ALLOW CORIOLIS METER VERIFICATION TO REDUCE YOUR ERCB DIRECTIVE 17 PROVING COSTS

Paper #1047 Presented at CSHM 2010, Calgary, AB Canada. Used with permission

Timothy J. Cunningham
Principal Engineer
Micro Motion, Inc.
7070 Winchester Circle
Boulder, Colorado 80301

INTRODUCTION

Flowmeters are commonly *proved* by comparing the indicated flow measurement to a reference flow volume. Proving is sometimes called *validation*. Validation techniques generate a Meter Factor, a number near 1.0 that adjusts the Flow Calibration Factor (FCF) so that the unit under test matches the reference volume.

Flowmeters are also commonly *verified* by tracking a secondary variable that is highly correlated to the flow measurement. For example, orifice plates can be inspected and measured to verify accuracy. Other verification techniques include spindown tests for turbine meters and speed of sound and transducer gain checks for ultrasonic meters. Verification techniques give a yes/no indication of whether the meter is meeting its flow accuracy specification.

Coriolis meters have historically used secondary parameters to verify performance, e.g. drive gain (drive power). Unfortunately drive gain is not directly correlated with the flow measurement. A method of verifying Coriolis meters by using a known density fluid has been used successfully, but this approach can be difficult to implement.

An improved method of Coriolis flowmeter verification uses the onboard electronics to compare the stiffness of the meter to a factory baseline. Since the stiffness is directly related to the FCF, this verification technique confirms that the meter is accurately measuring flow. A recent enhancement to the stiffness verification technique allows verification with no interruption of the flow measurement. This enhancement means that Coriolis meters in custody transfer applications can now use this technique.

Alberta’s Energy Resources Conservation Board (ERCB) Directive 17 gives the requirements for measuring upstream oil and gas. Section 2 of Directive 17, which defines the Calibration and Proving requirements for both oil and gas meters, states, “That is, if a meter has built-in diagnostics to continuously monitor the condition of the primary element, inspection is not required until an alarm or error is generated by the meter or as recommended by the manufacturer, such as in some types of Coriolis meters.” Stiffness verification meets these requirements for a built-in diagnostic. By using meter verification, proving may be extended until the onboard diagnostics advises it is time to prove. Meter verification can be included along with proving in the Site Measurement Plan, resulting in significant savings in proving costs because of extended proving intervals.

This paper will start with a discussion of Coriolis flowmeter operation and why stiffness is important.

CORIOLIS FLOWMETER OPERATION

A Coriolis mass flowmeter directly measures the mass flow rate of a fluid by vibrating (driving) a fluid-conveying tube at resonance. Figure 1 shows a simplified “U” shaped tube geometry. Flow enters one leg of the tube and exits the other leg. The cross product of the moving fluid with the tube vibration develops Coriolis forces, as shown in Figure 1a., with F_C being the Coriolis force on the fluid and F_t being the equal and opposite force on the tube. The tube is commonly vibrated in a fundamental bending mode, Figure 1b.

A more realistic dual “U” tube flowmeter is shown in Figure 2. The flow enters from the pipeline and is split at an inlet manifold between the 2 U-shaped flowtubes. The flow is then rejoined at an exit manifold and continues down the pipeline. The tube vibrates in a balanced, out-of-phase fundamental bending mode, like a tuning fork. The Coriolis 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 2. The time delay at two locations, which is called δt, is used to calculate mass flow rate.

The mass flow rate through a Coriolis sensor is directly proportional to this time delay with the proportionality constant being the flow calibration factor (FCF) [1]. The mass flow rate through a sensor, $\dot{m}$, is given by

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

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

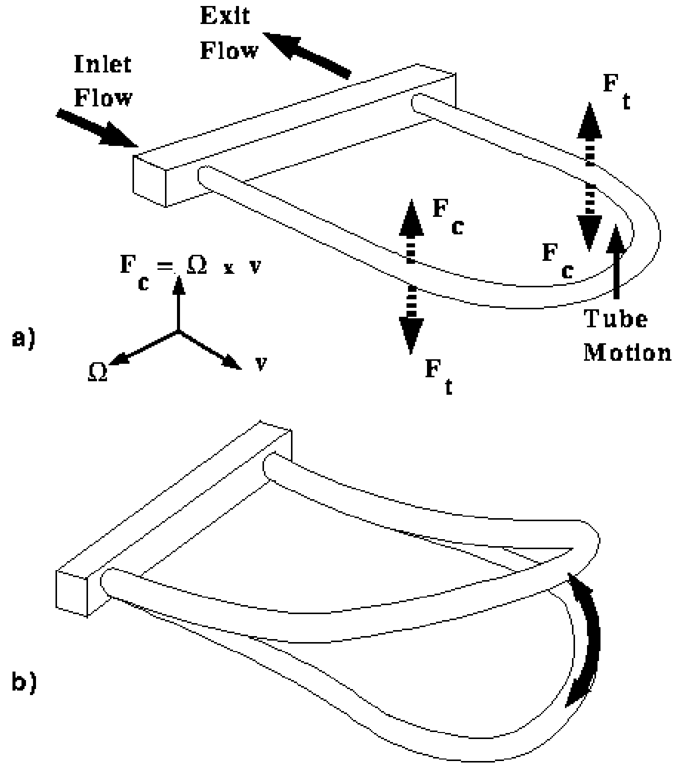

Figure 1. Coriolis Flowmeter Operation

CORIOLIS METERS AND VOLUMETRIC FLOW RATE

Coriolis flowmeters give a direct reading of the mass flow rate. They also separately, independently, measure the density of the process fluid that is in the flowtubes. The density measurement is a function of the resonant frequency of the flowmeter. The flowmeter can then calculate the volumetric flow from the two independent quantities

$$Q = \dot{m} / \rho \tag{2}$$

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 mass. Coriolis meters can also produce a standard volume output.

ELECTROMAGNETIC TRANSDUCERS

The flowtubes' motion is perturbed by the mass flow. Transducers are needed to measure the flow tube motion and produce an electrical signal. The transducers used to measure flow (called "pickoffs") are voice coil velocity transducers, with the magnet mounted on one tube and the coil on the other tube, as shown in Figure 2. These transducers produce a voltage proportional to the tube velocity. Since the tube is vibrating at resonance the pickoff voltage is sinusoidal. The flowmeter's DSP based electronics process the pickoff voltages to measure flow.

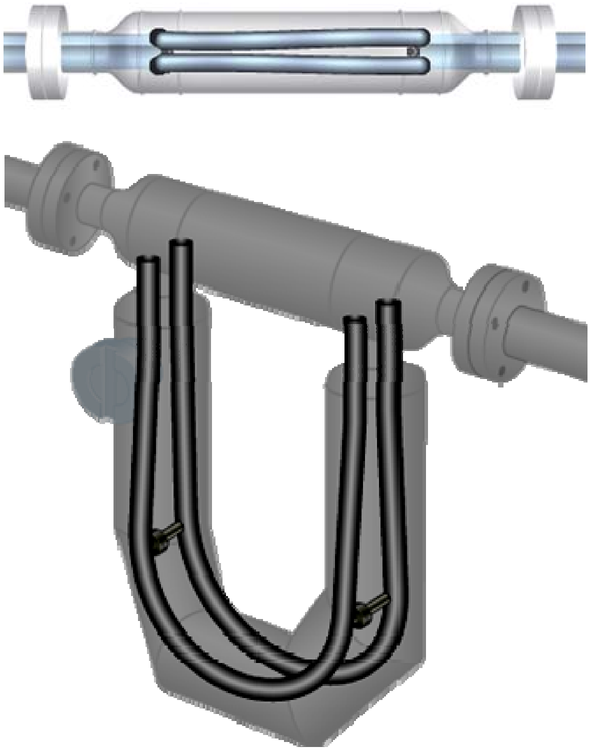

Figure 2. Coriolis Mass Flowmeter

Not shown in the figure is the driver transducer, another voice coil. Sinusoidal current is applied to the coil, which, in conjunction with the magnet, produces equal and opposite forces on the flow tubes. The electronics also use the pickoff signals in a closed-loop control scheme to maintain the resonant motion at a constant amplitude.

A later section of this paper will discuss how these transducers are used in the stiffness verification measurement. The next section will show how the stiffness is directly related to the FCF.

STIFFNESS AND FCF

The equation for mass flow, Equation (1), can be derived from first principles, for example starting with the Housner differential equation describing a fluid-conveying beam [2, 3]. Going through this derivation in detail would show that the FCF is actually the stiffness of the flowmeter. However, a much simpler dimensional analysis, which uses the fundamental physical units of length, mass, and time, shows that the FCF has units of stiffness. The dimensional analysis starts by rearranging equation (1) to isolate the FCF term.

$$FCF = \frac{\dot{m}}{\delta t} \tag{3}$$

As discussed above, Equation (3) shows that the units of the FCF are mass flow rate/time delay. This is shown dimensionally using fundamental physical units as

$$FCF \approx \frac{\left(\frac{Mass}{Time}\right)}{Time} \tag{4}$$

(The $\approx$ can be read as "has units of".) For example, FCF is commonly expressed in units of (gm/sec)/μsec. In a consistent system of units, mass can be represented by force/acceleration, taking advantage of Newton's Second Law. Plugging this into equation (4) shows very simply that the flow calibration factor has units of stiffness (Force/Length).

$$FCF \approx \frac{\left(\frac{Mass}{Time}\right)}{Time} = \frac{\left(\frac{Force / acceleration}{Time}\right)}{Time} \\ \frac{\left(\frac{Force / (Length * Time^2)}{Time}\right)}{Time} = \frac{Force}{Length} \tag{5}$$

The importance of stiffness is shown in Figure 2, where the Coriolis forces act to deform the flowtubes, which deform according to their stiffness. The deformation results in the primary flow signal δt, which is converted into mass flow by the FCF. The equivalence of FCF and stiffness shows why stiffness is the secondary parameter that should be used for verification. If the stiffness remains the same as the factory baseline, the factory FCF is correct.

Other secondary parameters used as verification diagnostics, such as fluid density, drive gain, pickoff amplitude, or damping, do not have the same independent relationship to the FCF and are therefore not reliable FCF indicators. One way to view this lack of independence is to look at the units of these other parameters. Drive gain has fundamental units of force or power (force*length/time), frequently expressed as a percentage of full scale force or power. Damping is dimensionless or in units of force/(length/time). Amplitude has units of length. These parameters are sometimes expressed in the raw electrical units of voltage or current. None of these other parameters has the same units as the FCF and so do not directly relate to the flowmeter calibration.

Another reason that these other parameters don't make a good FCF verification parameter is that they can be strongly affected by the process fluid. Drive gain and damping in particular can be strongly influenced by process conditions. For example gas breakout in live oil can cause the drive gain to increase dramatically due to the presence of small well distributed gas bubble in the process fluid. But a Coriolis meter will continue to give accurate flow measurement under these conditions. The accuracy is unaffected because the the drive gain does not correlate to a change in the FCF.

These other parameters can be very good diagnostics for the process and might want to be monitored for that reason, but should not be used to verify the FCF.

On the other hand, process fluids by definition do not have any stiffness. Therefore, the stiffness measurement is unaffected by process fluids. There are some special cases where the process can affect stiffness. For example if the tube gets coated by a stiff fluid, e.g. asphalt, the FCF may be affected if the stiffness measurement indicates a change. But in general the stiffness measurement is unaffected by fluid density or flowrate.

Knowing that the flowtube stiffness is the correct verification parameter, the problem now becomes one of how to determine it.

STIFFNESS MEASUREMENT

Stiffness is a familiar concept, relating the amount of force necessary to displace a spring a given distance,

$$k = F / d \tag{6}$$

where k is the stiffness of the spring, F is the force and d is the amount of displacement as shown in Figure 3. Stiffness is easily measured statically with force and displacement transducers. During the development of meter verification the static stiffness of the flowtubes was measured to provide a known reference. Static stiffness measurements required an uncased meter and specialized tooling.

Modal analysis and structural dynamics theory shows that stiffness can be measured dynamically. The simplest dynamic stiffness measurement is based upon the equation for the resonant frequency of a vibrating structure.

$$frequency = \sqrt{{stiffness}/{mass}}, \quad f = \sqrt{{k}/{m}} \tag{7}$$

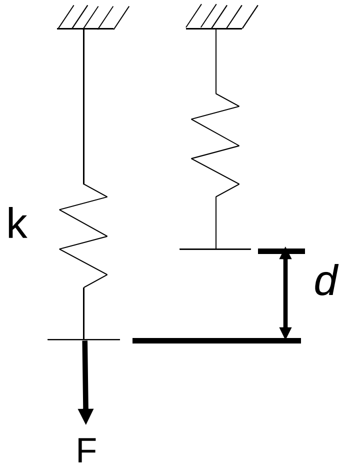

Figure 3. Stiffness Definition

Measuring the resonant frequency precisely allows the tracking of the ratio of the flowtube mass and stiffness, but does not uniquely define the stiffness. Indeed, this simple dynamic approach to stiffness measurement, frequency measurement, is used in two ways by Coriolis meters.

First, Coriolis meters independently measure density by calibrating the frequency measurement at two known fluid densities, typically air and water. The density is measured by relating the measured frequency to the known frequency/density pairs [4]. Since the frequency is dependent upon both stiffness and mass, the inherent assumption in density measurement is that the tube stiffness is unchanged from the factory values. Since Coriolis flowmeters have no moving parts and generally experience no change in their calibration (or stiffness) over the 10+ years of their life, the assumption of unchanging stiffness is a good one. Therefore, the resonant frequency tracks the fluid density.

The second use of frequency based stiffness approach uses Equation (7) and reverses the density measurement assumption. If the tube is filled with a known density fluid, typically air or water, then the measured frequency should exactly match the calibrated frequency for that fluid. Knowing the density of fluid, if the frequency matches the calibration frequency then the stiffness of the meter is unchanged; hence the meter is calibrated correctly. This so-called known density method is used successfully in many applications and is an excellent method to detect tube coating [5].

However, in many applications it is very difficult to fill the meter with a known density fluid. Meter verification uses a different approach than frequency measurement to dynamically measure the stiffness, which makes the verification process work on any process fluid.

DYNAMIC STIFFNESS MEASUREMENT

Equation (7) defines a resonant frequency of a structure. When the structure is excited by a small force at the resonance frequency, the result is a large displacement. Coriolis meters utilize the reduced force needed at resonance to minimize the energy for sustaining the tube vibration which is required for the Coriolis δt measurement. The vibrational motion is defined as the system response. The system response divided by the input force as a function of frequency is called a frequency response function (FRF). Measuring the input force and the response at the resonant frequency provide one point of the meter's FRF. However, one point of the FRF is not enough to measure the structure's stiffness. Measuring the stiffness of the meter requires FRF measurements at additional frequencies. Inputting forces at additional frequencies and measuring the response at those frequencies allows the stiffness to be measured dynamically, forming the heart of meter verification. Figure 4 shows a typical FRF. The peak is at the resonant frequency. Two additional frequencies are input at frequencies lower than resonance, and two frequencies at a higher frequency. These additional frequencies are called the test tones. The value of the FRF at each of these frequencies is show by a diamond.

The normal flow and density measurements are unaffected by the additional test tones. Since the exact frequency of the injected tones is controlled by the electronics, it can be effectively filtered out of the frequency and δt measurement. As a result, the meter verification can be performed at any time without impacting the flow or density measurement.

The dynamic stiffness measurement uses the standard voice-coil driver to provide the input force into the structure. The electronics outputs the four test tones in addition to the standard drive signal as electrical currents at the specific frequencies. The applied force is directly proportional to the current as defined by the standard electromagnetic constants of the driver. The response of the structure at these five frequencies is measured by the standard pickoffs which are used in the normal flow measurement. The voice-coil pickoffs produce a voltage proportional to velocity.

Measuring the stiffness dynamically via the measurement of FRFs has another advantage. In addition to checking the primary structural element, i.e. the flow tube, the stiffness measurement thoroughly exercises the flowmeter electronics. A good stiffness measurement insures that the electromechanical transducers (e.g. pickoffs, drivers, RTD, internal wiring), electronic components (e.g. analog front end amplifiers, analog-to-digital converters), and software are all performing correctly.

The shape of the FRF curve is defined by the stiffness, mass, and damping of the flowtubes [6]. The

FRF curve is dominated by the stiffness at low frequency, rises to a peak at the resonance frequency, and decreases as the mass effects take over at high frequencies. Advanced digital signal processing (DSP) is required in the flowmeter electronics to measure the FRF and to perform a mathematical curve fit to independently determine these three parameters. The electronics captures a significant amount of data during the verification process, but only the stiffness is reported to the customer, since that is the correct FCF diagnostic parameter.

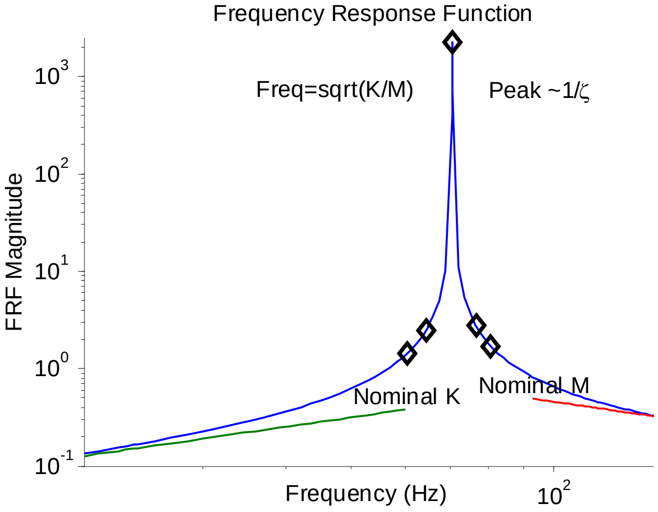

Figure 4. Frequency response function

Because the stiffness is measured using the driver and pickoffs, it is scaled by their electromagnetic constants. This scaling makes it difficult for the user to interpret. The presentation of the stiffness data is a key component of meter verification.

CORIOLIS FLOWMETER VERIFICATION

A key factor in verification is the fact that Coriolis flowmeters contain no moving parts and data shows that they typically last for 10 or more years with no change in calibration. They are also unique among flow measurement devices in that the mass flow measurement is almost never affected by the process fluids. The underlying expectation of Coriolis verification is that there should be no change in the flow calibration factor (FCF). However in many applications, such as custody transfer where the flowmeter is used essentially as a cash register, a method of verifying the accuracy of the flowmeter is highly desirable.

Since the raw stiffness numbers are hard to interpret, combined with the fact that no change is expected, makes the presentation of the stiffness results suited to a “% change” approach. This approach requires that every flowmeter have a factory baseline stiffness measurement performed during calibration. This factory baseline is used to normalize subsequent stiffness results. This normalized value is called the *stiffness uncertainty* and it is calculated per Equation (8).

$$stiffness_{uncertainty} = \left(\frac{stiffness_{measured}}{stiffness_{factory\ baseline}} - 1\right)\% \quad (8)$$

The stiffness uncertainty can be plotted to provide a quantitative verification of the FCF.

CORIOLIS FCF STABILITY

Coriolis meter history shows that there is little variation in the FCF over time. For example, reference Coriolis meters are used to verify the accuracy of manufacturer’s calibration facilities. These meters are checked against a gravimetric standard on a regular basis. Reference meters which are 10+ years old still have the same calibration as the day they were built.

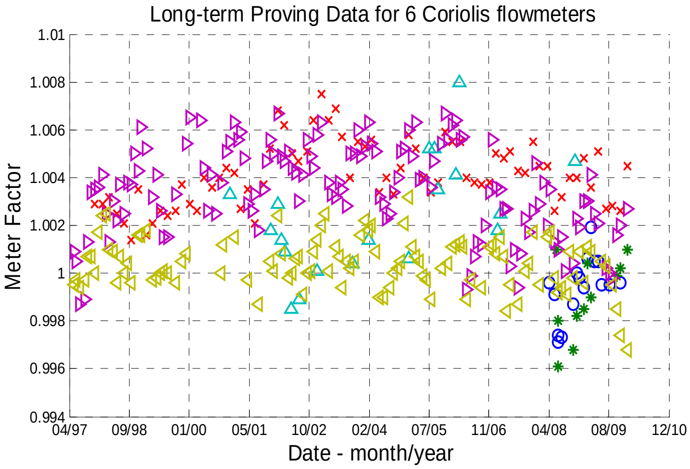

Figure 5. Long-term Coriolis Proving Data

Coriolis meters are commonly proved in the field. The calculated volumetric flow from the Coriolis meter is compared to the standard volume of a prover [7,8]. The provings generate a meter factor that usually is constant over the lifetime of the meter. Figure 5 shows a plot of the meter factor from six Coriolis meters that have been proved for as long as 13 years. The proving data indicates that the meter factor has the same average value as when it left the factory.

The stability of the calibration is also apparent in the stiffness uncertainty measurements.

STIFFNESS UNCERTAINTY VARIATION VS FCF VARIATION

Meter verification was designed so that under controlled conditions, the variation in results is small relative to the accuracy of the flowmeter. However, a variety of field effects can cause variation in the meter verification results [9]. Figure 6 shows meter verification results from a typical installation. You can see that, like the proving results in Figure 5, there is a small bias, some variation, and a possible trend in the data. The stiffness measurement is subject to several field effects, e.g. flow noise, temperature gradients in the electronics and flow tube, residual error due to non-exact temperature correction parameters, etc. These field effects affect the stiffness measurement, but do not actually affect the stiffness or FCF. The specification limits are set so that the variation in the stiffness measurement data due to field effects will not trigger a false alarm regarding the flowmeter accuracy. The typical stiffness uncertainty spec limits are ±4%. Variation in the stiffness uncertainty measurement due to field effects is discussed more fully in Reference [9]. The conclusion to draw from this graph is that all of the results are within the ±4% stiffness uncertainty specification limits; therefore this flowmeter is meeting its accuracy specification. (Typical Coriolis mass flow accuracy specification is 0.1%)

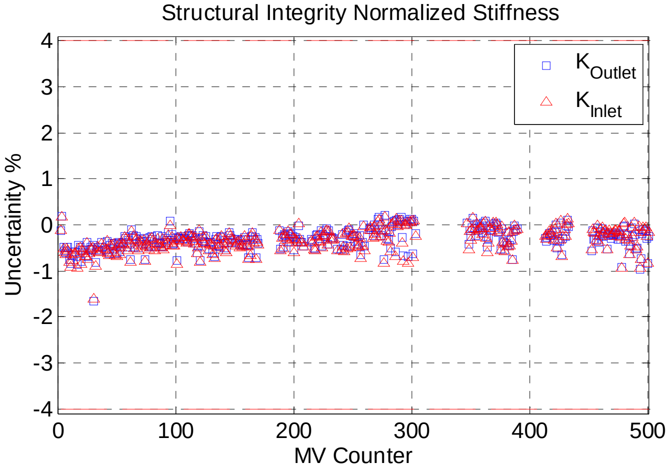

Figure 6. Typical Meter Verification Results

METER VERIFICATION STIFFNESS AND VOLUMETRIC FLOW ACCURACY

There are sometimes concerns that internal coatings on the flow tube will affect flowmeter accuracy. The discussion above makes it clear that if a coating does not affect the flowtube stiffness, the mass flow reading will still be correct. Coating on the flowtube may affect the density measurement accuracy. If the Coriolis meter is configured to give a volumetric flow based on the measured fluid density from the Coriolis meter, then there may be an flow error due to coating. However, measurement inaccuracies due to coating occur infrequently. If coating is a concern, there are several methods for coating detection in Coriolis meters, the most common being the known density approach or the drive gain monitoring approach discussed above.

METER VERIFICATION AND DIRECTIVE 17

Sections 2.5.2.1 and 2.6 of ERCB's Directive 17 states "Internal metering diagnostics may be used to determine if the primary measurement element is within acceptable operating parameters and checked at the same required intervals as an internal inspection. Then internal inspection is not required until an alarm or error is generated by the device or as recommended by the manufacturer. The operator must maintain documentation on the diagnostic capability of the measurement system …"

Stiffness-based meter verification checks if the primary measurement element is within acceptable operating parameters. Since the stiffness check is performed with the onboard transmitter electronics, meter verification also confirms that the electronics are operating correctly. Meter verification can reduce the need for or extend the interval of internal inspection or proving without compromising measurement accuracy.

If meter verification detects a problem, it will set an alarm. Inspection of the Coriolis meter is then recommended. Host-based meter verification software, provided by the manufacturer, can store, track, and plot results, and generate the reports necessary to comply with the Directive. Additionally, the host-based software will track any configuration and zero changes, adding further confidence to the verification process.

Since meter verification is so easy to perform, it is recommended to run it at more frequent intervals than strictly required by the Directive. Running meter verification once a day or once a week would not be excessive. Advanced features of meter verification include setting up device-based or host-based scheduling. Meter verification would then be triggered with no need for operator interaction. Another advanced feature is that the device-triggered verification results can be stored on the transmitter and then downloaded to a host system on a longer term schedule. The verifications in Figure 6 were set up to be triggered by the device three times a day. A laptop was connected to the flowmeter via its HART interface around once/week at which point the device-stored data gets downloaded to the laptop. The laptop stores the meter verification data in a database, and can generate a report per Directive 17. Occasional lapses in the weekly schedule due to holidays or vacations show up as gaps in the data, but the overall wealth of the results is not compromised.

POTENTIAL COST SAVINGS WITH METER VERIFICATION

Directive 17 allows meter verification to be used to extend proving intervals, which can result in significant cost savings. For example, without meter verification a meter might typically be proved 12 times/year. With meter verification the proving interval can be extended until the verification triggers an alarm. Since Coriolis meters are not expected to change, that means that a verification alarm will most likely never be triggered.

However, proving a Coriolis meter at the initial installation and thereafter on an annual basis would be a good conservative recommendation. Costs for a typical prove might be $200 plus technician time and mileage. A bill of $500 per prove would not be uncommon. With meter verification, the total cost savings for the 11 unneeded proves would therefore be $5,500/year.

CONCLUSION

Coriolis flowmeters have some clear benefits for measuring oil and gas. They provide accurate measurements under harsh measuring conditions. With no moving parts, the accuracy does not degrade over time. The improved accuracy and reduced maintenance requirements of Coriolis flowmeters can save money on process measurement points.

A new feature of Coriolis meters is the addition of the meter verification stiffness diagnostic, which confirms the accurate operation of the flowmeter. Stiffness is measured using the onboard electronics, with no interruption to the process measurement. The stiffness measurement is directly related to the flowmeter calibration. Meter verification confirms that the calibration is the same as when it left the factory. The stiffness is not affected by the process and can be measured under flowing conditions without interrupting the process measurements, making it an ideal diagnostic.

Directive 17 allows extending proving intervals by the use of internal meter diagnostics. Meter verification is a robust diagnostic that meets the requirements of Directive 17. The addition of the internal meter verification diagnostics to Coriolis flowmeters provides significant cost savings by providing for extended proving intervals.

REFERENCES

[1] Micro Motion TUTOR, http://www.emersonprocess.com/micromotion/tutor/index.html.

[2] *Effect of detector masses on calibration of Coriolis flowmeters*, Lange U., Levien A., Pankratz T., Raszillier H., Flow Measurement Instrumentation, Volume 5 Number 4, 1994.

[3] *A Finite Element for the Vibration Analysis of a Fluid-conveying Timoshenko Beam,* Stack C., Garnett R., Pawlas G., 34th SDM conference proceedings, 1993, AIAA

[4] *Coriolis: Little Known Process Analyzer*, O'Banion, T., Micro Motion White Paper WP-00574, www.micromotion.com, 2005.

[5] *Using a Coriolis Flowmeter's Multivariable Characteristics to Validate Calibration Stability*, Micro Motion White Paper WP-00517, www.micromotion.com, 2003.

[6] *Coriolis Flowmeter Verification via Embedded Modal Analysis*, Rensing, M., Cunningham, T., Proceedings of IMAC XXVIII, Society for Experimental Mechanics, 2010

[7] *The Proof is in the Proving*, Whitman, S., Micro Motion White Paper WP-00667, www.micromotion.com, 2004.

[8] *Proving Coriolis Flowmeters*, Apple, C., 72th International School of Hydrocarbon Measurement, 1997

[9] *Using Structural Integrity Meter Verification to Track Corrosion in Coriolis Flowmeters*, Cunningham T., Micro Motion White Paper WP-01196, www.micromotion.com, 2009.

ACKNOWLEDGEMENTS

I'd like to thank Guy Fulkerth of Keyera and George Hargreaves of Spartan Controls for their assistance in the preparation of this paper.