
CsHM
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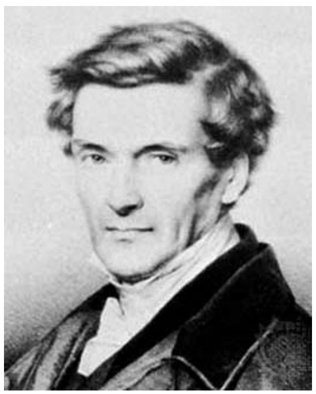
Paper # #2015-0164
Verification of Coriolis Flow Meter Calibration



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

Agenda

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- Coriolis Mass Flowmeter Theory of Operation
- Proving, Verification, and Coriolis Robustness
- Coriolis Meter Verification Review
- Statistical Hypothesis Testing
- Direct Stiffness Verification Results
- Conclusion

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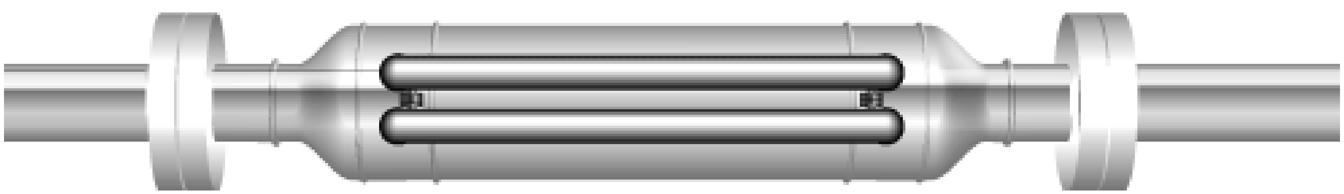
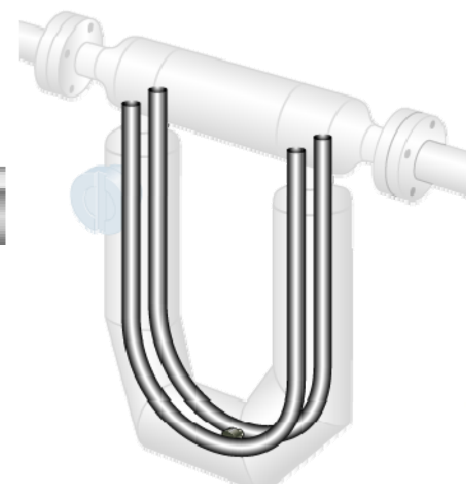
Coriolis Meters Directly Measure Massflow

- Process fluid enters the sensor and flow is split with half the flow through each tube
- Tubes are oscillated at the first out-of-phase bending mode by closed-loop control system





How Does It Measure Mass Flow?

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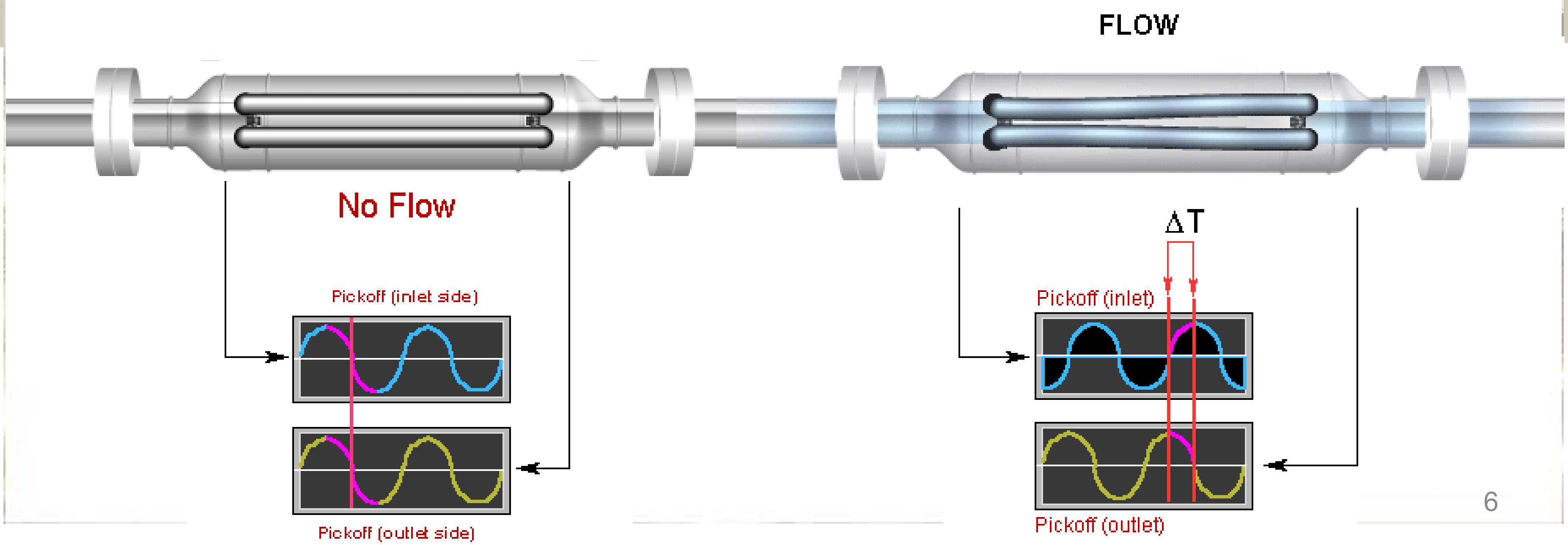
- No flow $\Rightarrow$ no Coriolis effect
- Pickoff signals in phase with each other
- With flow, Coriolis forces are induced
- Coriolis forces cause flow tubes to twist
- Twist causes a time delay, δt, between pickoffs
- $\delta t \propto$ mass flow rate



Flow Calibration Factor and Zero

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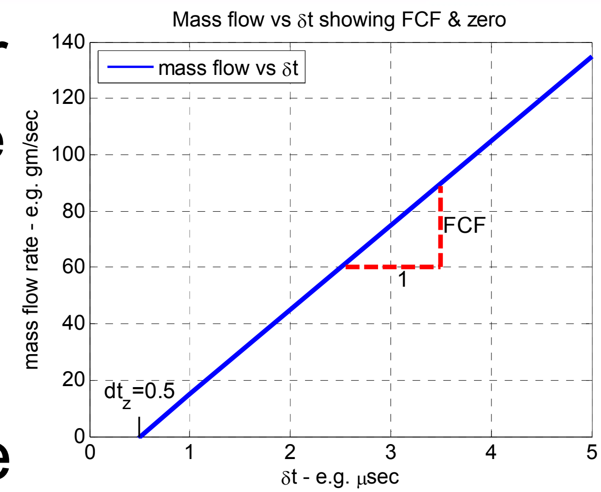
- Coriolis meters are inherently linear
  - Flow Calibration Factor (FCF) $\Rightarrow$ slope
  - Zero offset (δt_z) $\Rightarrow$ intercept

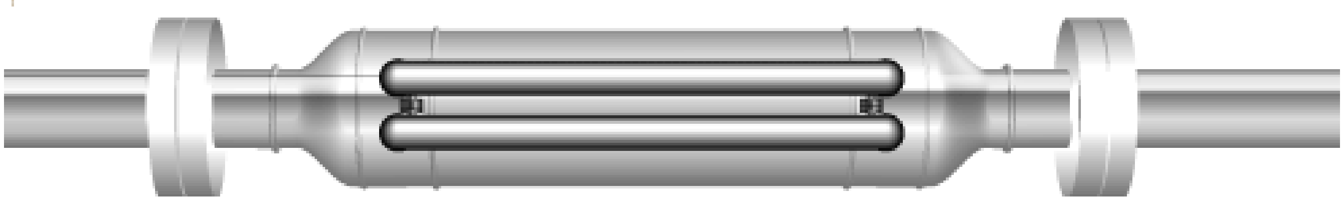
$$\dot{m} = FCF \cdot (\delta t - \delta t_Z)$$

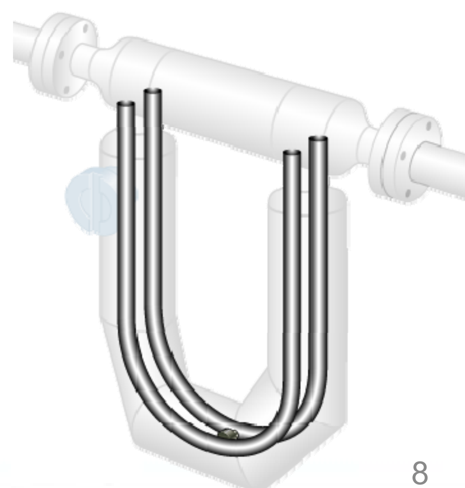


- Zero verification not discussed here
  - Many techniques, much information on zeroing
  - Modern Coriolis meters have stable zeros, use factory zero
- Flow Calibration Factor (FCF) units of mass flow/time
  - e.g. (gm/sec)/μsec $\quad FCF = \dfrac{\dot{m}}{\delta t}$
- FCF for mass flow is correlated to “stiffness”

Coriolis Density & Volumetric Flow Measurement

- Density is measured independently of mass flow
- Both measurements are used to calculate volumetric flow rate
  - Density of instantaneous mixture in tubes
- Coriolis meters also output standard volume
  - Instantaneous, standard, sampled, calculated density
- Coriolis transmitters totalize flow
  - Total mass
  - Total volume





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Terminology

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- **Calibration**: Establishing the relationship between flow and signal produced by sensor.
  - Relates the flow to the time delay to give FCF
- **Proving, Validation**: Confirming flow performance by comparing a primary flow standard to meter under test
  - Provings generates a meter factor
- **Verification**: Establishing confidence in performance by analysis of secondary variables correlated with primary flow measurement
  - Verifications gives a “Go/No Go” message

Coriolis Robustness

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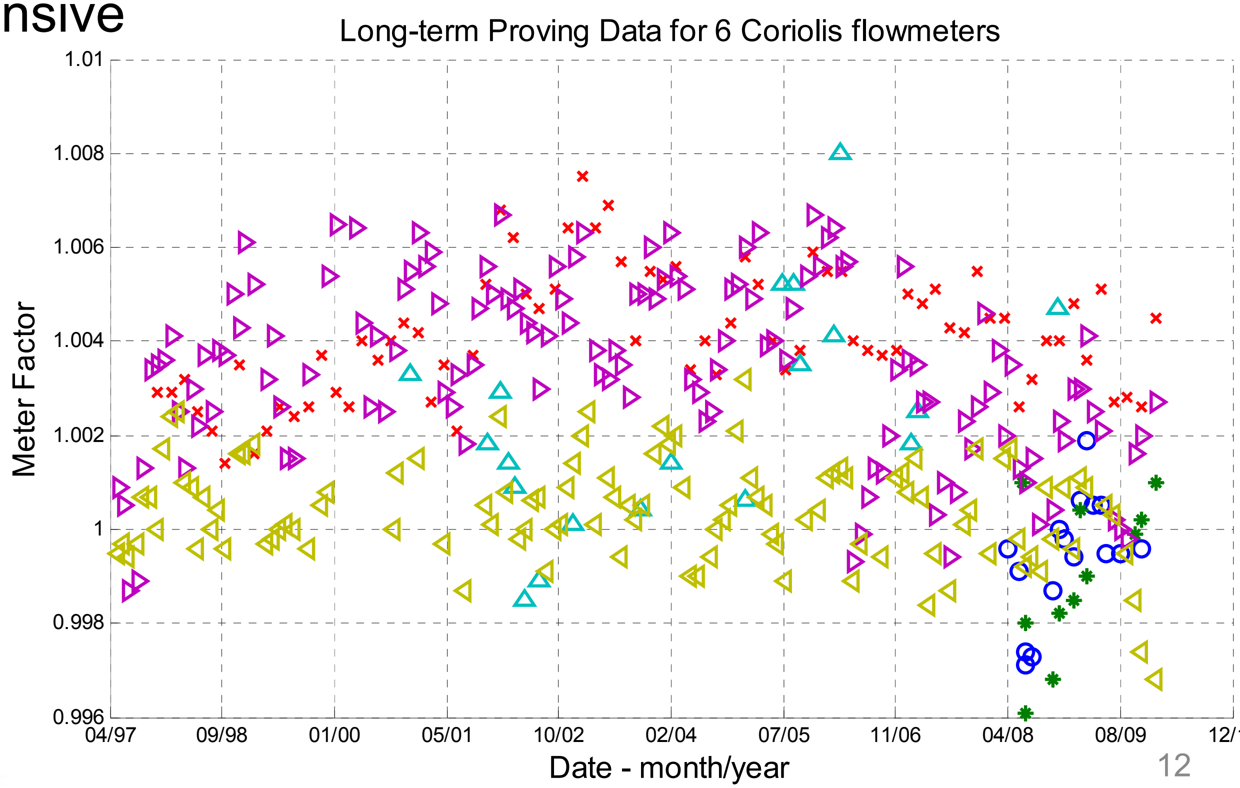
- No change in FCF expected over the life of the meter
  - Meter proving gives consistent meter factors
  - Measurement not dependent on flow profile
  - Expect no repair/rebuild over the life of the meter
  - No moving parts means no change in calibration
- Coriolis MTBF
  - Exida, SIS life expectancy
- Coriolis flowmeter robustness is key to its value
  - Very low operating costs offset higher initial price

Coriolis Meters Show Stable Provings

- Coriolis meters can be proven
  - Must be configured correctly
- Coriolis provings are very stable
  - 13 meters, 375 points over 13 years
  - No change in meter factor
- Provings are expensive
  - $175,000
- Value add?



Directive 17 Coriolis Exceptions

- Directive 17 recognizes Coriolis meter stability
  - Provides for proving exceptions

Table 2.1. Meter proving frequency requirements and proving methods

		Proving method					
Application	Meter type	Pipe/ compact/ small volume prover	Master meter	Volumetric vessel/tank prover	Bench proving	Calibrate transmitter	Proving frequency
Live oil/condensate (meter at well/battery or test meter)	PD/turbine	A[1]	A	A	A[2]	N/A	Annual
	Vortex/coriolis	A[3]	A[3]	A[3]	A[2, 3]	N/A	Annual
	Differential producer	N/A	N/A	N/A	N/A	A	Annual
Live oil/condensate (gas plant inlet separator or cross border)	PD/turbine	A[3]	A	A	A[2]	N/A	Semi-annual
	Vortex/coriolis	A[3]	A[3]	A[3]	A[2, 3]	N/A	Semi-annual
	Differential producer	N/A	N/A	N/A	N/A	A	Semi-annual
Dead oil, stable HVP liquids, or delivery points[4]	PD/turbine	A	A	A[5]	N/A	N/A	Monthly[6]
	Coriolis/ ultrasonic	A	A	A[5]	N/A	N/A	Monthly[6]
Water	PD/turbine	A	A	A	A[2]	N/A	Annual
	Vortex/coriolis/ magnetic/ ultrasonic	A[3]	A[3]	A[3]	A[2, 3]	NA	Annual
	Differential producer	N/A	N/A	N/A	N/A	A	Annual

1 A = acceptable method; N/A = not applicable.

2 See Sections 2.7.1, 2.8.2.1, and 2.10 for bench proving information.

3 For meter proving exceptions, see Section 2.6.1.

Directive 17 Coriolis Diagnostics

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- Directive 17 recognizes that Coriolis vendors have developed new diagnostics and verification techniques in response to user requests

2.6.1 Exceptions

1. If a meter used to measure fluids at flow-line conditions is a type that uses no internal moving parts (e.g., orifice meter, vortex meter, cone meter, Coriolis meter, ultrasonic meter), it does not require proving, provided that all the following conditions are met:

   - The flow through the meter must be continuous (not intermittent) or the meter must qualify for bench proving or be a Coriolis-type meter with sufficient structural integrity internal diagnostics (see below) …

   - The internal components of the primary meter device must be removed from service at the same frequency as indicated in Table 2.1, inspected, replaced or repaired if found to be damaged, and then placed back in service, in accordance with procedures specified by the API, the AGA, other relevant standards organizations, other applicable industry-accepted procedures, or the device manufacturer's recommended procedures, whichever are most applicable and appropriate. Internal metering diagnostics may be used to determine if the structural integrity of 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. An initial baseline diagnostic profile must be performed and documented during the commissioning process. The operator must maintain documentation on the diagnostic capability of the measurement system and make that available to the ERCB on request.

Coriolis Structural Integrity Verification

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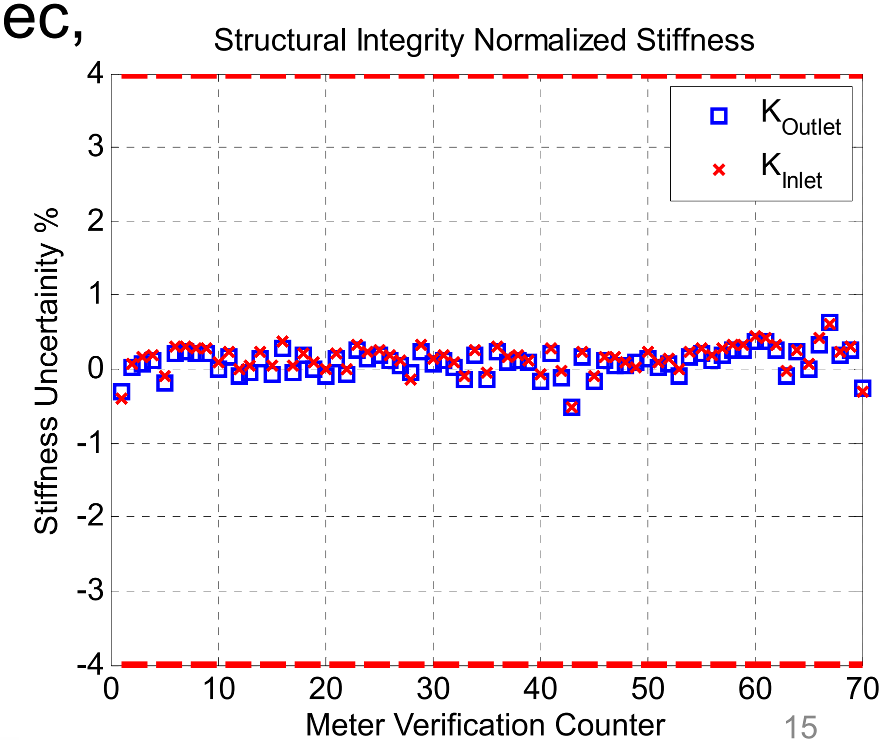
- Verification results mirror stable provings
  - Around 70 verifications over 6 months
  - Some bias and variation apparent
  - Data is "stationary", statistics unchanging over time
  - Stiffness results are in-spec, mass FCF is unchanged
- Directive 17 says no need to prove (in many applications)
  - Extend proving interval
  - Save money



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Key Verification Points

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- Verification will not replace proving
  - Proving regulated by legal & contractual arrangements
  - Proving checks entire flow measurement system
- Verifications verify calibration (span)
  - Configuration, I/O, zero not necessarily verified
  - Built-in to verification technique/procedure/software?
  - If not, need verify these separately?
- Coriolis robustness underlies value of verification
- Documentation and commissioning are critical
  - Multiple verifications at startup
  - Set up routine verifications and documentation at the beginning

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1. If a meter used to measure fluids at flow-line conditions is a type that uses no internal moving parts (e.g., orifice meter, vortex meter, cone meter, Coriolis meter, ultrasonic meter), it does not require proving, provided that all the following conditions are met:
   - … An initial baseline diagnostic profile must be performed and documented during the commissioning process. The operator must maintain documentation on the diagnostic capability of the measurement system and make that available to the ERCB on request.

Verification Overview

- Why are you going to verify?
  - Leverage Directive 17 to extend proving intervals
  - Flowmeter or process troubleshooting
- How are you going to verify?
  - Flowmeter device/local display, standalone laptop computers, integrated into DCS
  - Analog I/O or digital comm, wired or wireless
  - What communications protocol; HART, Modbus, …
  - Dedicated Asset Management software
- How often are you going to verify?
  - Verifications are much easier, cheaper, and quicker than proving
  - Done more frequently, generate statistical confidence
- Who is going to do it?
  - Operations
  - Maintenance, Instrument techs
  - Meter Vendor
  - Third party, e.g. proving service provider, cloud-based system

Verification Methods

- Focus on stiffness based methods
- Recall Mass Flow Calibration Factor (FCF) has units of mass flow/time, e.g. (gm/sec)/μsec
- Dimensional analysis shows FCF ⇔ Stiffness

$$FCF = \frac{\dot{m}}{\delta t} \qquad FCF \approx \frac{\left(Mass \big/ Time \right)}{Time}$$

$$FCF \approx \frac{\left(\dfrac{Force \,/\, acceleration}{Time} \right)}{Time} = \frac{\left(\dfrac{Force \,/\, (Length \,/\, Time^2)}{Time} \right)}{Time} \approx \frac{Force}{Length}$$

- FCF fundamental units of stiffness (force/length)
- No change in flow tube stiffness ⇔ no change in FCF

Coriolis Stiffness Verification

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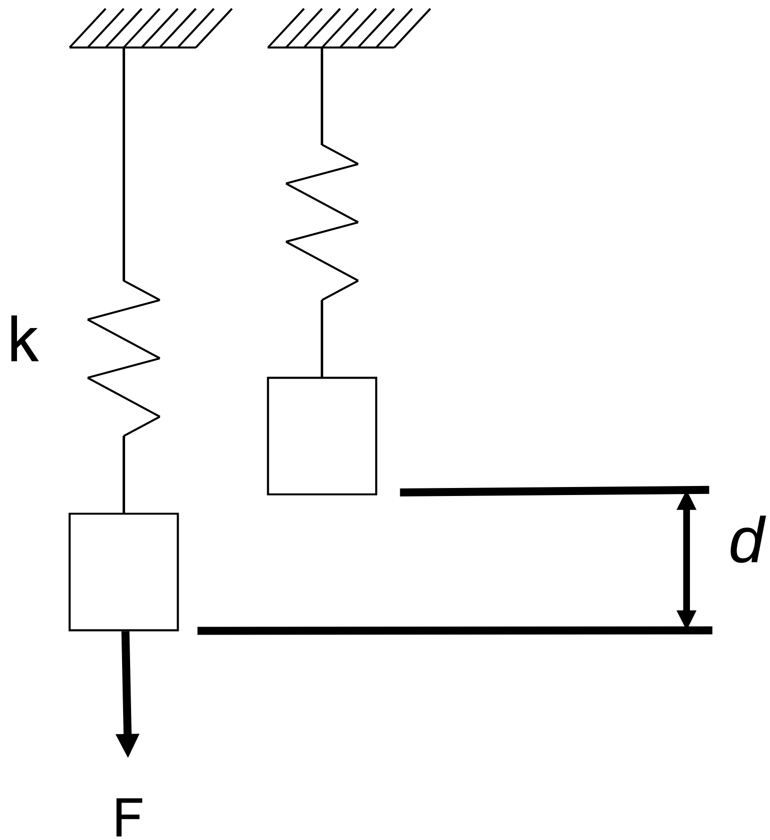
- Relationship between FCF & stiffness led to development of stiffness-based verification techniques
  - No "absolute stiffness number" generated
  - Measure change in stiffness from a baseline
- Several different stiffness verification methods
  - Known density
  - Drive/Coriolis mode frequency ratio
  - Wall thickness verification
  - Direct stiffness measurement
- All approach verification from structural dynamics theory
  - Different requirements and assumptions in each method

We can measure stiffness statically



$$k = \frac{F}{d}$$

k = Stiffness of spring or flow tube

F = Force or drive force on flow tube

d = Amplitude of movement or flow tube deflection

- One equation, one unknown
- Determine stiffness exactly by measuring F and d once
- Mass is not involved in measurement

Dynamics and Verification

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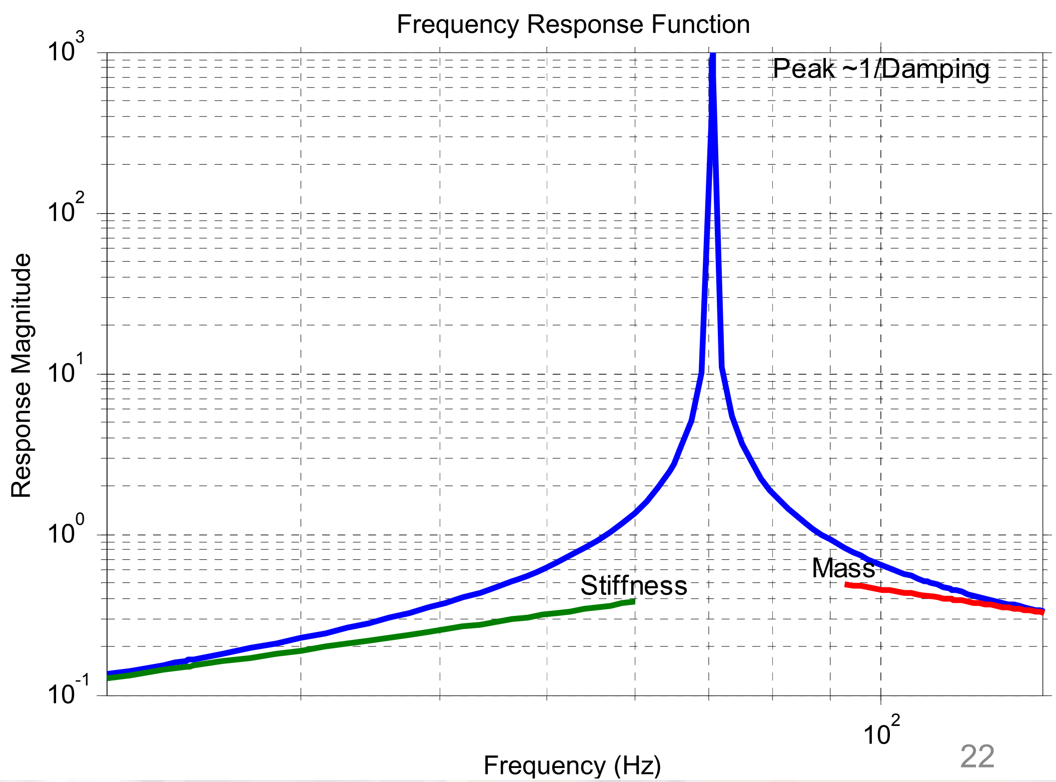
- Verification measures stiffness dynamically
- Dynamic stiffness measurement must solve for 3 unknowns: stiffness, mass, & damping
- Requires at least 3 equations, or, some assumptions (constraints)

$$FRF = \frac{j\omega}{-M\omega^2 + jC\omega + K}$$



Stiffness Verification Techniques

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- Common assumptions and constraints
  - Damping is small
  - Use resonant frequency, ratio of stiffness/mass
- Techniques vary in ease of use
  - Stop flow?
  - Stop measurement?
  - Need additional hardware?
  - Need remote host (PC, DCS, asset management system)?
- Review stiffness verification methods
  - Known density
  - Drive/Coriolis mode frequency ratio
  - Wall thickness verification
  - Direct stiffness measurement

Known Density Verification

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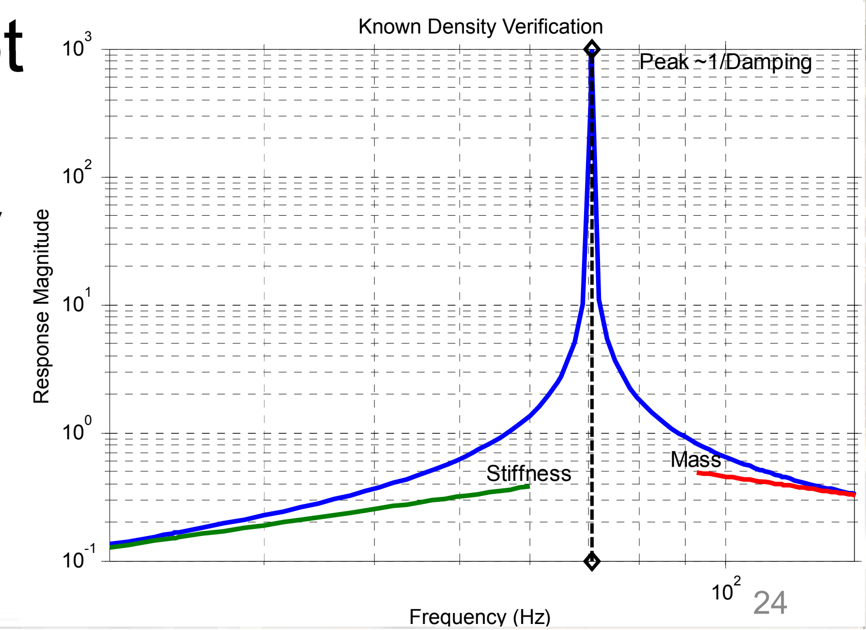
- 1 equation
  - Uses 1 resonant frequency
  - Assumes fluid density is accurately known
  - Typically air or water
- Vendor independent, compatible with all Coriolis meters that measure density
- Can be challenging or not depending on installation
- Confirms drive frequency is unchanged from baseline



Coriolis Stiffness Verification

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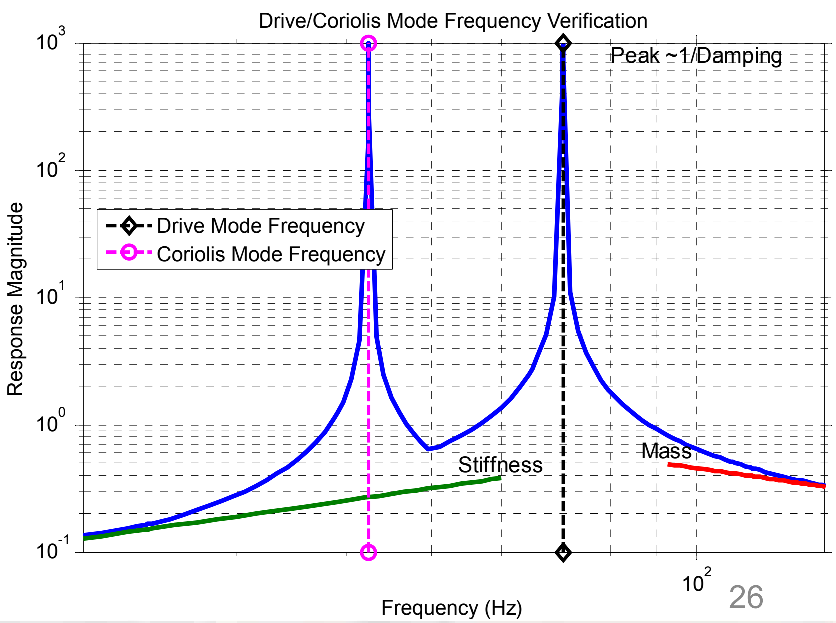
- Known density
- Drive/Coriolis mode frequency ratio
- Wall thickness verification
- Direct stiffness measurement

Drive/Coriolis mode frequency ratio

- 2 equations
  - Uses 2 resonant frequencies
- Measure Coriolis mode frequency by putting transmitter in verification mode
- Ratioing drive and Coriolis frequencies eliminates effect of process fluid, verifies tube stiffness
- Unchanged ratio ⇔ unchanged stiffness ⇔ good FCF



Coriolis Stiffness Verification

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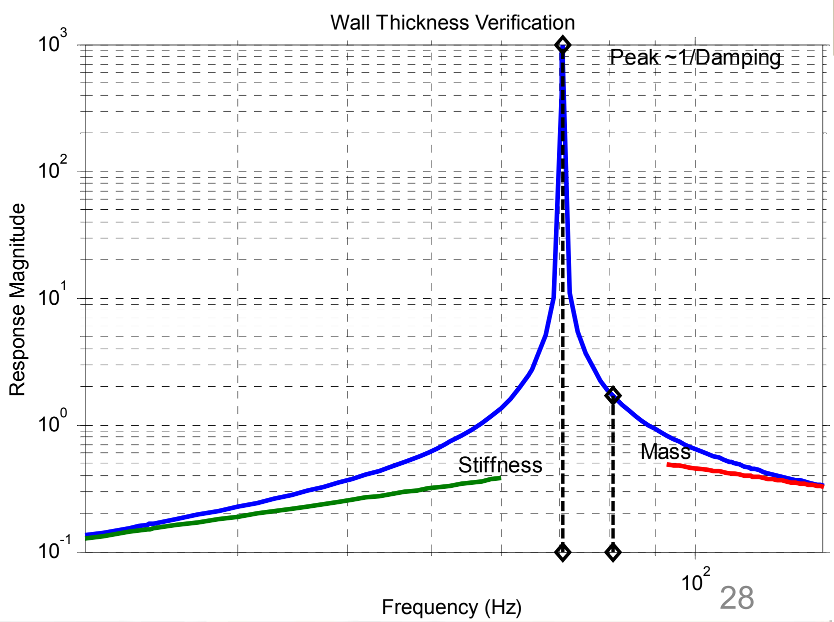
- Known density
- Drive/Coriolis mode frequency ratio
- Wall thickness verification
- Direct stiffness measurement

Wall thickness verification

- 2 equations
  – Drive frequency plus 1 tone at 120% of drive frequency
- Transforms FRF equation from stiffness to wall thickness
- Verifies unchanging wall thickness

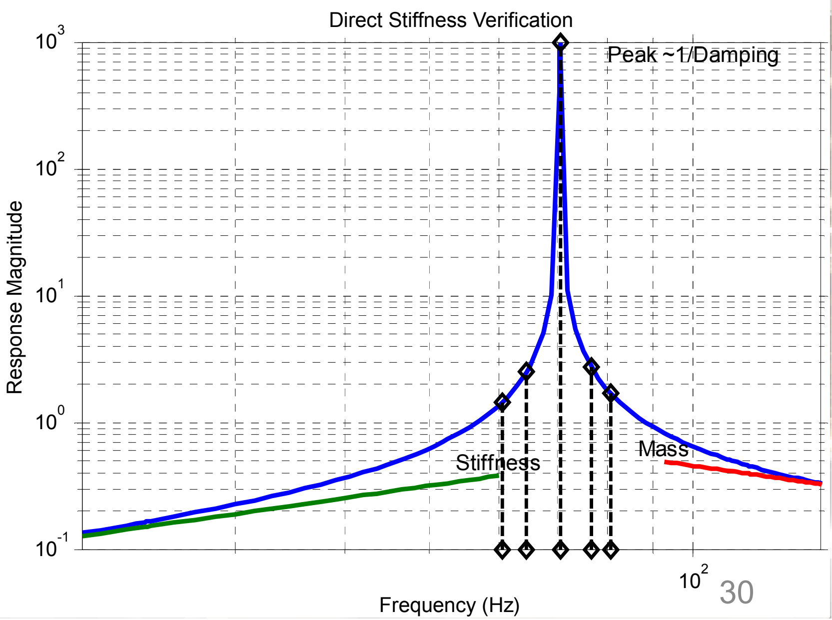


Coriolis Stiffness Verification

- Known density
- Drive/Coriolis mode frequency ratio
- Wall thickness verification
- Direct stiffness measurement

Direct Stiffness Verification

- 10 equations
  - Drive frequency plus 4 tones at both pickoffs
  - Directly solves for stiffness, mass, and damping independently
  - Overdetermined solution reduces variation
- Measured stiffness is compared to factory value to confirm FCF



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Hypothesis Testing Overview

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- Used in many fields: medicine, pharmaceutical, radar, target recognition, law

Sample Hypothesis Testing Matrix			
		Verdict of Jury	
		Guilty	Innocent
Did the Defendant Commit the Crime	Yes	Deserved Jail Time	Back on the Street
	No	Falsely Imprisoned	Proven Innocent

- Great tool to understand and compare Coriolis verification techniques
- 2x2 matrix can be organized in many different ways, nomenclature can vary

Proving Metrology

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- Proving requires (assumes?) that prover is 3x to 10x more repeatable, accurate, reproducible than meter under test
- Easy to understand:
  - Prover (jury) is always correct
  - Meter is always suspect
- Hypothesis testing matrix reduced to 1 column
- Corrective action is clear

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

Verification Metrology

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- Takes into account that “jury” might be wrong
- Accounts for verification possibilities and statistics
- Accounts for robustness and low failure rates of Coriolis meters
- Note organization of hypothesis testing matrix, nomen-clature for positive/negative
  - Diagonal terms vs off-diagonal terms

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

Hypothesis Testing Statistics 101

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- Hypothesis testing statistics around Coriolis flowmeters and verification give confidence in Directive 17's exceptions for proving
- Coriolis failures are very rare
  - (Hard to get data for second row of matrix)
- Verification statistics and results should be treated differently than proving statistics and results
- Verification variation under lab conditions on a par with flow repeatability
  - Variation may increase with field effects
  - Verification failure limits ≠ flow/proving failure limits

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True Positives

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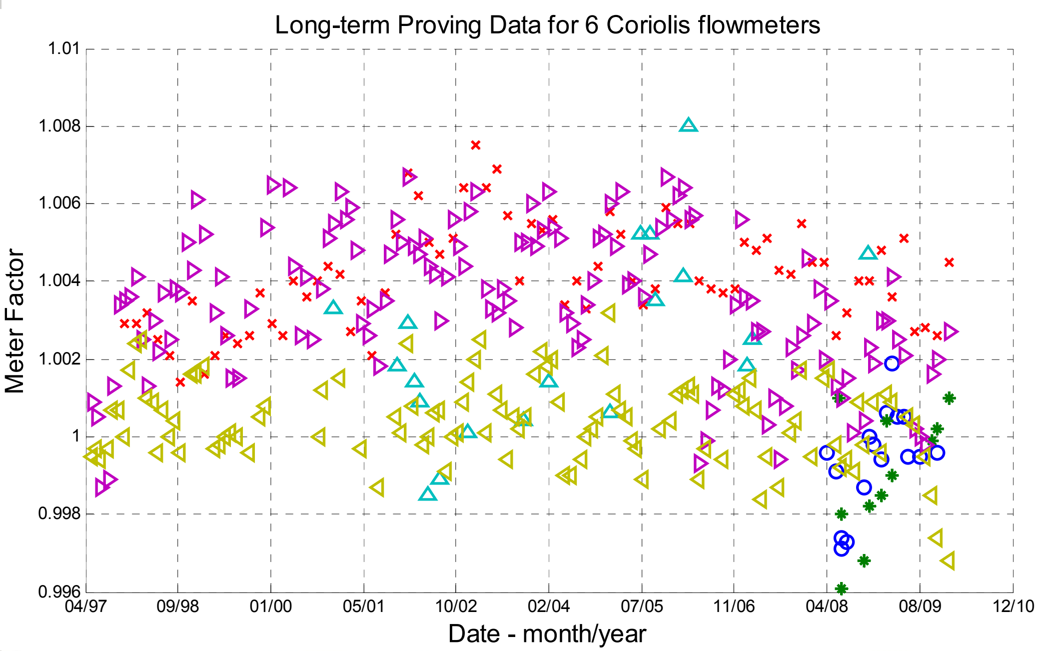
- Getting results for any cell in the hypothesis testing matrix requires both flow testing and verification results
- Vast majority of tests will be true positives
  - Flow accuracy in spec
  - Verification passes

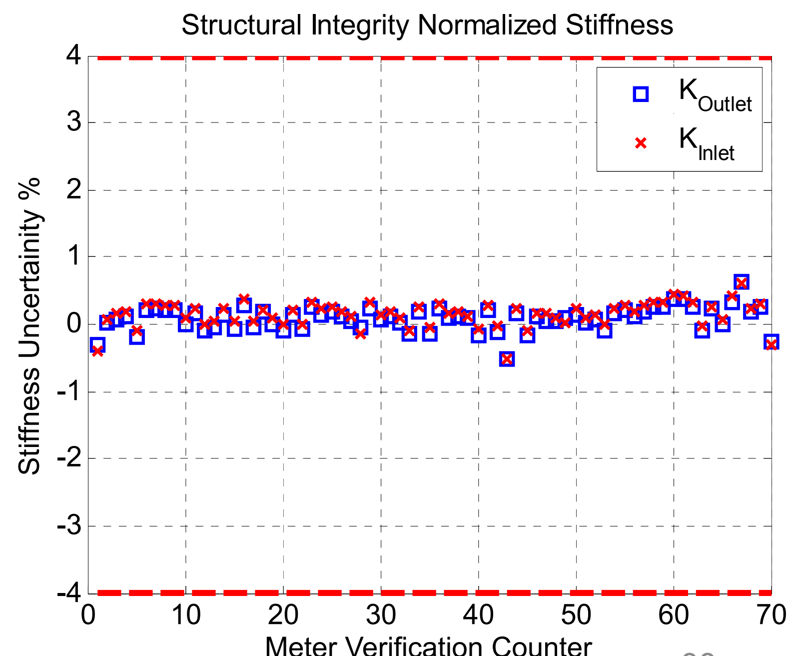
		Verification Result	
		Pass	Fail
Meter Condition	Meter is accurate	**True Positive**	False Alarm
	Meter is inaccurate	Covert Failure	True Negative

True Positive (#1)

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

- Cavern storage application
- Meter passes proving
- Meter passes verification
  - Verification results within 0.5%, well within failure limits

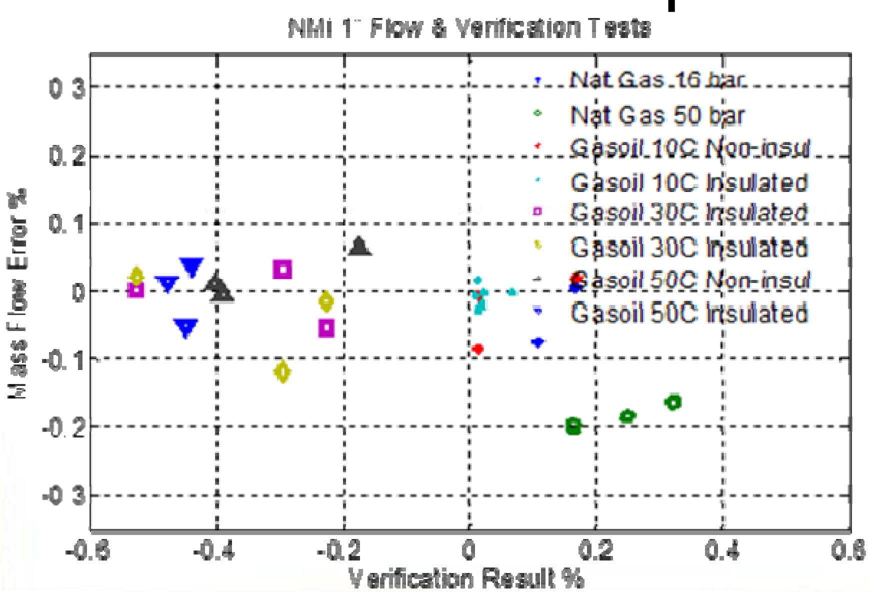


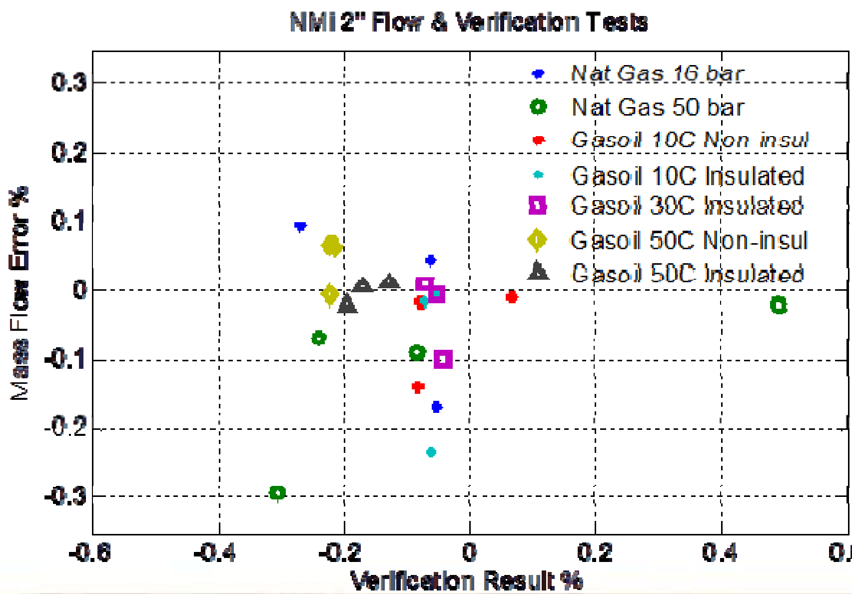


True Positive (#2)

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

- NMi testing 1” & 2” meters
  - Gasoil 10C, 30C, and 50C (NEL)
  - Natural gas 16 and 50 bar (Pigsar)
  - Multiple rates
  - Verifications run at all process conditions
- All flow results within specification
- Verifications all pass within 0.6%





True Negatives

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- Meter failures are very rare
- Worked with repair and quality departments
- Identified 2 meters that failed both calibration and direct stiffness verification

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

True Negative (#1)

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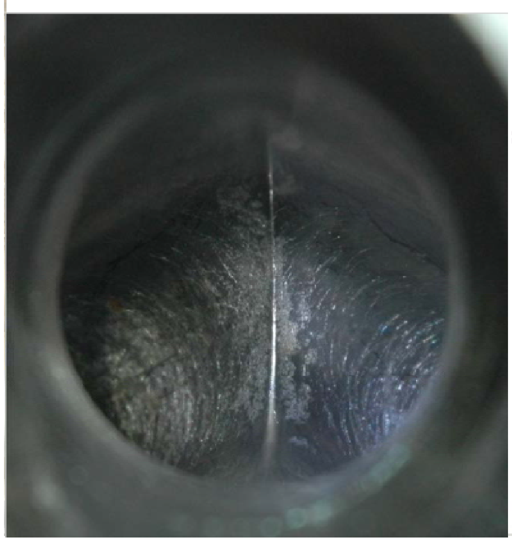
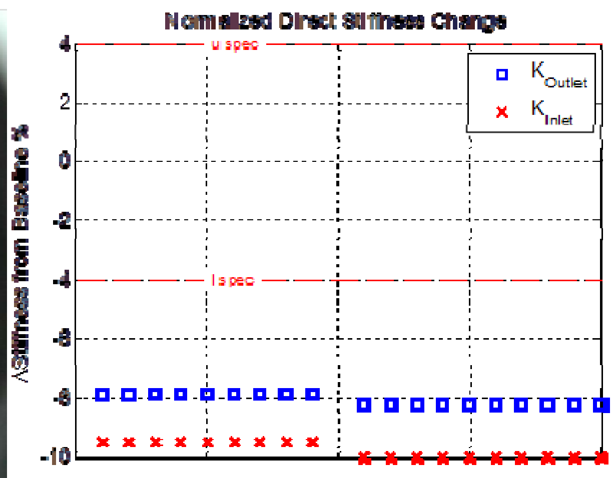
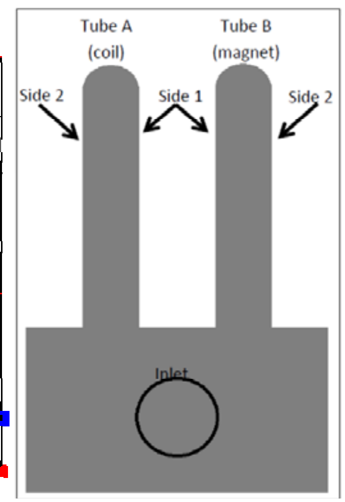
		Verification Result	
		Pass	Fail
Meter Condition	Meter is accurate	True Positive	False Alarm
	Meter is inaccurate	Covert Failure	**True Negative**

- Meter used in acidic slurry
- Damage visible on inlet manifold
- Inlet pickoff stiffness -10%, Outlet pickoff -8%
- Factory flow testing showed density reading ~0.25 gm/cm^3 high, mass flow error of over +10% high
- All consistent with a decrease in stiffness
- Tube thinning detected on one tube







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%

True Negative (#2)

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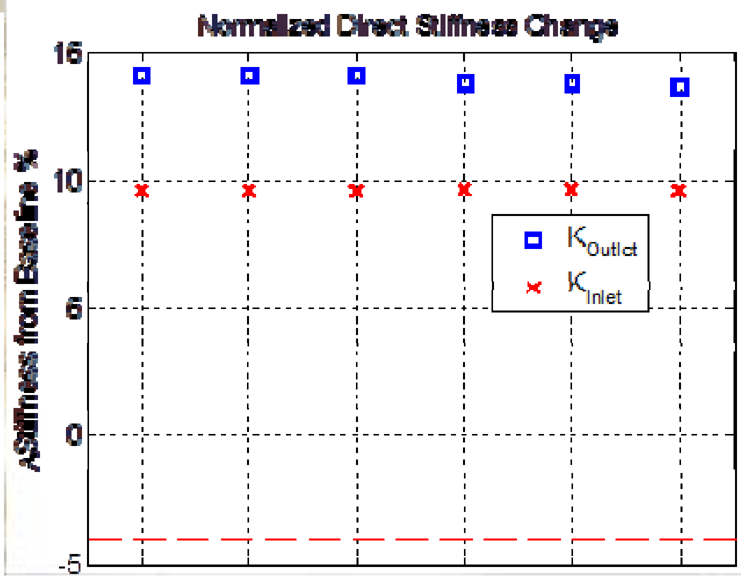
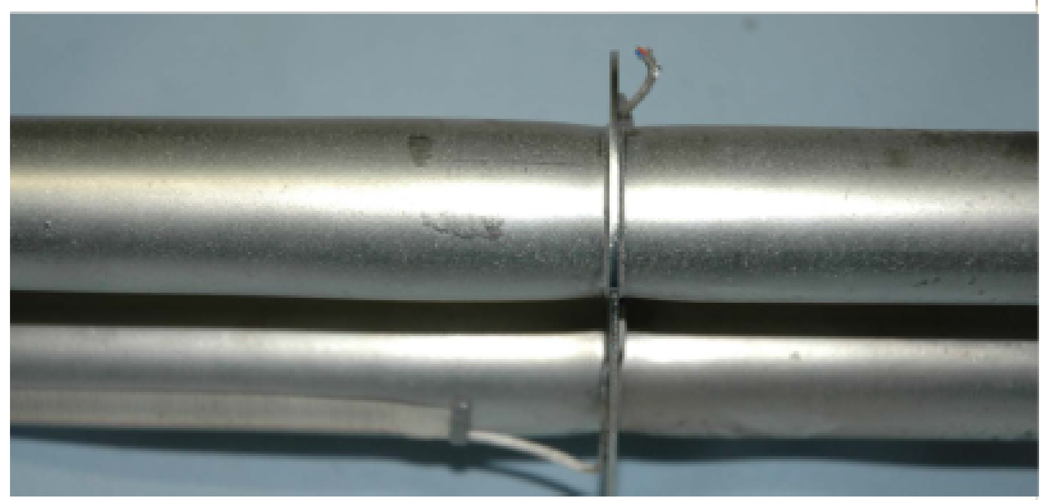
		Verification Result	
		Pass	Fail
Meter Condition	Meter is accurate	True Positive	False Alarm
	Meter is inaccurate	Covert Failure	True Negative

- Meter wouldn't prove after FAT
- Pickoff stiffness increased over 10%
- Factory flow testing showed density reading ~0.2 gm/cm3 low, mass flow error of ~4% low
- All consistent with a increase in stiffness
- Inspection clearly showed overpressurized tubes





False Alarms & Covert Failures

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

- Statistical analyses required to calculate off-diagonal outcomes
- Coriolis meter failures are very rare
- False alarms can be expensive
  - Rerun verification to see if verification failure repeats
- If meter failure is expected in a particular application, consult vendor for methods to minimize covert failures
- Directive 17 does not require these analyses

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- Coriolis flowmeters should not change calibration over the life of the meter
- Several verification techniques available for Coriolis meters to assure valid calibration
- Run verification frequently
- Leverage Directive 17, extend proving intervals
- Work with your vendor!