AN *IN-SITU* VERIFICATION TECHNOLOGY FOR CORIOLIS FLOWMETERS

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Abstract: Structural Integrity Meter Verification is a robust new Coriolis verification technology which uses the onboard electronics to very accurately measure the stiffness of the flowtubes. The flow tube stiffness is directly related to the flow calibration factor and is uninfluenced by process conditions. Meter Verification compares the measured stiffness to the factory baseline stiffness to confirm that the flow calibration factor is unchanged from the factory value. Structural Integrity Meter Verification also performs additional electronics and software checks to ensure accurate measurement. This new technology allows users to save money and reduce downtime by verifying Coriolis meters *in situ*.

Sometimes Coriolis meters are used with corrosive fluids that can etch away the tube or with erosive fluids that can cause localized thinning of the tubes. In these applications the precision and accuracy of the Coriolis flowmeter outweighs the replacement costs. A Coriolis meter has been deliberately corroded while tracking the flow calibration factor and the stiffness. Finite element analysis was used to analyze the relationship between stiffness and flow calibration factor for erosive applications. Meter Verification results for these cases are compared to the experimental and analytical data.

1. INTRODUCTION

Flowmeters are commonly *validated* by comparing the indicated flow measurement to a reference flow measurement. Flowmeters are also commonly *verified* by tracking a secondary variable that is highly correlated to the flow measurement. For example, orifice plates can be measured to verify accuracy. Other verification techniques include spindown tests for turbine meters and speed of sound and transducer gain checks for ultrasonic meters.

Coriolis meters have historically used secondary variables to verify performance, e.g. drive gain. Unfortunately drive gain is only loosely correlated with the flow measurement. A method of verification using a known density fluid has been used successfully, but this approach is prone to user error.

In response to customer demand for an easy to use meter verification methodology for Coriolis flowmeters, Micro Motion has developed Structural Integrity Meter Verification that uses the onboard electronics to verify the integrity of the flow tube as well as the electromechanical components, the transmitter electronics, and the transmitter software.

2. CORIOLIS FLOWMETER BACKGROUND

Structural Integrity Meter Verification uses the stiffness of the flow tubes as the secondary variable to verify the correctness of the Flow Calibration Factor (FCF). The FCF is the proportionality constant that relates the time delay, δt , to the mass flow rate, $\dot{m}$.

$$\dot{m} = FCF \cdot \delta t \tag{1}$$

Equation (1) can be derived from first principles, for example starting with the Housner differential equation describing a fluid-conveying beam [1, 2]. These derivations result in a term corresponding to the FCF as shown in Equation (2).

$$\dot{m} = C \frac{EI}{L^3} \cdot \delta t \tag{2}$$

where C is a dimensionless geometric constant related to the boundary conditions and beam properties. The EI/L^3 term, corresponding to the FCF, has units of force/length, the units of stiffness.

Going through these derivations in detail to show this relationship between stiffness and flow calibration factor is beyond the scope of this paper. However a much simpler dimensional analysis of Equation (1) shows that the FCF has units of stiffness.

Rearranging equation (1)

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

shows that the units of the FCF are mass flow rate/time delay. This is shown dimensionally as

$$\frac{\left(\frac{Mass}{Time}\right)}{Time} \quad (4)$$

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 of gravity), taking advantage of Newton's Second Law. Plugging this into equation (4)

$$\frac{\left(\frac{Mass}{Time}\right)}{Time} = \frac{\left(\frac{Force * Time^2 / Length}{Time}\right)}{Time} = \frac{Force}{Length} \quad (5)$$

shows very simply that the flow calibration factor has units of stiffness (Force/Length).

The equivalence of FCF and stiffness shows why stiffness is the secondary variable that is highly correlated to the FCF. The problem now becomes one of how to determine the stiffness of the flow tubes.

2.1 Meter Verification Theory

Coriolis Structural Integrity Meter Verification uses techniques from Experimental Modal Analysis and Structural Dynamics theory to very accurately measure the stiffness of the flow tubes using the embedded electronics and onboard pickoff and drive coil and magnets.

Figure 1 shows a typical Coriolis mass flow meter. The drive coil and magnet at the top center in-between the tubes is used to drive the Coriolis flowmeter at resonance. A feedback control system in the flowmeter electronics applies a sinusoidal current to the drive coil to maintain resonance at a specific amplitude. The two pickoff coils and magnets produce a voltage in response to the resonance motion. The pickoffs are used as the feedback signal to control amplitude. The transmitter's digital signal processing uses the pickoff responses to estimate the frequency of vibration, used in the density measurement, as well as the time delay between the two pickoff sinusoids, δt, needed for the mass flow measurement. Further details discussing the operation of a Coriolis flowmeter are given in Reference [3].

Meter Verification runs on top of the standard Coriolis signal processing and drive control. A series of tones are added to the drive signal. These tones excite off-resonance responses in the two pickoffs. The embedded flowmeter electronics measures these tonal inputs and responses to produce a frequency response function (FRF).

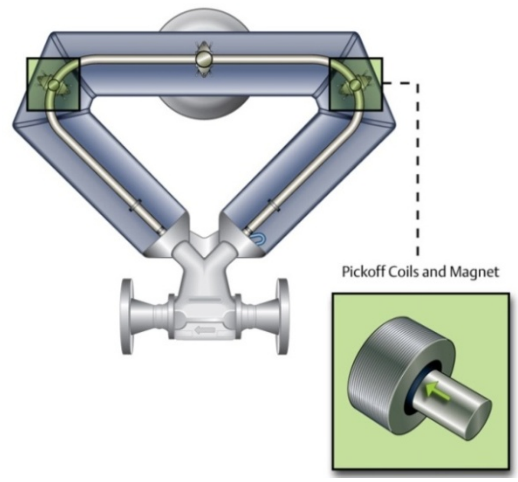

Figure 1. Typical Coriolis Flowmeter

A structural dynamics FRF can be modeled as a second order system with the parameters of stiffness (K), mass (M), and damping (C). Applying electromagnetic theory to the problem, the FRF can be defined by pickoff voltage/input current.

$$FRF = \dot{H}(\omega) = \frac{\dot{X}(\omega)}{F(\omega)} = \frac{j\omega}{-M\omega^2 + jC\omega + K} \quad (6)$$

The Meter Verification results are based on fitting the measured FRF to the second order model to independently estimate K, M, and C. Figure 2 shows this graphically. The lower frequency portion of the FRF is dominated by the stiffness. The higher frequency portion is dominated by the mass. These mass and stiffness lines, as they are called, are shown in the plot, and are actually reciprocals of the mass and stiffness.

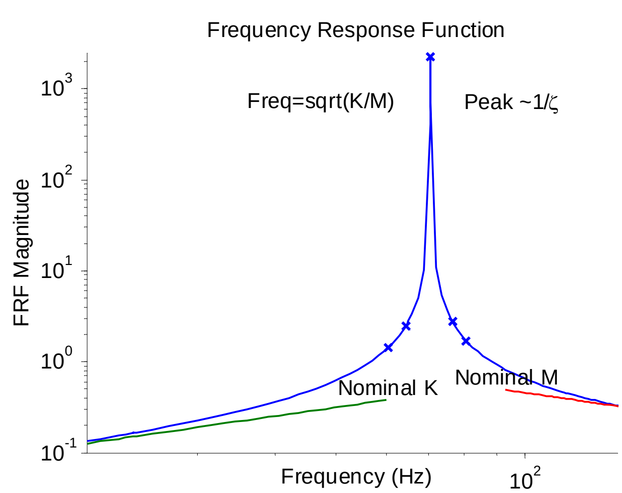

Figure 2. Nominal Frequency Response Function

The resonant frequency is determined by the square root of ratio of the mass and stiffness. The height of the resonant peak is determined by the non-dimensional damping coefficient ζ, which is related to the damping, C, by Equation (7).

$$\zeta = {C}/{2\sqrt{KM}} \qquad (7)$$

The embedded core processor performs the signal processing necessary to generate the FRF; curve fits the FRF to generate estimates for K, M, and C; and handles all of the bookkeeping to keep track of the results generated by Meter Verification.

3. RESULTS

Meter Verification distills all of its results down to two simple numbers that it presents to the customer. Meter Verification starts with the factory baseline verifications during the standard meter calibration process, which Micro Motion performs on both air and water as part of its comprehensive diagnostic program. However since the process fluid does not change the stiffness of the meter, the factory baseline stiffnesses on air and water are statistically the same. Each meter verification measurement is normalized by the average of these stiffnesses and converted into a *stiffness uncertainty*, which is the percentage change in the measured stiffness from the factory baselines.

$$stiffness_{uncertainty} = \left(\frac{stiffness_{measured}}{\frac{\left(stiffness_{factory,air} + stiffness_{factory,water}\right)}{2}} - 1 \right)\% \qquad (8)$$

Normalizing the stiffness uncertainty in this way makes it easy to track any changes in the flowmeter by using a format that is convenient to view. (This *stiffness uncertainty* should not be confused with the term *measurement uncertainty* as it is used in metrological terms.)

3.1 Meter Verification Stability

The signal processing used in Meter Verification has been designed to enhance the stability of the measurement. Each stiffness uncertainty measurement is the average of the stiffness estimates from many FRFs. In turn, each FRF that is fit is averaged from many individual FRF measurements. This averaging results in a very stable stiffness uncertainty estimate. In line with standard measurement techniques, the variation in the meter verification uncertainty is several times better than the base flow accuracy. Figure 3 shows a typical meter verification uncertainty plot with a standard deviation of less than 0.01% under laboratory conditions. Note that stiffness uncertainty is calculated for each of the two pickoffs, further increasing the confidence in the measurement.

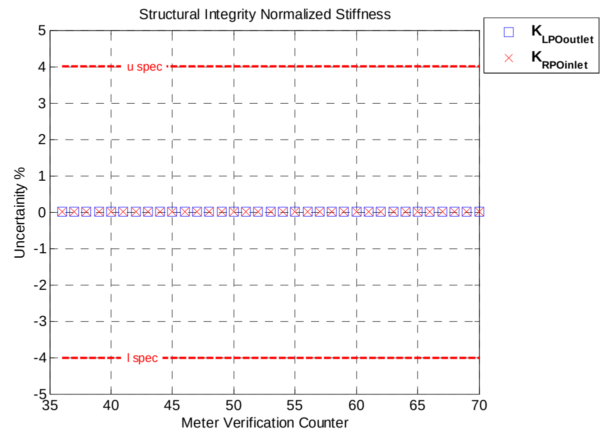

Figure 3. Meter Verification Stability

Meter Verification uncertainty variation is of course subject to field effects. The specification limits for stiffness uncertainty are set such that under the full range of field effects there is a 3σ probability against giving a false alarm. Meter Verification, specification limits and field effects are discussed more fully in References [4] and [5].

3.2 Meter Verification Corrosion Detection

Because Coriolis meters operate with no moving parts, the calibration is expected to be unchanged over the life of the meter. Most customers using Meter Verification will expect to see stiffness uncertainty results around 0%, indicating that the meter is unchanged from the factory baseline. However, because of their value proposition, Coriolis meters are sometimes used with incompatible, corrosive, fluids where the lifetime of the meter may be on the order of 1 to 2 years. For these applications, Meter Verification can be used to detect changes due to corrosion in the tubes.

Finite element analysis (FEA) is used extensively in the design of Coriolis flowmeters [6]. FEA can also model the effects of corrosion in flowmeters. The details of this FE work are beyond the scope of this paper, but these analyses illustrate some of the technology behind Meter Verification.

Figure 4 is an extension of Figure 2, where the nominal FRF is shown in blue. The FE model was modified to simulate corrosion and used to generate a second FRF, shown in green. Note that with the corroded tubes the frequency has decreased. A key feature of the meter verification technology is that the test tones used to generate the FRF are dynamically determined, based on the instantaneous drive frequency. These test tones are shown as blue x's for the nominal case and as green o's for the corroded case.

Most importantly, the independent estimations of the mass, stiffness, and damping are unaffected by the actual resonant frequency. The change in stiffness instead is detected by the shift in the estimated value for K. Figure 4 shows that the corroded tubes have an FRF with a higher stiffness line, corresponding to less stiffness, than the nominal case. The curve fit correctly estimates the change in stiffness independently from the change in resonant frequency.

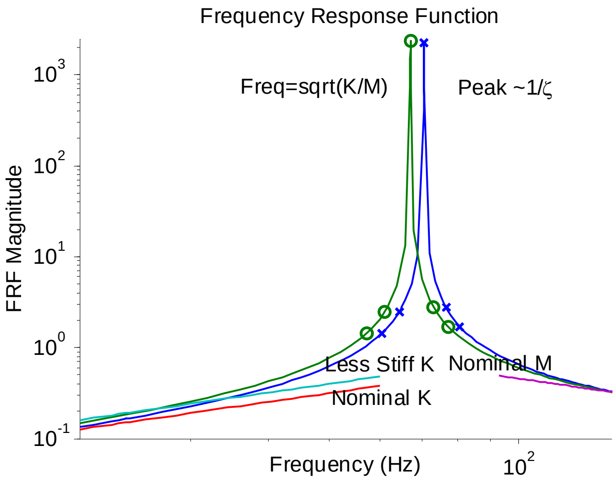

Figure 4. Change in FRF with Stiffness Reduction

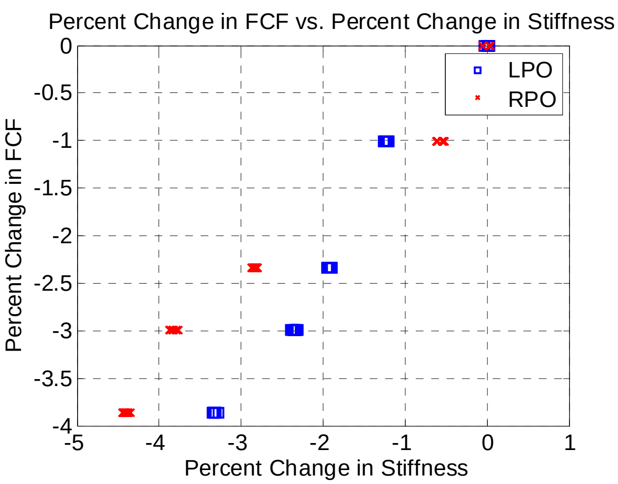

Figure 5. FCF vs Stiffness with Corrosion

To experimentally verify the ability of Meter Verification to detect corrosion, a flowmeter was corroded using a very strong, incompatible, acid. At each corrosion step the flowmeter was recalibrated to get the new FCF. Figure 5 shows the change in FCF versus the change in stiffness for each corrosion step. Note that even with careful laboratory technique, the corrosion is not uniform as indicated by the different change in stiffness for the left and right pickoffs (LPO, RPO). However note that the FCF change has an approximately 1 to 1 relationship with the averaged change in stiffness, as expected due to their essential equality.

These results show that corrosion is very detectable with Meter Verification. Another application of Coriolis flowmeters where wear is expected is with erosive slurries, the subject of next section.

3.3 Meter Verification Erosion Detection

It is difficult to do a controlled experiment for erosive wear of a Coriolis meter. However finite element analysis can be used to investigate the detectability of erosion with Meter Verification. Figure 6 shows a beam finite element model used to analyze erosion. The red elements on the inlet tube bend are where most of the erosion is expected. The wall thickness of these elements was progressively decreased with the stiffness uncertainty and FCF calculated at each iteration. The FE results are shown in Figure 7. Note how the LPO and RPO stiffnesses change it opposite directions, a hallmark of nonuniform changes to the flow tubes. These stiffness uncertainties have diverged from the baseline with a total spread of about 1% for an FCF decrease of ~1.2%

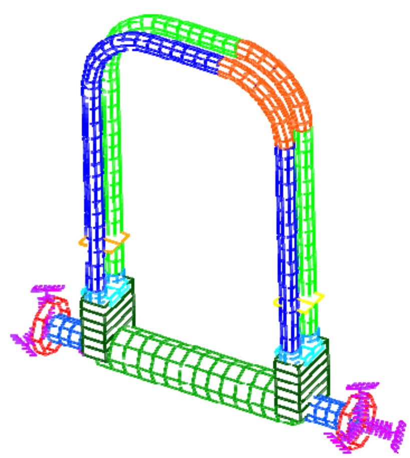

Figure 6. Beam FE Model for Erosion Study

It is interesting to note that the RPO stiffness has increased even though the RPO is on the inlet side of the tubes, where the thinning has happened. The LPO stiffness has decreased even though no change occurred on that side of the flow tubes. Non--intuitive results like these occur frequently in structural dynamics problems. A thought experiment gives insight into the increase in stiffness of the RPO with a decrease in tube stiffness. Imagine that the inlet bend was completely removed, the limiting case of stiffness reduction. In that case the RPO would not move at all with a force applied at the driver, essentially becoming infinitely stiff. Intuition must be used with care when interpreting Meter Verification results.

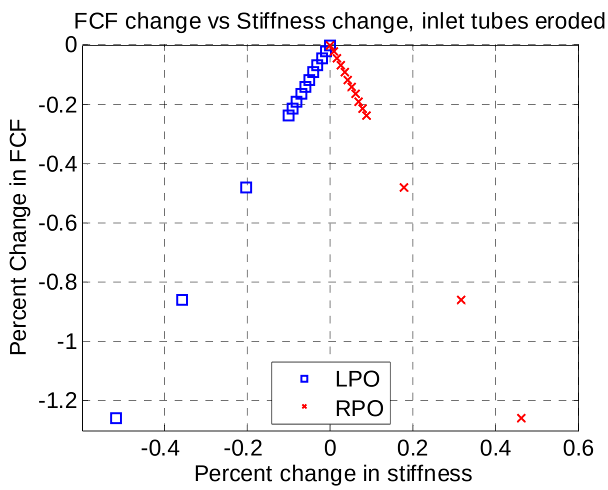

Figure 7. Fcf vs Stiffness with Erosion

4. DISCUSSION

Meter Verification measures stiffness to ensure the integrity of the sensing element, the flow tubes. Additionally the electronics associated with the flow measurement need to be verified. Structural Integrity Meter Verification confirms the integrity of the flowmeter electronics by verifying the stiffness with the same transducers, analog electronics, digital electronics, and software used for the flow measurement. Any change in the electronics will cause the stiffness uncertainty to go out of specification. Therefore good stiffness uncertainty confirms both the sensing element and the electronics.

Verification is unlike flowmeter validation methodologies such as proving, in which the unit under test's flow output is compared to a primary flow output. Verifications require several additional checks to confirm overall flowmeter performance. These checks include confirming the software configuration, the flowmeter' s zero, and the proper functioning of the analog outputs. A complete verification might include checking the analog output functionality with the built-in diagnostic/trim functions.

Structural Integrity Meter Verification includes a built-in check of the software configuration, comparing it to the previously verified values. Additionally Meter Verification checks the current zero against the factory zero and the last-verified zero. Meter Verification also provides a graphical output of the results and the ability to print a report of the current verification. All of these features combine to completely check the performance of the entire flowmeter.

5. CONCLUSION

Structural Integrity Meter Verification is a robust technology for *in-situ* verification of Coriolis flowmeters. It can be used with confidence as a cost-effective, robust, means of verifying Coriolis flowmeter performance. For applications where Coriolis flowmeter degradation is expected, for example with corrosive fluids, Meter Verification is a good tool for detecting flowmeter wear.

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