Design and construction of a novel Coriolis mass flow rate meter

The Coriolis principle for measuring flow rates has great advantages compared to other flow measurement principles, the most important being that mass flow is measured directly. Up to now the measurement of low flow rates posed a great challenge. In a joint research project, the University of Twente and mechatronics company DEMCON worked on the mechatronic design and construction of a novel Coriolis mass flow meter for low flow rates. Innovations included shape and fixation of the meter tube, contactless (pure torque) actuation of the tube oscillation and contactless sensing of Coriolis force-induced displacements. As a result, the accuracy of the mini Coriolis is ten times better than that of existing, commercially available Coriolis mass flow rate meters. The resulting instrument is being produced and sold via Bronkhorst Cori-Tech.

• *Aditya Mehendale, Rini Zwikker and Wybren Jouwsma* •

The accurate and quick measurement of small mass flow rates (~ 1-10 mg/s) of fluids is considered an 'enabling technology' in the semiconductor, fine-chemical, and food & drugs industries. Flowmeters based on the Coriolis effect offer the most direct sensing of the mass flow rate. For this reason, they do not need complicated translation or linearization tables to compensate for the effects of other physical parameters (e.g. density, state, temperature, heat capacity or viscosity) of the medium that they measure, as is for example the case with the well-known thermal flow rate meter principle. It also makes Coriolis meters versatile – the same instrument can, without need for factory calibration, measure diverse fluid media, liquids as well as gases. Additionally, Coriolis meters have a quick response, and can principally offer an all-metal fluid interface with no wearing parts.

The Coriolis effect

A Coriolis force is a pseudo force that is generated when a mass is forced to travel along a straight path in a rotating system. This is apparent in a hurricane on the earth (a rotating system): when air flows towards a low-pressure region from surrounding areas, instead of following a straight path, it 'swirls', in a 'towards + sideways' motion. The sideways motion component of the swirl may be attributed to the Coriolis (pseudo) force. To harness this force for the purpose of measurement, a rotating tube may be used. The measurand (mass flow rate) is forced through this tube. The Coriolis force will then be observed as a sideways force (counteracting the swirl) acting upon this tube in presence of mass flow; see the box for an elaboration on the Coriolis meter principle.

The need for innovation

Based on the principle described in the box, Coriolis meters have been constructed for over fifty years, up till now mostly for medium to high flow rates; see Figure 2. This is because Coriolis meters scale poorly. Generally speaking, their performance degrades as the overall size decreases. From a constructional viewpoint, the Coriolis force is generated in an oscillating (rather than a continuously rotating) meter tube that carries the measurand fluid. In such a system, besides the Coriolis force, there are also inertial, dissipative and spring forces that act upon the meter tube. As the instrument is scaled down, these other forces become significantly larger than the generated Coriolis force. Several 'tricks' can be implemented to isolate these constructional forces from the Coriolis force, based on orthogonality – in the time

The Coriolis meter principle

In the construction of Figure 1, fluidic mass flow is introduced into a so-called 'active tube length' by means of two slip couplings and (compliant) bellows. The inlet and outlet are fixed, while the tube construction in between is driven to rotate by means of an external engine, such as an electric motor. A stiff frame couples the feeding sections of the pipe so that the inlet and outlet 'elbows', together with the frame, form a 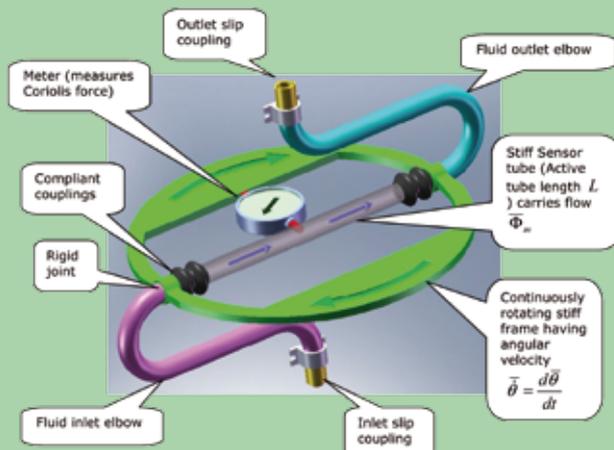stiff rotating construction. A (stiff) force sensor is positioned between the rigid frame and the central straight piece of 'sensor' tube between the two bellows (constituting the active tube length).

The resulting construction is rigid (meaning that the Coriolis force does not distort the tube geometry). As the construction rotates, and a mass flow is forced through it, all rotating parts of the tube (including the elbows) will experience a Coriolis force. This force will be restrained by the stiff construction – i.e. bearings around the slip couplings, and the rigid frame. The (sideways) Coriolis force in the middle section of the tube will also be restrained, but via the (stiff) force sensor. The reading on this sensor will thus indicate the net Coriolis force acting on the central rotating tube section, pushing against the rigid frame. It can be derived [1] that the Coriolis force amounts to:

$$F_{Coriolis} = -2l \cdot \left(\dot{\bar{\vartheta}} \times \bar{\Phi} \right)$$

So, a displacement due to the Coriolis force is orthogonal to the flow as well as to the rotation direction. The Coriolis mass flow meter tube may thus be viewed as a 'modulator', which has as an output (Coriolis force) that is proportional to the product of the angular velocity of the tube $\left(\dot{\bar{\vartheta}} \right)$ and the measurand $\bar{\Phi}$ (mass flow rate). It increases with active tube length l.

Figure 1. An illustrative rotating-tube Coriolis mass flow rate meter.

Figure 2. Large omega-shaped twin tube Coriolis meter for petrochemical applications (Rheonik RHM160).

Figure 3. Schematic of a pure torque actuator; the Coriolis tube carries an alternating current.

domain, in eigenmodes and in terms of position (unobservable and uncontrollable modes, symmetry, etc.).

As with all flowmeters, it is desirable to make an instrument with high repeatability and small offset-drift. To avoid the need for characterization, linearity is also desirable. Due to the unwanted forces of relatively large magnitudes interfering with the Coriolis force, a large drift can arise in the meter's reading. Designing a meter (for a small flow rate) with an acceptably small drift is the most challenging task.

In defining the requirements for the new Coriolis meter, functional (flow rate range, accuracy, zero stability, pressure drop, medium density determination, response speed) as well as technical (small dimensions, eigenfrequency range versus mains frequencies) aspects were taken into account. The subsystems that were considered in the design process, included the tube, the actuator, the sensor system, data processing and finally the housing, which has to act as a stiff basis for the other subsystems. See the box for typical requirements.

Mechatronics

The design of a Coriolis flow meter involved multidisciplinary elements: fluid dynamics, precision engineering construction principles, mechanical design of the oscillating tube and surroundings, sensor and actuator design, electronics for driving, sensing and processing, and

software for data manipulation and control. This called for a mechatronics design approach, including a statically determined construction, orthogonality of modes, constructional symmetries, strategic sensor and actuator placement and separation in the frequency domain. Processing (compensation for higher-order physical effects) was also required in order to reduce sensitivity errors. This was done by means of purely time-domain measurements, correction using multiple position sensors, and (sensitivity) correction for medium density and temperature. The principal innovations that were realised in the course of the project, included the shape and fixation of the measurement tube, the contactless excitation of the tube, and the contactless sensing of Coriolis force-induced displacements.

Excitation

It is advantageous to have contactless actuation to drive the Coriolis tube into oscillatory motion. This avoids potential interference caused by actuator parts attached to the tube. Therefore, Lorentz force actuation was selected; see Figure 3. The tube, itself acting as the (alternating) current carrier, is exposed in two (oppositely oriented) magnetic gaps, which carry flux lines in anti-parallel directions. As the two gaps are in 'series', the flux densities in the gaps are (nearly) identical, and the Lorentz forces generated in the gaps will be equal-and-opposite – in fact constituting an almost ideal torque. Being a torque actuator, its position (in the horizontal direction in Figure 3) does not significantly affect the nature of the actuation. The frequency of the oscillation is chosen so as to correspond with a tube eigenfrequency. This minimizes the actuator effort needed to drive the tube.

Tube shape

A crucial 'trick' in Coriolis meter design is selecting the optimal tube shape. Already, numerous unique tube shapes have been patented, which suggests that it may be

Typical requirements

– Dynamic measurement range 1 g/h - 1 kg/h.
– Zero stability ≤ 0.1% of full scale.
– Accuracy ≤ 0.2% of reading + zero-stability.
– Settling time (98%) ≤ 1 sec for a setpoint change (i.e., deviation of actual flow rate from the setpoint being less than 2% of full scale).
– Pressure drop (water) ≤ 1 bar at full scale.
– Operating pressure ≤ 200 bar.
– Accuracy for medium density ≤ 10 kg/m³

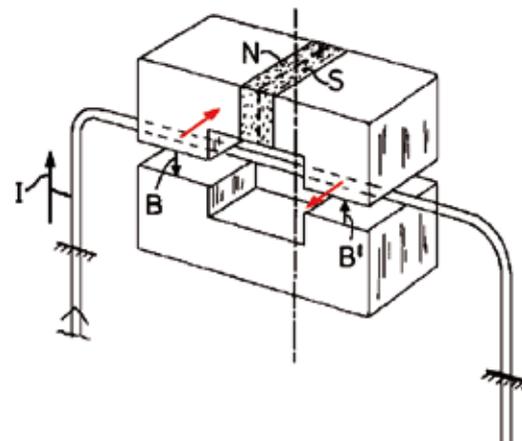impossible to arrive at "the one best tube shape". In this project, the following aspects were considered:

- Attachment
  The way in which the tube is attached to the fixed world should not affect its properties and motion. This suggests the use of a statically determined, vibration-free foundation. If the inlet and outlet of the tube can be placed close to each other, thermal stresses in the foundation are less likely to distort the shape of the tube.
- Independent modes
  The Coriolis force is generated in a direction perpendicular to the mass flow, as well as to the rotation. Given that oscillation at one eigenfrequency in a particular eigenmode is the source of said rotational motion, this implies that the Coriolis force will act on a different eigenmode of the tube. In case this (very small) force is to be sensed indirectly (i.e. by observing deflection in the tube), the tube deflection mode (the response) should have a well-defined characteristic (transfer function gain) at the oscillation frequency. This suggests, that the eigenfrequency of the response mode should be away from the oscillation frequency. (This is contrary to the intuition to place the response mode's eigenfrequency close to the excitation eigenfrequency to maximize gain, because in that case the gain and the phase change a lot with minor property changes). Furthermore, the unused oscillation modes of the tube should be designed far away from the excitation and response modes, to prevent parasitic interactions.
- Maximizing the response
  To generate a large Coriolis force, the rotating tube segment should be as large as possible. The tube should be either compliant or light in the response mode, depending on whether stiffness or mass determines the response. The moment arm of the Coriolis force upon the response mode should be as large as possible. This increases the achieved mechanical deflection (caused by a small Coriolis force).
- A mechanically 'closed' form
  To minimize the effect of unavoidable asymmetries, the energy storage elements (elastic element, and centre of mass) of the oscillatory system should be close to the axis of rotation. For the same reason, it is advantageous to have the possibility to place the oscillation actuator near the rotation axis of the response mode.
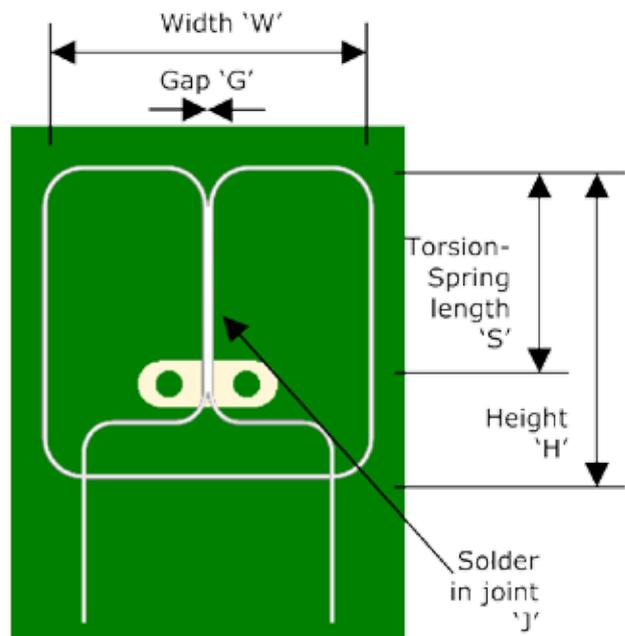

Figure 4. The 'window'-shaped Coriolis tube, shown with the relevant dimensions.

Based upon these considerations, the 'window' shape was designed; see Figure 4. To be able to obtain an accurate tube shape, a dedicated bending tool was constructed by DEMCON.

Mode analysis

Following the discussion on independent modes, finite element simulations were performed to gain insight in the eigenfrequencies of the tube, as determined by the tube dimensions; Figure 5 shows a typical example. Here, the frequency of the mode that can be associated with the Coriolis response ('swing') lies below the eigenfrequency (used for the excitation). From detailed considerations it was concluded that this is to be preferred above the reverse situation, $f_{Coriolis} > f_{eigen}$. A complicating factor in this respect is that the mains frequency and its odd harmonics have to be avoided, to prevent interference.

Mode 1 – Swing
Approx. $0.58 \cdot f_{eigen}$

Wave (in-plane)
Approx. $0.82 \cdot f_{eigen}$

Mode 2 – Twist
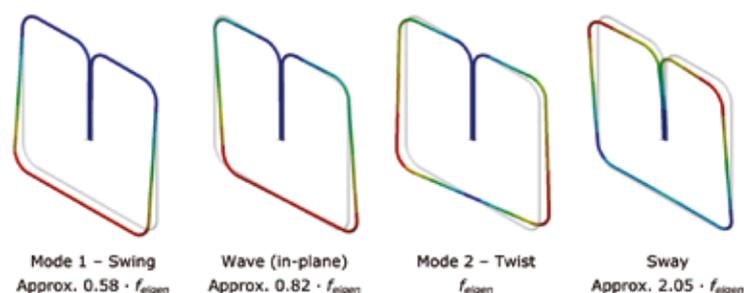f_{eigen}

Sway
Approx. $2.05 \cdot f_{eigen}$

Figure 5. Tube eigenfrequencies determined by finite element simulations, after optimisation of the dimensions.

Measurement

For contactless measurement of the Coriolis force, optical transmissive (interruption-based) position sensing was selected. An aligned pair consisting of an optical emitter (typically a LED) and an optical detector (typically a phototransistor) forms a basic sensing entity. Light from the emitter traverses a gap and is incident upon the detector. By placing an occluding element in this gap, the amount of light reaching the detector may be modulated, thus proportionally modulating the photocurrent that is generated; see Figure 6. This photocurrent may be converted to an analog signal suitable to be digitized and interpreted by a digital signal processor (DSP). A vane placed on the Coriolis tube may act as the occluding element.

The excitation motion of the active portion of the tube needs to be a rotation, in order to generate a Coriolis force. For a periodic excitation, the motion resulting from a Coriolis force is a periodic translation. For any given point on the tube these rotation and translation motions are orthogonal, i.e. appear as a superposition. These two motions ('excitation' and 'response') should be separated in order to isolate the response motion (which represents the Coriolis force). Two factors can be used to aid this separation:

1. As the excitation motion is a rotation, it has an axis. At this axis, the position change of the tube due to rotation is zero; here, the motion is purely due to translation. Alternatively, if two position sensors observe the tube symmetrically around the rotation axis, the common-mode signal (mean of the two) corresponds to the translation, while the difference corresponds to the excitation (rotation) motion.
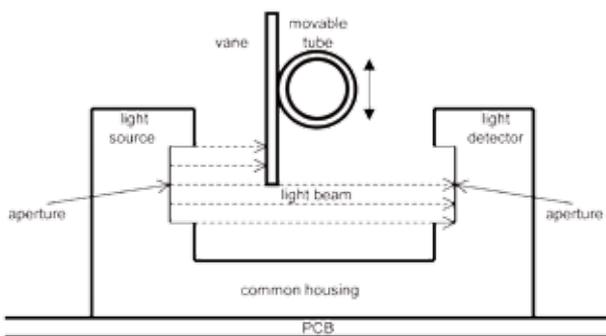
2. The Coriolis force is by definition in phase with the angular excitation velocity of the active tube section, which is excited in a simple harmonic (sinusoidal) motion. This means that the Coriolis force is 90° phase-shifted from the excitation motion. The Coriolis force is generated at the frequency of the excitation motion, not at the eigenfrequency of the Coriolis mode. The Coriolis motion is therefore either in phase or in opposite phase with the Coriolis force. Knowing the exact phase of one of the two – the excitation or the response – can enable the isolation of the response motion.

As a result from this – and essential for the measurement – is that the Coriolis motion for any point on the tube is not only orthogonal (resulting in superposition) but also 90° phase-shifted from the excitation motion. This allows a measurement of the Coriolis force to be done in terms of phasor-angle differences only, i.e. entirely in the time domain.

Consider two sensors placed symmetrically around the excitation rotation axis. Each simultaneously measures the superposition of amplitudes of a point on the tube caused by rotation (excitation) and translation (Coriolis). The excitation motion can be considered a phasor arrow, its length corresponding to the amplitude of excitation as seen by the sensor, and its direction to the phase. As the position sensors are placed on two sides of the rotation axis, the excitation phasors are 180° out-of-phase – thus represented by anti-parallel arrows; see Figure 7. The Coriolis translation of the tube can be represented as two in-phase phasors for both sensors. As explained above the Coriolis phasors are 90° phase-shifted from the excitation phasors.

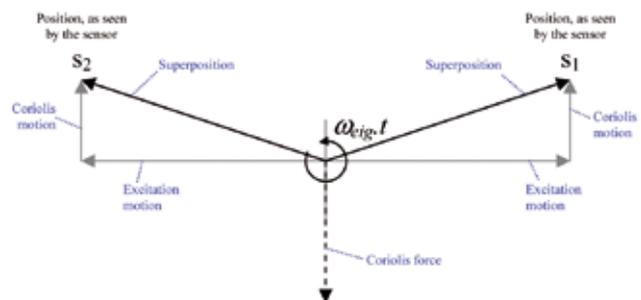Figure 6. Occlusion-based optical position sensing.

Figure 7. Phase diagram of the Coriolis tube's displacement. The two position sensors 'see' anti-parallel excitation phasors and parallel response phasors.

The superposition of the excitation sine and the Coriolis cosine results in a phase shift of both sensor signals relative to the excitation. This phase shift on each of the two position sensors is in opposite direction, causing a change of the relative phase angle between both phasors. This phase shift is a direct measure for the mass flow rate through the tube.

The advantage of this time domain approach is that it is ratiometric: the phase shift is only determined by the ratio between Coriolis and excitation amplitudes, not by their absolute values. It is therefore insensitive to excitation amplitude and sensor sensitivity, and any drift thereof. This makes the gain and offset calibration of (position) sensors unnecessary.

To maximize the position sensor ratio gain, the two sensors are placed close to the rotation axis, thus detecting relatively small rotation-induced displacements, wheras measuring the full Coriolis-induced displacement. A third position sensor, lying in one line with the other two sensors, is added to allow for correction of a rotation axis shift; see Figure 8. Using the fact that all three sensors measure the same Coriolis-induced displacment, a shift of the rotation axis can be calculated.

Phase detection
Various phase detection schemes are available for accurately measuring a phase difference between two signals. A dual zero-crossing detector may be the simplest option. However, a so-called dual quadrature detection scheme was selected, because it offers several advantages, such as lower measurement noise, the possibility of rejecting of harmonics, and ease of implementation on inexpensive commercial DSPs. This detection method uses phase-locked loop algorithms to observe the complete waveform, not just the zero-crossing instants, to extract phase information.

Performance
In conclusion of the research project, from the subsystems described above a Coriolis flowmeter prototype with an all-steel fluid interface was constructed, having a specified full-scale ("FS") mass flow rate of 200 g/h (~55 mg/s) of water. This instrument was shown to have a long-term zero-stability better than 0.1% FS and sensitivity stability better than 0.1%, density independence of sensitivity (within 0.2% for liquids), negligible temperature effect on
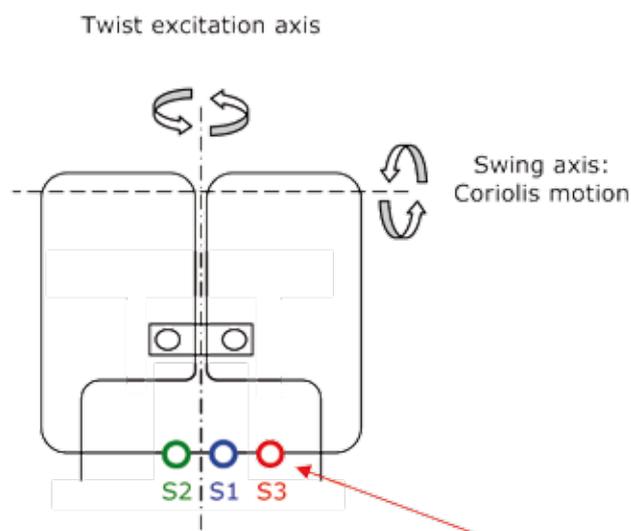

Figure 8. Position sensors S1 and S2 are placed near the rotation axis. A third position sensor S3 is added to allow for correction of a rotation axis shift.

drift and sensitivity, and a settling time of less than 0.1 seconds. For higher and/or negative pressure drops, the instrument was seen to operate from –50xFS to +50xFS (i.e., from –10 kg/h to +10 kg/h) without performance degradation – particularly important in order to tolerate flow pulsations in dosing applications.

Subsequently, instruments for various flow rate ranges were built and studied. Figure 9 gives an indication of the high accuracy that is associated with measuring flow using these instruments. The relative measurement errors of several instruments were compared to a 'conventional true value', measured by a reference instrument. The results in Figure 9 for water show that the relative error is within 0.2% over a large part of the flow rate range. From this it may be concluded that this novel type of Coriolis mass flow rate meter has an accuracy that is ten times better than that of existing, commercially available instruments for this low flow range.

Commercial instrument
Based upon this research outcome, a commercial instrument was developed, that is now available in a compact housing (130 x 60 x 30 mm) in three versions, each having a different measuring range: 100 g/h, 1 kg/h and 10 kg/h, respectively. Up to now, over six patent
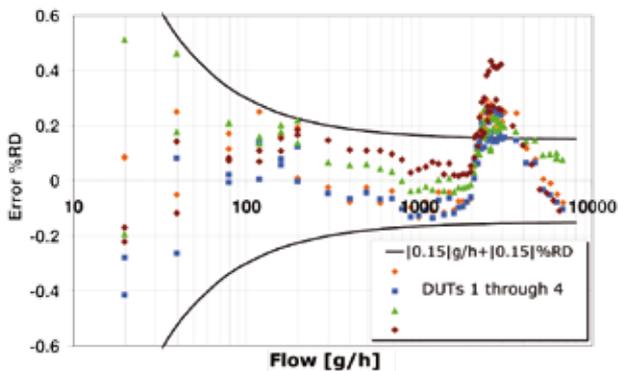
Figure 9. Relative measurement errors for various instruments (DUTs 1 through 4). The rise in error observed for flow rates above 2,000 g/h is ascribed to the laminar-turbulent flow transition of the medium (water). The 'trumpet curve' shown corresponds to a boundary beyond which the error is larger than acceptable; here, the boundary is expressed as a combination of relative (0.15% of reading) and absolute (0.15% of full scale) error.

applications have been filed. Since April 2008, the instruments, named mini CORI-FLOW, are being produced and sold by Bronkhorst Cori-Tech; see Figure 10. At the 'Het Instrument' trade fair in 2008, the mini CORI-FLOW was awarded the Novelty Award.

Authors' note

Aditya Mehendale received his Bachelor's Degree in Electronics Engineering from the University of Pune, India, and his Master's Degree in Mechatronics from the University of Twente, Enschede, the Netherlands. He worked as a Ph.D. student in the Measurement and Instrumentation group at the same university, on the design and construction of the Coriolis meter decribed in this article, in close collaboration with mechatronics company DEMCON. In 2008 he received his Ph.D. Now, he works as a researcher stationed at DEMCON for the university's Mechanical Automation and Mechatronics group, in the field of MEMS-based Coriolis devices.
Rini Zwikker is senior mechatronic systems engineer and project leader at DEMCON in Oldenzaal, the Netherlands. He was in charge of the Coriolis meter project.
Wybren Jouwsma is technical director of Bronkhorst Cori-Tech.

Reference

A. Mehendale, "Coriolis Mass Flow Rate Meters for Low Flows", Ph.D. thesis, University of Twente, 2008, ISBN 978-90-365-2727-9.

Figure 10. The mini CORI-FLOW, housing a novel Coriolis meter for low mass flow rates.

Information

www.bronkhorst-cori-tech.com
www.ce.utwente.nl
www.demcon.nl