Linearity of Coriolis Flowmeters at Full Scale Value

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Aim

- To address the factors affecting the Coriolis Flow Meter (CFM) linearity.
- To explain what the developers do to ensure a high level of CFM linearity.
- Present experimental evidence to confirm the high level of CFM linearity (Mainly after 1/5 of the measuring range).
Outline

- Coriolis flowmeter (CFM): Basic principle of operation
- Factors affecting CFM linearity
- Key techniques to improve CFM linearity
- Experimental evidence on CFM linearity at full scale value
- Conclusions
**CFM Basic principle of operation**

*Fluid-conveying pipe fixed at both ends, driven by an oscillatory force at its natural frequency*

If \( m_f = 0 \)

**Oscillatory driving force vector**

\[
\vec{F}_d = \vec{F}_d \cdot \sin(\omega_d \cdot t)
\]

**Coriolis force vector**

\[
\vec{F}_C = 2 \cdot m_f \cdot \vec{v}_f \times \vec{\Omega}
\]

\[\vec{F}_C = 0\]

NO phase shift between \( s_1 \) and \( s_2 \).
CFM Basic principle of operation

\[ I f \ m_f > 0 \]

Oscillatory driving force vector

\[ \vec{F}_d = \vec{F}_d \cdot \sin(\omega_d \cdot t) \]

Coriolis force vector

\[ \vec{F}_C = 2 \cdot m_f \cdot \vec{v}_f \times \vec{\Omega} \]

\[ \vec{v}_f > 0 \quad \rightarrow \quad \vec{F}_C > 0 \]  

Phase shift between \( s_1 \) and \( s_2 \).

Coriolis forces acting along the measuring tube!
Phase shift ($\Delta \phi$) proportional to mass flow

$$\Delta \phi \propto \dot{m}_f$$

Alternatively, in terms of time delay ($\Delta \tau$)

$$\Delta \tau = \frac{\Delta \phi}{\omega_d} \propto \dot{m}_f$$

**Ex: Reference**

*Journal of Sound and Vibration (1989) 132(3), 473-489*

**Modelling of the Coriolis Mass Flowmeter**

G. Sultan and J. Hemp
Department of Fluid Engineering and Instrumentation, School of Mechanical Engineering, Cranfield Institute of Technology, Cranfield, Bedford, MK43 0AL, U.K.

(Received 8 August 1988, and in revised form 12 January 1989)
CFM Basic principle of operation

A CFM has a linear response!
...but how linear is it?

Answer:
The level of linearity depends on the CFM designer expertise on key fundamental areas:

- Linearity
  - Fluid dynamics
  - Mechanical design
  - Manufacturing process

![Graph showing time delay vs. fluid velocity for Water and Kerosene](Image)
Key techniques to improve linearity

But before we start...

**Accuracy**
- Pressure
- Temperature
- Speed of sound
- Fluid density (single tube)

**Linearity**
Key techniques to improve linearity

But before we start...

Linearity

Fluid dynamics
- Low Reynolds number effect
- Cavitation

Mechanical design
- Zero point (CFM balance)

Manufacturing process
- Zero point (CFM balance)
Key techniques to improve linearity

Linearity → Fluid dynamics → Low Reynolds number effect (Re < 10000)

\[ \text{Re} = \frac{VD}{v} = \frac{\rho VD}{\eta} = \frac{4\pi}{\eta D} \]

To learn more:
P. Ceglia, “Effect of Reynolds number on CFM”, 2nd European Workshop on CFM and USM, Lisbon, Portugal, March, 2014
Key techniques to improve linearity

Linearity → Fluid dynamics → Cavitation

- **Cavitation**: “formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature”.

Recommendations to prevent cavitation:
- Proper sizing of CFM according process conditions.
- Avoid low upstream pressure.
- Avoid fluid velocities out of manufacturer specs.

To learn more:

**Cavitation**

Two-phase flow (liquid + vapor)
Key techniques to improve linearity

**Linearity → Mechanical design → Zero point (CFM balance concept)**

It is the near self-cancellation (or significant attenuation) of the oscillating system’s acting-reacting forces and torques.

\[ \sum F = 0 ; \sum T = 0 \]

An ideal **balanced CFM** is an oscillating system, which is mechanically decoupled from the surrounding.

**Example: Doubled-tube CFM**
- Measuring tubes with equal geometry and mass
- The tubes oscillate at the same resonance frequency and amplitude
- Two equal forces and torques act on the tubes but in opposite directions
Key techniques to improve linearity

**Linearity → Mechanical design → Zero point (CFM balance concept)**

**Basic representation of CFM with V.A.**

\[ F_d \]
\[ m_{CFM} \]
\[ k_{CFM} \]
\[ m_{VA} \]
\[ k_{VA} \]
\[ D_{VA} \]

\[ m_{VA} \gg m_{CFM} \]

The heavy mass and damping elements of the V.A. greatly attenuate the transmitted vibration to the CFM housing.

**Simplified front view**

- Measuring tube
- CFM
- Driver
- Housing
- Seismic mass
- Damping elements
- Vibration Absorber (V.A.)
Experimental evidence of CFM linearity at full scale value

**Linearity**: Measurement difference between flowmeter and a reference system (i.e. calibration rig) at a defined flow range. An absolute linear flowmeter will overlap the reference measurement line over the entire flow range.

**Zero Point offset** ($ZP_{CFM}$): It is the measurement offset caused by the CFM sensitivity to certain meter’s and/or process parameters.

\[
RME_{\text{linearity}} = \pm \frac{ZP_{CFM}}{m_{CFM}} \cdot 100\%
\]

![Graph showing measurement error in terms of CFM linearity (RME_{\text{linearity}})](image)
Experimental evidence of CFM linearity at full scale value

Maximum Permissible Error band (MPE):
Encloses the extreme value of the measurement error attributed in part to the CFM’s repeatability, reproducibility, hysteresis, to some extend the meter’s drift and linearity.

![Graph showing CFM linearity at full scale value](image)
Key techniques to improve linearity

**Linearity → Manufacturing process → Zero point (CFM balance concept)**

- Measuring tubes from the same lot (i.e. doubled-bended tube CFM), to have nearly identical material properties.

- Equal length, shape and cross section area of measuring tubes within specified narrowed tolerance.

- The **bending process** of curved-shape CFMs must ensure a high level of reproducibility.

- Negligible eccentricity when mounting the CFM driver and displacement sensors.

![Diagram of CFM with tolerance levels](image)
Experimental evidence of CFM linearity at full scale value

Test set up:

• Flow standards with low measurement uncertainty ($U = \pm 0.05\%$ and $U = \pm 0.08\%)$.
  Aim: Depict the linearity with minor influence from other process parameters.

• Maximum flow range according to manufacturer specs. (or closed to that, depending on measurement capabilities of available calibration rigs).

• Large number of measurement data to characterize the linearity curve.

• Linearity analysis for different sensor types but same transmitter, to attain equal measurement conditions.

• Hysteresis test
### Experimental evidence of CFM linearity at full scale value

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Application</th>
<th>Nominal Diameter [mm]</th>
<th>Flow range [kg/h]</th>
<th>MPE band [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Promass A</td>
<td>-Low flow rates</td>
<td>1…4</td>
<td>0…450</td>
<td>0,1</td>
</tr>
<tr>
<td>Single bended-tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Promass I</td>
<td>-High viscous fluids</td>
<td>8…80</td>
<td>0…180 000</td>
<td>0,1</td>
</tr>
<tr>
<td>Single straight-tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Promass S</td>
<td>-Food &amp; Beverages</td>
<td>8…50</td>
<td>0…70000</td>
<td>0,1</td>
</tr>
<tr>
<td>Single bended-tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Promass F</td>
<td>-Universal</td>
<td>8…250</td>
<td>0…2 200 000</td>
<td>0,05 or 0,1</td>
</tr>
<tr>
<td>Doubled bended-tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Promass X</td>
<td>-High flow rates -Oil &amp; Gas</td>
<td>300…400</td>
<td>0…4 100 000</td>
<td>0,05 or 0,1</td>
</tr>
<tr>
<td>Four bended-tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental evidence of CFM linearity at full scale value

Promass A
DN 01
Experimental evidence of CFM linearity at full scale value

Promass I
DN 25

Promass I DN25 1", full scale value=10.19m/s=18000kg/h, 465 measurements
Experimental evidence of CFM linearity at full scale value

Promass S DN 25

PROMASS S DN 25 1", full scale value=10.19m/s=18000kg/h, 243 measurements
Experimental evidence of CFM linearity at full scale value

Promass F
DN 08

PROMASS F DN08 3/8", full scale value=11.05m/s=2000kg/h, 1938 measurements

rel. deviation [%]

massflow [% o.f.s.]
Experimental evidence of CFM linearity at full scale value

Promass F
DN 25

![Graph showing linearity of Promass F DN 25 flowmeter](image.png)
Experimental evidence of CFM linearity at full scale value

Promass F
DN 50

PROMASS F DN50 2", full scale value=9.55m/s=67500kg/h, 648 measurements

rel. deviation [%]

massflow [% o.f.s.]
Experimental evidence of CFM linearity at full scale value

Promass F
DN 100
Experimental evidence of CFM linearity at full scale value

Promass X
DN 350

PROMASS 84 X, full scale value=12m/s=4200tons/h, 618 measurements

Water (E+H)
Naphtha (SPSE/France)
Conclusions

- **CFM are inherently highly linear devices** due to the underlined measurement principle.

- The **CFM manufacturers ensure linearity** of measurement in practice through the meter design and manufacturing processes.

- For a well-designed CFM, the **Zero Point (ZP) is the main contributor to a CFM non-linear response.**
Conclusions

- A single calibration factor is valid across the full range of the CFM as long as the point is taken at a flow velocity, where the effect of ZP is minimal and cavitation is avoided. In practice, this is between 1 to 2 m/s with water.

- From the linearity perspective, additional calibration points do not add significant benefit to the CFM measuring performance.

- The Maximum Permissible Error band (MPE) depicted on calibration certificates encloses the extreme value of the measurement error attributed in part to the CFM’s repeatability, reproducibility, hysteresis, to some extend the meter’s drift, and importantly the linearity.
Thank you for your attention!