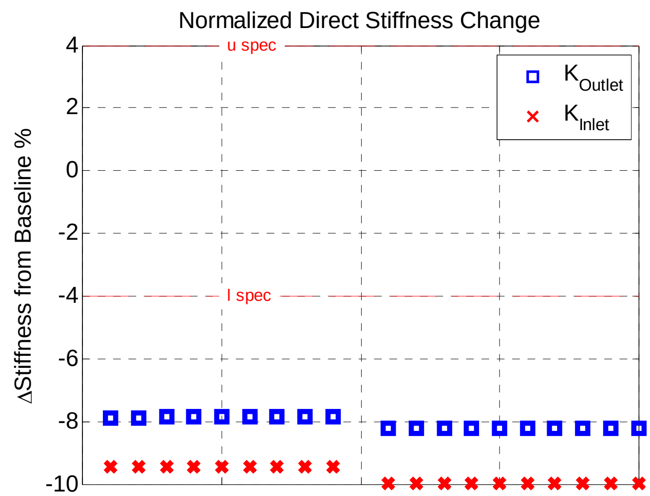


Figure 8. Direct Stiffness Verification - Eroded Meter

In the case of the eroded meter, the change in stiffness was well outside of specification before the meter was pulled out of service. If the user had established a work practice to routinely run meter verification and collect the results, the damage would have been detected and the meter pulled out of service much sooner. Frequent verifications are particularly important in processes where corrosion or erosion is expected.

For the overpressurized meter, the user was not aware of meter verification. If verification results were available, the user would have simplified their troubleshooting and identified the problem more quickly. Presenting the verification results to the vendor would have streamlined the return and replacement process as well.

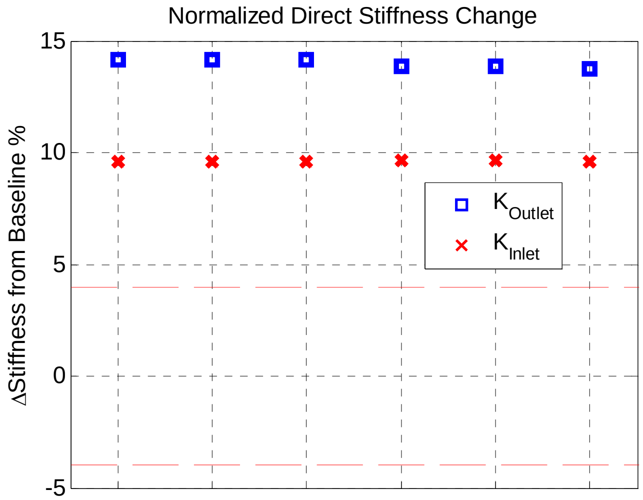


Figure 9 Direct Stiffness Verification - Over Pressurized Meter

Figure 10. Over Pressurized Tube Failure

Both of these cases point out the need to have an in-depth dialogue between users and vendors to understand the process, the application, and best way to incorporate verification into work practices.

The previous two sections discussed true positive and true negative results, the diagonal terms of the hypothesis testing matrix. The next section discusses the off diagonal terms, false positives and false negatives.

EXAMPLE VERIFICATION RESULTS – FALSE ALARMS AND COVERT FAILURES, CELLS 2 & 3

Any verification technique has to balance the possibility of false alarms against the possibility of covert failures. Users don't want to spend what might be a lot of time and money stopping a process and troubleshooting a meter if it is really okay. But they don't want to leave a meter in service if it is really inaccurate or dangerous.

If meters were verified under laboratory conditions, there wouldn't be many issues. Recalling the discussions on proving and verification metrology, as the variation of the verification gets smaller we approach the case where we don't need to consider false results. The inherently small variation of some verification techniques under lab conditions is on a par with the flow measurement accuracy. This good repeatability is seen in Figure 8 and Figure 9 where the verification data was recorded in a lab.

The need to consider false verification results comes about because field effects and process conditions can increase the variability of verification results. Field verification data in Figure 3 shows variation to due to changes in pressure, temperature, flow rate, density, etc.

The hypothesis testing matrix provides the appropriate methodology to deal with the false results issue. For example, to deal with false alarms due to variation effects, vendors could set their failure limits very wide. Verification would never indicate a failure with these wide limits and users would never get a false alarm. No meters would ever be pulled out for troubleshooting because there would never be an alarm. Users would not waste any money on spurious problems.

But wide failure limits are clearly a problem. The failed meters presented above would not have been pulled out if limits were set at 20%. Users would be getting bad measurements, or worse safety would have been compromised, because these meters would have been covert failures with these wide spec limits. Eventually the meters would have failed, overt failures.

Alternatively, to eliminate the possibility of covert failures, the failure limits could be set at 0.2%. Any hint of damage, erosion, or corrosion would be detected immediately. But then the user of the meter in Figure 3 would be constantly getting alarms that the meter has failed. Lots of money would be spent to prove that the meter is accurate and safe.

False alarms and covert failures cannot both be minimized. A balance must be struck in which the meter accuracy and safety is not compromised but which also does not result in too many false alarms. To strike this balance users must be aware if their process is incompatible with their Coriolis meter. Next, the vendor should provide information as to how their verification results are affected by process conditions and field effects. Vendors use this information to set a failure level for their verification results. For example vendors might make a statement such as with a 4% verification failure level, there is a false alarm rate of 0.3% over the entire range of process conditions

Vendor should also provide information as to how to react to a verification failure. For example repeating the verification one or many times will show if the verification failure was due to field effects or a real meter failure.

A very small percentage of users might be using Coriolis meters where they are expected to fail. For example, the Coriolis value proposition could be high enough that tolerating meter failure makes good business sense. For these users, verification can be very useful to manage measurement accuracy and safety. But covert failures in these applications need to be minimized. This small subset of users should have in-depth discussions with their vendors regarding meter verification technologies and how best to apply statistical methodologies to extract the most information for meter verification results.

CONCLUSION

This paper has discussed the robustness of Coriolis meters in most applications. It has pointed out the importance of understanding the process and application. Is the application like the majority of Coriolis applications where the meter is never expected to fail? Is the process fluid compatible with Coriolis meter?

For the majority of users the answers are yes. The meter is never expected to fail. The process is compatible with Coriolis technology. The risk of false alarms and covert failures is very low. Work practices can be set up to run meter verification frequently and data collection and reporting done on a regular basis to confirm that the meter is safe and accurate. Work practices should also account for being able to identify and react to a meter verification failure quickly.

These users can confidently use verification to extended proving intervals as specified in Directive 17.

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