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Using Structural Integrity Meter Verification to Track Corrosion in Coriolis Flowmeters

Structural Integrity Meter Verification Adds Value in Corrosive Applications

Micro Motion Coriolis flow meters are used in a wide variety of applications. In most of these applications the flowmeter never wears out. However, the value of Coriolis flowmeters is high enough that they are sometimes used in corrosive applications where they only last for a year or two. This corrosion can reduce the meter's flow and density measurement accuracy. The corrosion of the tube wall may also pose a safety hazard. For more information about using Coriolis flowmeters in a corrosive environment view white paper #00992: *Because Corrosion Happens - Best Practices for Material Selection*.

Structural Integrity Meter Verification (SIMV) is a feature offered by Micro Motion, Inc. that gives the customer the ability to do an in situ check of the flow and density calibrations. Checking the flow and density calibrations can lead to increased accuracy in corrosive applications. SIMV also checks the integrity of the flow tube and can augment the calendar-based flowmeter life cycle management typically used in these applications.

This white paper describes how Meter Verification can be used with corrosive fluid situations to monitor the condition of the flow meter. It discusses an experiment done at Micro Motion on a meter that was deliberately corroded and very carefully calibrated and verified to determine the relationship between stiffness and calibration constants. This paper also discusses Meter Verification detectability. Finally, this paper discusses how other diagnostic parameters, drive gain and damping, do not reflect the state of corrosion of the flow tubes.

Coriolis Meter Background

This paper assumes that the reader is familiar with Coriolis flowmeter operation. Readers that are new to density and flow measurement may first want to go to Micro Motion's website, www.emersonprocess.com/micromotion, and run the TUTOR application.

This paper also assumes that the reader is familiar with Micro Motion Structural Integrity Meter Verification. Readers needing information on Meter Verification should refer to white paper #00948 – *Using Structural Integrity Meter Verification to Verify Coriolis Flowmeters*, which gives the background for the theory and operation of Meter Verification.

Meter Verification and Flow Tube Stiffness

Recall that Meter Verification tracks the stiffness of the flow tube and compares it to the factory baseline stiffness measured during flowmeter calibration.

Recall that Meter Verification tracks the stiffness of the flow tube and compares it to the factory baseline stiffness measured during flowmeter calibration. Meter Verification assesses the condition of the active portion of the flowtube. Corrosion in only the manifold or the inactive portion of the tubes will not impact the measurements, nor the stiffness as measured by Meter Verification.

The previously mentioned white paper shows how this tube stiffness relates to the flow calibration factor (FCF) and to the density measurement. The fact that Coriolis meters have no moving parts and that the fluids cause no corrosion of the flow tube results in unchanging tube stiffness. In most applications it is expected that the tube stiffness will not change. This stable tube stiffness means that the original, factory-based, flow and density calibrations will be correct over the life of the meter.

Meter Verification will confirm the calibration stability by showing that the stiffness is the same as the factory baseline over the life of the meter. By monitoring and comparing the current stiffness to the factory stiffness, it is possible to determine if the density and mass flow rate measurements are correct. When using a clean, compatible fluid, the dimensional and material properties of the tube do not change from the factory condition.

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EMERSON. Process Management

When using Coriolis flowmeters with incompatible, corrosive, fluids the situation changes. The corrosive fluids can etch away the wall of the tube. Defined by engineering mechanics, the stiffness of the tube is dependent on the dimensions and geometry of the flow tube. The tube diameter, wall thickness and shape determine the overall stiffness. When the wall is etched away, the stiffness of the tube changes.

Understanding how tube stiffness is affected by corrosive fluids is very important in reducing downtime and maintaining accurate measurements in these applications.

Use of Meter Verification in Corrosive Environments

In most applications Coriolis flowmeters are compatible with the process fluid. A typical lifetime of a Coriolis meter is over 10 years. During its life a Coriolis flowmeter does not change its flow and density calibration. This stability is one of the features of Coriolis meters.

In a small segment of the marketplace Coriolis flow meters are used in corrosive environments where no compatible flow tube material is available. In these applications Coriolis meters sometimes corrode to the point where they may need to be replaced every 6 to 24 months. In these environments, the corrosive fluid reacts with the metal flow tubes, and some of these reactions can literally ‘eat’ away at the tubes and reduce the wall thickness of the tube. This reduction in material will cause mass flow and density measurement error. In the worst case, the wall becomes so corroded that there is a tube breach.

To quantify the effects of these adverse conditions, Micro Motion has conducted some testing where we deliberately corroded away the flow tube wall and tracked the changes in stiffness and calibration. The results from these tests give insight into the relationship between flow and density measurement and the Meter Verification results.

Experimental Results

Micro Motion used a strong acid to corrode a Coriolis flow meter. We used aqua regia, a very corrosive mixture of nitric and hydrochloric acids, which is not compatible with stainless steel flow tubes. In just five minutes, this acid would cause measurable corrosion of the tube wall. This corrosion in the tube wall reduces the stiffness and changes the calibration.

We sequentially corroded the meter four times. At each corrosion iteration we ran Meter Verification many times on both air and water to track the stiffness. We also performed a flow and density calibration at each corrosion iteration.

Figure 1 shows the Meter Verification results, plotting the percent change in stiffness (which is also called the Meter Verification “Stiffness Uncertainty”) as the meter was corroded. This graph shows both the air and water Meter Verifications. As expected, the data in this graph confirms that there is no difference in stiffness with respect to the process fluid.

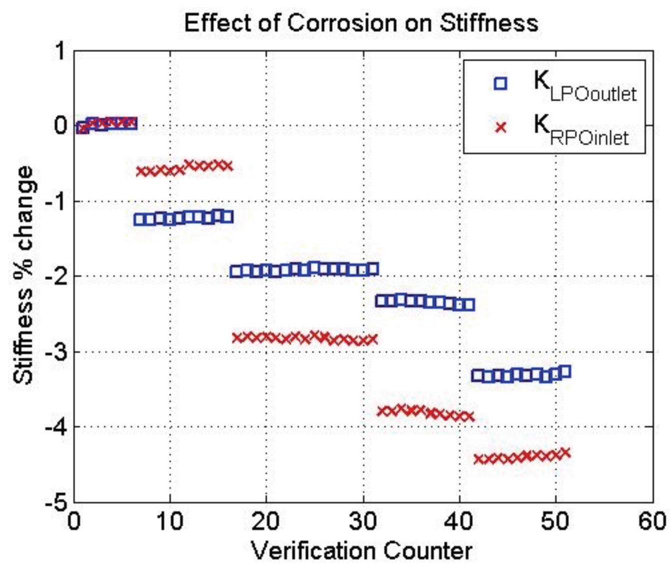

Figure 1. Stiffness Change vs. Corrosion

The first several data points were Verifications performed before the meter was corroded. And the stiffness is unchanged from the factory baseline.

The second set of data points show a reduction of about 1% in the stiffness. Meter Verification calculates the stiffness at the inlet and outlet pickoffs, as shown by the red x’s and the blue squares in Figure 1.

For the first corrosion iteration, we happen to have flowed the acid in the reverse-flow direction. While we intended to corrode the meter uniformly, you can see that the stiffness for the outlet pickoff (LPO) decreased more than the inlet pickoff. Because of the reverse flow direction the outlet pickoff was actually upstream of the inlet pickoff. The data indicates that there was actually more corrosion on the upstream side of the meter than on the downstream side.

We then corroded the meter again, this time in the normal flow direction, and repeated the verification and re-calibrations. This time you can see that the inlet pickoff (RPO), now the upstream pickoff, corroded more than the downstream pickoff. While we were unable to achieve uniform corrosion along the meter, we were able to repeat the effect of the higher corrosion in the upstream side of the meter.

We then repeated this process two more times. You can see in the figure that the erosion continues down to about 4% reduction in stiffness.

Before we discuss the effect of the stiffness on the calibration factors, let's discuss the detectability of the stiffness change with Meter Verification.

Meter Verification Specification Limits and False Alarms

Readers familiar with Meter Verification know that the stiffness uncertainty specification limits are set at ±4%. Looking at Figure 1, only the last set of corrosion conditions is out of specification. How then can we say that we can detect stiffness changes for the other corrosion conditions when all those points are within specification?

Let's start with why the specification limits are set at ±4%. Looking at the data in Figure 1, you can see that the variation of the data within each corrosion condition has a very small variation. This data was taken under lab conditions, i.e. with low flow, low pressure, and stable fluid and ambient temperatures. Under lab conditions, the variation of the stiffness measurement is better than the accuracy specification.

Customers may be collecting Meter Verification data under field conditions with unstable temperatures and temperature gradients, large pressure variations, and significant flow noise. The Meter Verification results are compensated for temperature, but temperature gradients can cause a bias or increased variation in the stiffness estimate due to residual uncompensated temperature errors. Pressure will cause a real stiffness change on a par with the density effect on pressure. The stiffness measurement is not compensated for pressure at this time. Flow noise at higher flow rates (>60% of nominal) will dramatically increase the standard deviation of the stiffness measurement. We are unable to compensate the measurement for this flow noise.

Taking all of these field effects into account, we have quantified the 3σ variation in stiffness uncertainty over the entire range of field effects to be 4%. Since we expect no change to the meters calibration, we want to minimize false alarms, i.e. indicating that the meter has changed when it really hasn't. So with the spec limits at 4% we will only have a false alarm ~0.1% of the time. Because of the constancy of the FCF, we are more concerned about false alarms than we are about detecting a real stiffness change.

Taking a series of Verifications, the user can assess if the mean stiffness value is changing by a number of statistical methods. The reader may be familiar with trend analysis, t-tests, Statistical Process Control, etc. These methods allow the detection of smaller changes than is possible with a strict spec limit methodology. All of these methods rely on taking a set of data points rather than a single measurement.

Meter Verification Detectability

For these corrosion tests Micro Motion did exactly that, taking a set of measurements at each corrosion condition. We then applied statistical methods to show that the stiffness had indeed changed between each set of corrosion conditions. Statistical methods show that these changes are significant, even though they are less than the 4% spec limits.

Figure 2 shows the data in Figure 1 plotted as mean values with error bars to indicate the variation. We chose three standard deviations for these error bars. This 3σ (three sigma) approach is common in statistics, encompassing ~99.9% of the data variation.

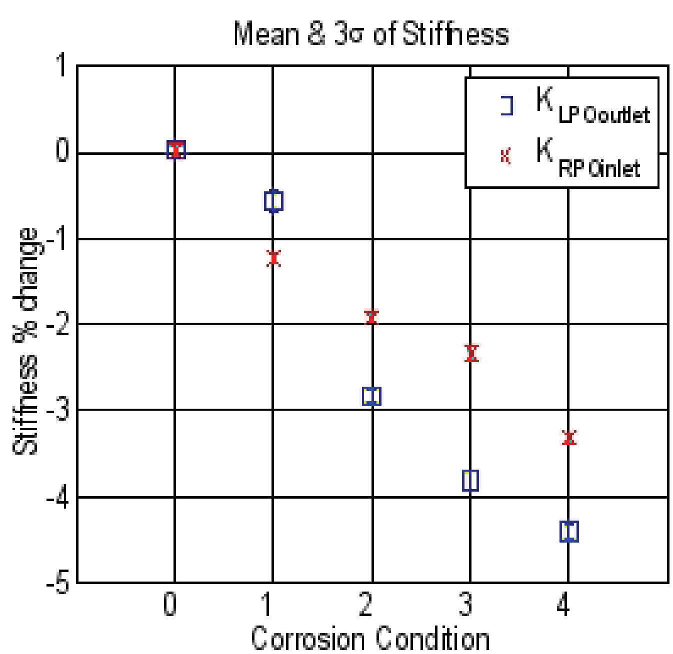

Figure 2. Mean and Error Bars of Stiffness Change

Without getting beleaguered in statistical equations, the error bars in Figure 2 show that the variation of the data under our test conditions is around the 0.1% level, consistent with the accuracy specification of these flowmeters. The figure graphically shows that the stiffness has changed for each corrosion condition with strong statistical significance. Figure 2 also shows that the inlet and outlet pickoffs corrode differently.

Having discussed the spec limits and detectability, let's get back to looking at the effect of corrosion-induced stiffness changes on calibration.

Stiffness Change Relates to Flow Calibration Factor (FCF) Change

After each corrosion condition the meter was calibrated for both flow and density. Figure 3 plots the percent change in FCF against the percent change in stiffness. Note in the plot that both the right and left pickoff stiffnesses are plotted. The plot shows that as the stiffnesses decrease, the FCF decreases. A smaller FCF means that there will be more flow signal for a given flow, as would be expected with tube thinning.

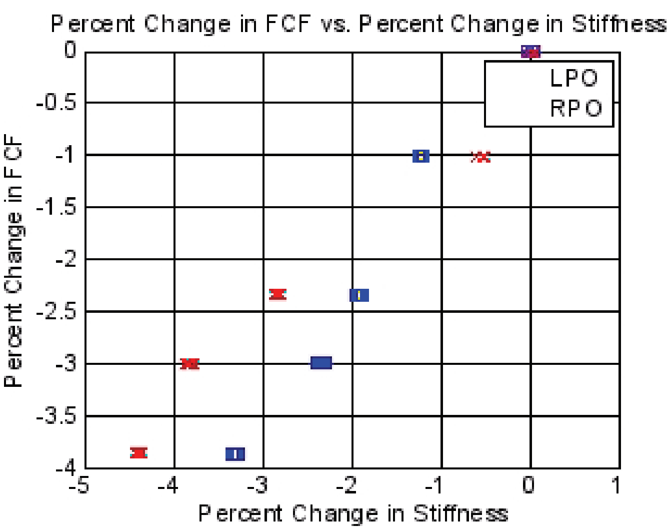

Figure 3. FCF Change vs. Stiffness Change

Figure 3 shows that the FCF and the average of the stiffness changes have approximately a 1:1 relationship. Under non-uniform stiffness changes this 1:1 relationship would not be expected.

Figure 3 shows that Meter Verification is very capable of detecting very small changes in flow calibration factor.

How Does This FCF Change Affect Mass Flow Error?

The decrease in FCF due to corrosion will of course affect the mass flow error. Figure 4 shows the typical percentage error in mass flow versus mass flow rate graph. You can see that corrosion causes a positive flow error in all cases, consistent with thinner tubes and a reduction in FCF. Looking at the graph in more detail, the mass flow error shows the combined effect of a change in flow cal factor and a change in zero. If there were only changes in FCF, the mass flow errors would be straight horizontal lines at each corrosion condition. If there was only a zero error, the high flow rate data would all be near 0% error and the low flow rate data would be offset showing the effect of the zero change.

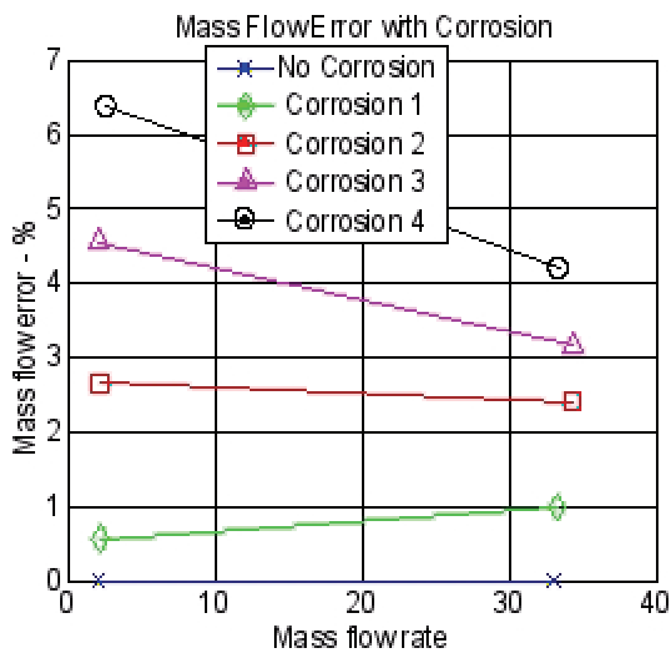

Figure 4. Mass Flow Error vs. Mass Flow Rate

Since we have measured the mass flow error at two mass flow rates we are able to separate out the effect of the flow cal factor change from a zero shift due to corrosion. Figure 5 shows that there is a zero shift due to corrosion on the order of 10 ns.

Discussing the effects of the zero shifts is beyond the scope of this paper. Suffice it to say that the nonuniform nature of the corrosion introduces asymmetry into the flow tubes, disrupting the carefully manufactured uniform set of flow tubes. This asymmetry has a small but definite effect on the zero.

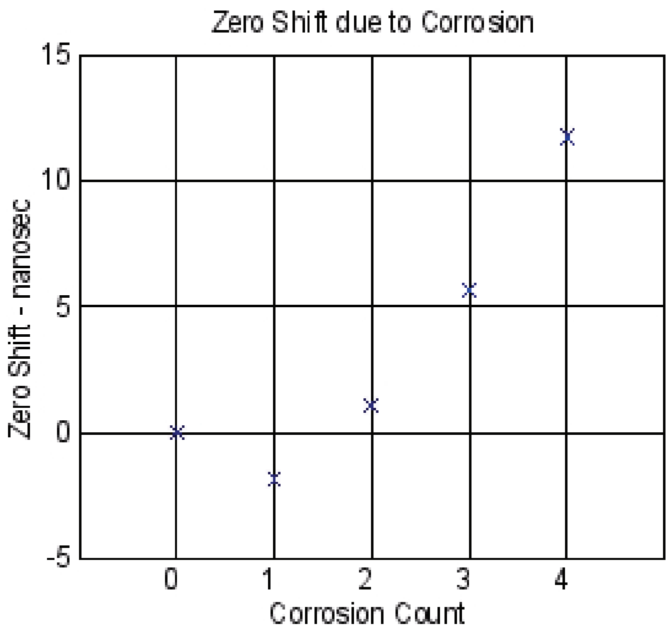

Figure 5. Zero Shift Due to Corrosion

Now let's look at changes in the density measurement due to corrosion.

Density Changes with Corrosion

Readers familiar with Coriolis density measurement know that it is a separate measurement independent of the mass flow measurement. The temperature compensated instantaneous frequency reading is used to measure the density of the fluid. Equation 1 shows that the frequency is proportional to the square root of the stiffness divided by the total mass. The density measurement assumes that the stiffness and mass of the flow tubes is unchanged and that any frequency change is due to a change in the mass of the fluid. An implicit density measurement assumption is that the interior volume of the flow tubes is unchanged as well.

$$\text{frequency} \propto \sqrt{\frac{\text{stiffness}}{\text{mass}_{\text{tube}} + \text{mass}_{\text{fluid}}}}$$

Equation 1. Frequency Related to Stiffness and Mass

However, in our corrosion cases, these assumptions are violated. Etching away the wall of the tube changes the stiffness of the tube, the mass of the tube, and the internal volume of the tube because the interior diameter has increased due to a decreased wall thickness. This secondary effect of interior volume increase causes additional density measurement error.

Let's look at the effect of corrosion on density measurement in more detail. Since frequency is a fundamental density measurement parameter, let's plot the frequency changes due to corrosion versus the stiffness changes. Figure 6 uses the averaged right and left pickoff stiffness changes as the abscissa. Averaging these two gives a better measure of the structural dynamic changes due to corrosion, and hence correlates more naturally with the frequency changes. The graph plots both the air frequency change and the water frequency change due to corrosion. Equation 1 would predict that a 4% stiffness decreased would lead to approximately a 2% decrease in frequency if stiffness were the only flow tube change. Figure 6 indicates that the frequency change is less than –1.5%. As previously mentioned, the tube mass will also decrease. A tube mass decrease would increase the frequency, partially offsetting the decrease due to stiffness.

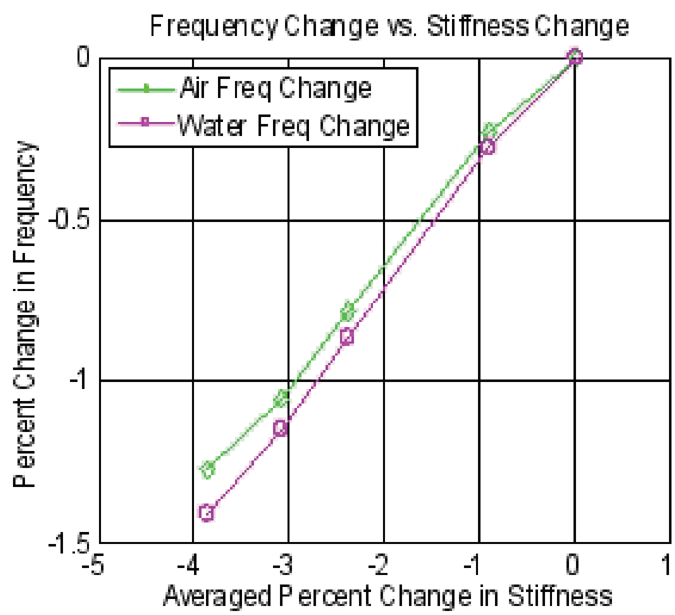

Figure 6. Frequency Change vs. Stiffness Change

Note also that the air frequency decreased less than the water frequency. This difference in frequency change is indicative of a change in tube volume. An increase in tube volume increases the mass of the fluid which leads to a larger decrease in tube frequency than a tube filled with air.

The decrease in frequency due to stiffness changes matches our engineering intuition. Let's now relate these changes to density measurement error in Figure 7. Again the abscissa is the averaged change in stiffness. But now we can see that the density error is positive for a decrease in stiffness, correlating to decrease in frequency. Figure 7 plots the error in density in grams/cc for both water and air.

Coriolis meter users will know that the density resolution on gases is not very good, so the air density error would not make sense in a real application, but is included here to illustrate the effects of stiffness changes. As mentioned previously, we took advantage of statistical methods to pull out a reliable air density measurement error. Also note that the quantitative values for the density error are dependent upon sensor size. The numbers here are typical but will be different for different sensor sizes.

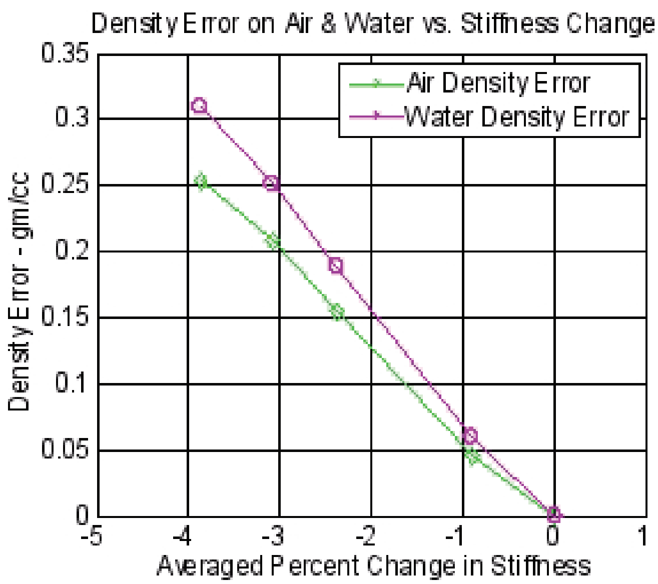

Figure 7. Density Error vs. Stiffness Change

Again we see that the water density error is larger than the air density error, due to the increase in tube volume. It is perhaps surprising that the small, 4%, decrease in stiffness causes the large 0.3 gm/cc density error, a 30% density error on water. But these numbers are correct, inherent in the physics of density measurement.

This wraps up the discussion of the effects of corrosion on process parameter measurement. We have shown how stiffness ties directly into flow and density measurement and how these changes in the stiffness directly affect these two measurements.   This direct correlation between this stiffness and calibration makes Meter Verification a very good diagnostic for corrosion detection.

There have been claims that damping measurements are a good diagnostic for detecting corrosion. We did not find this to be the case in our experiments.

Does Drive Gain or Damping Indicate Corrosion?

Discussions of damping typically require an understanding of drive gain as well. Drive gain is a measure of the current that is applied to the drive coil to generate the force necessary to vibrate the flow tubes at resonance. Drive gain turns out to be a very good diagnostic for entrained air as it is extremely sensitive to process fluid changes. However the sensitivity to process fluid makes drive gain a poor diagnostic for detecting corrosion since changes in drive gain are more likely to map to process fluid changes. Restating this, a diagnostic for process conditions does not necessarily make a good device diagnostic.

We tracked drive gain during the corrosion testing. Figure 8 shows that during all of Verifications as the meter was corroded, the drive gain is essentially unchanged. It also shows how the drive gain varies with process fluid, with the drive gain being slightly larger on water than on air, as expected.

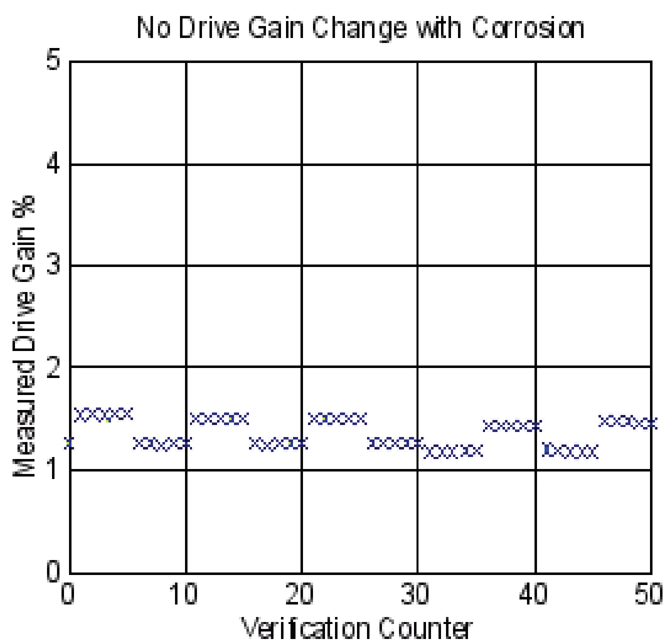

Figure 8. Drive Gain vs. Verification Counter

The mathematics of the Meter Verification algorithm requires us to estimate the damping coefficient. Figure 9 plots the normalized damping changes during the corrosion testing. Since damping tracks the drive gain, we see that the damping is slightly higher on water than on air, paralleling the drive gain plot in Figure 8. However note that the damping coefficient does not change with corrosion.

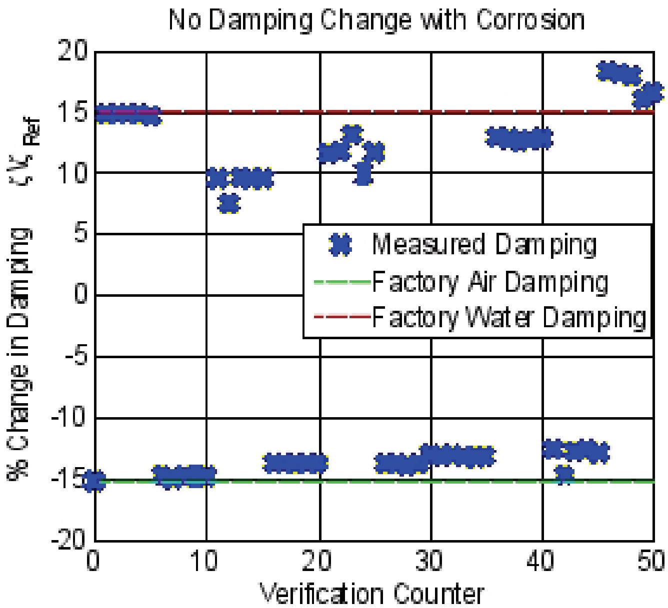

Figure 9. Damping Change vs. Verification Counter

Since damping is not a good diagnostic for flow tube changes and is extremely sensitive to process conditions, Micro Motion chooses not to present it in the Meter Verification user interface.

Summary

Structural Integrity Meter Verification allows the customer to monitor the physical condition of the Coriolis mass flow meter. In most cases we expect that the physical condition of the flow tubes does not degrade over the life of the meter. However we have shown that under corrosive conditions Meter Verification is very capable at detecting changes to the flow tube.

This paper discussed why the spec limits for Meter Verification are set at 4%. We showed how, by using statistics with the Meter Verification data, changes can be detected at well below this 4% level.

This paper also discussed how drive gain and damping are poor diagnostics for detecting corrosion.

The direct correlation between the flow and density measurements and the tube stiffness means that a change in stiffness will result in an error in process measurement. Customers using Coriolis flowmeters in corrosive conditions can use Meter Verification to track meter health to maintain measurement accuracy and to ensure meter integrity.

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