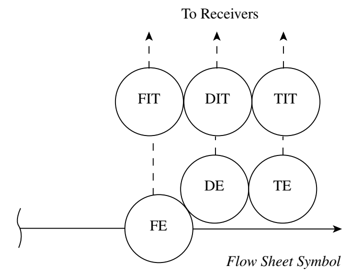
2.11 Mass Flowmeters, Coriolis

CATHY APPLE (1995) **MARTIN ANKLIN, WOLFGANG DRAHM** (2003)



Flow Sheet Symbol

Measured Variables	Mass flow, volume flow, density and temperature
Sizes	1/25 to 10 in. (1 to 250 mm)
Flow Range	0 to 63,000 lb/min (0 to 28,300 kg/min)
Fluids	Liquids, slurries, gases (compressed, low-pressure, etc.), liquefied gases; not gas-liquid mixtures
Output Signal	Linear frequency, analog, digital (HART, Profibus, FOUNDATION™ fieldbus, Modbus, scaled-pulse, display, alarm outputs, manufacturer-specified protocols)
Operating Pressure	Depends on tube size and flange rating: 1400 PSIG (100 bar) typical standard rating; 5000 PSIG (345 bars) typical high-pressure rating
Pressure Drop	Function of flow, viscosity, and design, varying from very low (<0.1 PSIG, 10 mbar) to moderately high (22 PSIG approximately 1.5 bar)
Operating Temperature	Depends on design: –60 to 400°F (–50 to 200°C) typical standard; 32 to 800°F (0 to 426°C) high-temperature, special versions also used for cryogenic applications
Materials of Construction	Stainless steel, Hastelloy®, titanium; special materials as tantalum, zirconium and others are available
Inaccuracy	±0.1% of rate ± (zero offset/mass flow rate) × 100% Zero offset depends on size and design of the flowmeter; for a 1-in. (25-mm) meter with a typical maximum flow rate of 650 lb/min (18,000 kg/h), the zero offset is typically 0.04 lb/min (0.9 kg/h), which is below 0.01% of the maximum flow value. Typical: 0.15% within the range of 10:1 of full-scale flow rate (FS) and 1% within the range of 100:1 of FS
Repeatability	Typical: 0.075% within the range of 10:1 of FS and 0.5% within the range of 100:1 of FS
Rangeability	Up to 100:1
Cost	Depends on size and design: 1/25 in. (1 mm), $5000; typical 1-in. (25-mm) meter, $7000; 6-in. (150-mm), $27,500
Partial List of Suppliers	ABB (www.abb.com) Bopp & Reuther (www.burhm.de) Danfoss A/S (www.danfoss.com)

Endress+Hauser Inc. (www.endress.com)
The Foxboro Co. (www.foxboro.com)
Krohne (www.krohne.com)
Micro Motion Inc. (www.emersonprocess.com)
Oval (www.oval.co.jp)
Rheonik (www.rheonik.de)
Schlumberger Industries (www.slb.com)
Smith Systems Inc. (www.smith-systems-inc.com)
Yokogawa (www.yokogawa.com)

In recent decades, there has been a great deal of interest in Coriolis mass flowmeters (CMFs). The market for CMFs grew dramatically in the late 1980s and the 1990s. Today, CMFs are widely accepted in many industrial fields, and their performance has improved steadily. One of the advantages of CMFs is that they measure the true mass flow directly, whereas other types measure only volumetric flow. The high accuracy and rangeability of CMFs is another reason for their fast growth and acceptance in industry. The commercially available units show a broad variety of designs, such as single-tube, dual-tube, bent-tube, and straight-tube. Since CMFs are available that incorporate different tube materials (e.g., stainless steel, Hastelloy®, titanium, zirconium, tantalum, and lined tubes), they can be used for all kinds of liquids or gases. CMFs are most common in the food and beverage, chemical and pharmaceutical, and, increasingly, oil and gas industries.

MEASURING PRINCIPLE AND THEORY

Principle

Coriolis mass flowmeters have the proven ability to record the total mass flow to better than 0.1% for water at moderate velocities. Each Coriolis instrument gets its own calibration factor that depends only on the geometrical data and material properties of the tube. Thus, the calibration factor is independent of fluid properties. The measuring principle of CMF is Coriolis force, which appears in rotating and oscillating (vibrating) systems. Such a vibrating system is shown in Figure 2.11a for a straight tube. The tube is excited by an external force $\vec{F}_E$. The excitation frequency is kept at the natural frequency of the tube, which minimizes the energy needed for vibration. The general expression for the Coriolis force is $\vec{F}_C = 2 \cdot m \cdot \vec{v} \times \vec{\omega}$, where $\vec{q} = m \cdot \vec{v}$ is mass flow and

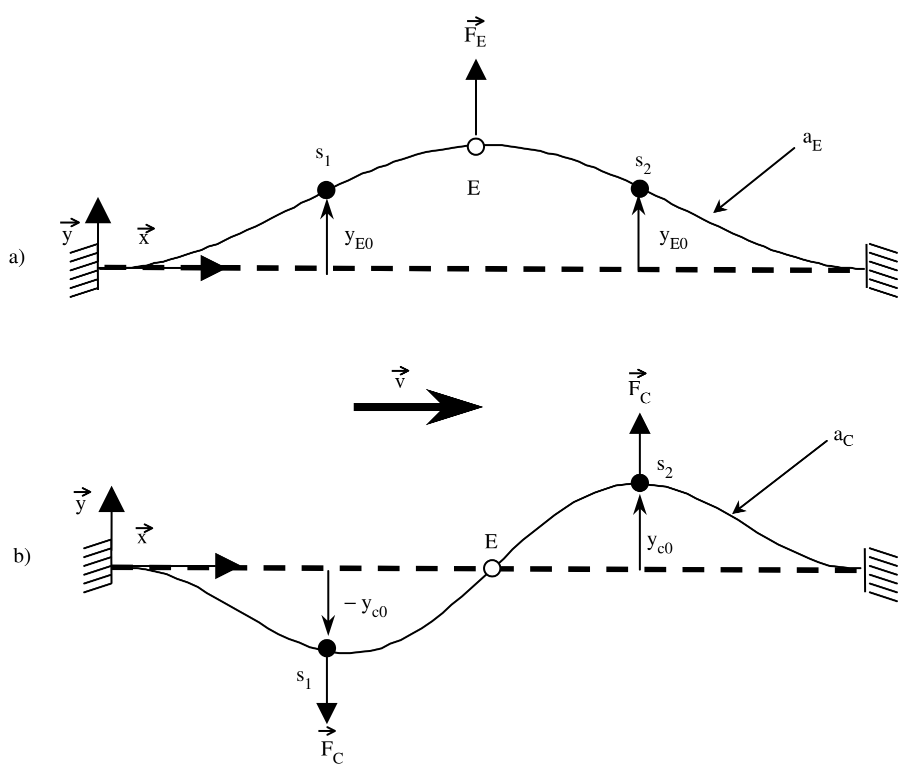


FIG. 2.11a
Panel a) describes the movement of a straight tube conveying a fluid, which is oscillating at the excitation frequency. The oscillation is maintained with the excitation force F_E at location E. The measuring signal is detected with the two sensors S_1 and S_2. When the fluid begins to flow, the Coriolis force F_C induces an oscillation as shown in panel b). The final lateral displacement is the superposition of both oscillations.

$\vec{\omega}$ is the rotation vector. When fluid is not flowing within a vibrating tube, the Coriolis force is zero ($\vec{F}_C = 0$). When fluid begins to flow, the Coriolis force is no longer zero ($\vec{F}_C \neq 0$), and the shape of the tube is illustrated by superimposing Figure 2.11a, panel (a) and panel (b). At the inlet section, the Coriolis force tends to decelerate the movement of the oscillating tube, whereas, for the outlet section, the Coriolis force tends to accelerate the movement. In the middle of the tube, the Coriolis force is always zero, since either $\vec{\omega}$ is zero for straight tubes or $\vec{q}$ is parallel with $\vec{\omega}$ for curved tubes, bringing the product $\vec{q} \times \vec{\omega}$ to zero. As soon as the fluid begins to flow, the Coriolis force induces a phase shift along the tube. This phase shift is proportional to the mass flow. The mass flow can then be determined by measuring the phase shift between two sensor positions, S_1 and S_2. Since the oscillation is kept at the natural frequency of the system, the frequency changes with changing density of the fluid in the tube; i.e., the natural frequency increases with decreasing density. Therefore, by knowing the actual frequency of the system, the density of the fluid can be calculated directly. Another direct measurement, in addition to mass flow and density, is the fluid temperature, which is measured by the CMF.

Theory

In the literature, there are different approaches to describe the dynamics of vibrating tube conveying a fluid or a gas (see, for example, Païdousses and Li[1] or Raszillier and Durst)[2]. The general problem is very complex, and an analytical solution can only be obtained for a simple system with an ideal tube conveying an incompressible and nonviscous fluid. For more complex systems, solutions can be found only through approximations or using finite element methods. In this section, we derive an analytical solution to determine mass flow in a simplified system. However, by solving this simple model, we gain insight into the major physical effects of CMF.

We consider a straight tube conveying a fluid. We first look at the first *eigenmode** of this system, which is shown in Figure 2.11a, panel (a). The tube is fixed at both ends, and the velocity $\vec{v}$ of the fluid shall be zero. The movement of the sensors S_1 and S_2 is described by the differential equation,

$$M_E \cdot \ddot{y}_E + K_E y_E = F_E \qquad \textbf{2.11(1)}$$

where

y_E = lateral excitation displacement at the sensor
F_E = excitation force
M_E = effective mass
K_E = the stiffness of the tube for the excitation mode
$\ddot{y} = \frac{d^2 y}{dt^2}$

We are looking for solutions with $y_E(t) = \hat{y}_E \sin(\omega t)$ and $F_E(t) = \hat{F}_E \cdot \sin(\omega t)$. The eigenfrequencies of this system are found by setting the excitation force $F_E(t)$ to zero. Inserting the trial function for $y_E(t)$ in Equation 2.11(1), we get the frequency of the first eigenmode,

$$\omega_E = \omega_E(\rho_{\text{Fluid}}) = \sqrt{\frac{K_E}{M_E}} \qquad \textbf{2.11(2)}$$

Aside from the tube properties, ω_E depends only on fluid density. Therefore, using Equation 2.11(2), the fluid density can directly be determined by measuring the frequency of the eigenmode. Now, we include the excitation force $F_E(t)$ to determine the lateral displacement at the sensors. Solving Equation 2.11(1) with trial functions $y_E(t)$ and $F_E(t)$ and Equation 2.11(2), we get

$$\hat{y}_E = \frac{\hat{F}_E}{K_E \cdot \left(1 - \frac{\omega^2}{\omega_E^2}\right)} \qquad \textbf{2.11(3)}$$

For commercially available instruments the amplitude for $\hat{y}_E$ varies between 10 μm and 1 mm, and the frequency, $f_E = \omega_E/2\pi$, typically ranges from 80 Hz to 1100 Hz. Equation 2.11(3) also shows that the excitation force $\hat{F}_E$ is at a minimum when the driving frequency, ω, is similar to the frequency of the eigenmode, ω_E. In a real system, damping will prevent the lateral movement from becoming infinite even if ω equals ω_E. When the fluid begins to flow, the second mode is induced by the Coriolis force as shown in Figure 2.11a, panel (b). For the Coriolis mode, the differential equation is

$$M_C \cdot \ddot{y}_C + K_C y_C = F_C \qquad \textbf{2.11(4)}$$

where y_C is the lateral Coriolis displacement of the tube at S_1 and S_2, F_C is the Coriolis force, M_C is the effective mass, and K_C represents the stiffness of the tube for the Coriolis mode. The trial function for the lateral displacement of the Coriolis mode is $y_C(t) = \hat{y}_C \cdot \cos(\omega t)$, and the function for the Coriolis force is $F_C(t) = \hat{F}_C \cdot \cos(\omega t)$. Using the same procedure as above, we get the frequency of the Coriolis mode $\omega_C = \sqrt{K_C/M_C}$, which is typically 2.7 times higher than ω_E. The lateral displacement at the sensors becomes

$$\hat{y}_C = \frac{\hat{F}_C}{K_C \cdot \left(1 - \frac{\omega_E^2}{\omega_C^2}\right)} \qquad \textbf{2.11(5)}$$

The Coriolis force F_C is calculated by integration along the tube

$$F_C = \int_0^{L/2} \dot{m} \cdot \dot{y}_E \cdot a'_E(x) \cdot a_C(x) \cdot dx$$
$$F_C = \dot{m} \cdot C_{EC} \cdot \dot{y}_E \qquad \textbf{2.11(6)}$$

* Resonance frequency or the first resonance frequency.

where C_{EC} is a coupling factor between the excitation and the Coriolis mode, $\dot{m}$ is the mass flow, L is the length of the tube, $a'_E = (da_E)/(dx)$ is the derivative of the normalized excitation mode shape, $\dot{y}_E \cdot a'$ is the local rotation velocity, and a_C is the normalized Coriolis mode shape shown in Figure 2.11a, panel (b). If we define $\text{v}_E = \dot{y}_E$ and with $\hat{\text{v}}_E = \hat{y}_E \cdot \omega$, we get $\dot{y}_E = \hat{y}_E \cdot \omega \cdot \cos(\omega t) = \hat{\text{v}}_E \cdot \cos(\omega t)$. Thus, Equation 2.11(6) becomes $\hat{F}_C = \dot{m} \cdot C_{EC} \cdot \hat{\text{v}}_E$, and the lateral displacement of the sensors, Equation 2.11(5), becomes

$$\hat{y}_C = \frac{\dot{m} \cdot C_{EC} \cdot \hat{\text{v}}_E}{K_C \cdot \left(1 - \dfrac{\omega_E^2}{\omega_C^2}\right)} \qquad \textbf{2.11(7)}$$

As described before, the final lateral displacement of S_1 and S_2 is the superposition of excitation mode and Coriolis mode. As seen in Figure 2.11a, the total lateral displacement of S_1 is $y_{S1} = y_E - y_C$, and for S_2 it is $y_{S2} = y_E + y_C$. The time difference $\Delta\tau$ between the two sensors becomes

$$\Delta\tau = \frac{\Delta\varphi}{\omega_E} \approx \frac{2 \cdot \hat{y}_C}{\omega_E \cdot \hat{y}_E} = \frac{2 \cdot \hat{y}_C}{\hat{\text{v}}_E} = \frac{2}{\omega_E} \cdot \frac{\overline{(y_{S2} - y_{S1})}}{\overline{(y_{S2} + y_{S1})}} \qquad \textbf{2.11(8)}$$

where $\Delta\tau$ is the time lag and $\Delta\varphi$ is the phase shift between the two sensors. Now, we can determine the mass flow by inserting Equation 2.11(7) into 2.11(8), producing $\dot{m} = \frac{K_C \cdot (1 - \omega_E^2/\omega_C^2)}{2 \cdot C_{EC}} \cdot \Delta\tau$, where the expression $\frac{K_C \cdot (1 - \omega_E^2/\omega_C^2)}{2 \cdot C_{EC}}$ is a constant value C. Thus, by knowing $\Delta\tau$, the mass flow of a CMF can be determined through the simple equation

$$\dot{m} = C \cdot \Delta\tau \qquad \textbf{2.11(9)}$$

where the constant C does not depend on fluid properties. For commercially available CMFs, this constant is determined for each unit through calibration. Although we have derived the formula to determine the mass flow of this system, the model does not include effects such as axial pressure, inline pressure, temperature, pulsation, compressibility, and so on. As mentioned before, analytical calculations including such effects are very cumbersome and can be achieved only as approximations. The experimentally found influences of these effects on mass flow measurements will be described below.

DESIGN OF CMF

Figure 2.11b shows the tube assembly of a CMF. Generally, it consists of two components: the flow tube assembly and the electronics. Typically, two electrodynamic pickups generate electrical signals containing the flow information. The signal processing unit implemented in the electronics calculates the flow from these signals, which are very small in amplitude. The flow is split into two tubes as shown in Figure 2.11b. Sensors are mounted at the inlet and outlet section of the tubes, measuring the phase difference between these two points. The tubes are forced into oscillation by the driver, which is mounted between the two tubes. Thus, the tubes are automatically driven in counterphase, which is the preferred type of motion. To vibrate the flow tubes, all commercially available CMFs use a magnet and a coil as the driving mechanism. Typically, the coil is mounted on one tube, and the magnet is mounted on the opposite tube. To protect the measuring system from any external disturbances, the tubes are fixed into a rigid carrier housing, which is strong

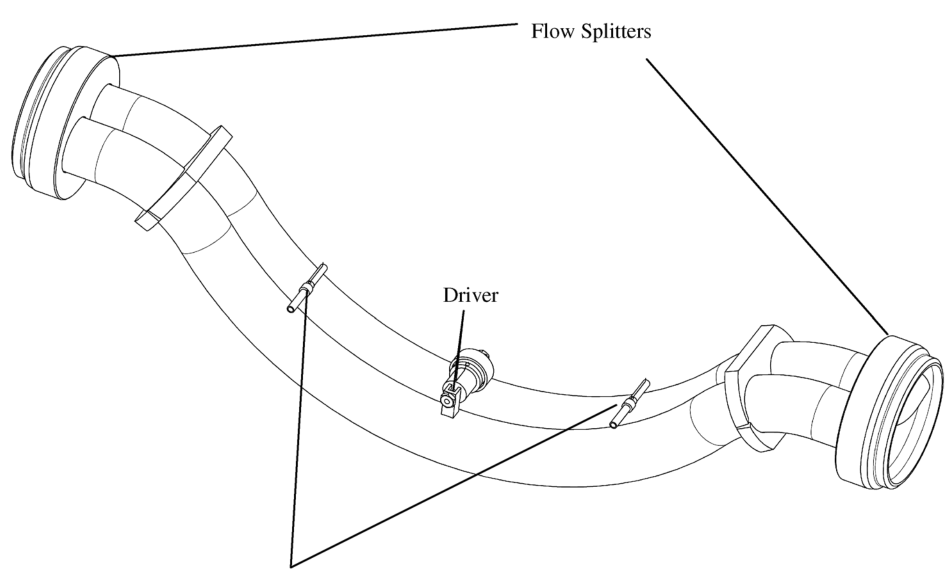


FIG. 2.11b
Tube assembly of a typical Coriolis flowmeter.

enough to isolate the system from the environment. This carrier housing is not shown in Figure 2.11b.

The tubes are vibrated at their natural frequency. As shown before, this frequency requires the least amount of energy to excite the system. Even large meters can be vibrated with only a few milliamps of excitation current. The natural frequency depends mainly on the mass of the system and the elastic properties of the measuring tubes. The total mass of the system includes the mass of the tube itself, the mass of the fluid within the tube, and the mass of any attached items such as driver and sensors. Therefore, since the material properties remain constant, a change in natural frequency directly indicates a change in the density of the fluid. As described before, this change in frequency can be used to determine the density of the fluid.

Balancing Systems for CMF

CMF are among the most accurate flowmeters on the market. This accuracy is achieved over a wide measuring range, which is required because, for example, liquids with high viscosities do not reach high velocities and have low total mass flow. A high turndown from maximum flow is also needed for gas flow measurements because, even at high pressure and at high velocity, the total mass flow rate for gas is small in comparison to mass flow rate of fluids. The accuracy for lower flow rates is limited by the zero-point errors. An error of 0.005% of full scale due to zero-point instability is typical.

In the previous section on "Theory," it is shown that mass flow induces very small displacements along the measuring tube. These displacements have to be measured accurately, even though the instruments are often mounted in a harsh process environment. A key parameter to achieve a precise and stable CMF reading is the decoupling of the internal measuring system from any environmental and external disturbances. If CMFs are not decoupled to near perfection, the oscillations from the measuring tube will be transmitted to the connected process piping, which in turn begins to vibrate as well. Vibrating process piping can then cause the CMF to be excited by undefined vibrations. Depending on the magnitude and the strength of such external excitations, this can lead to a disturbed reading of the CMF. Therefore, it is an important requirement of a CMF to be a balanced system, in which oscillations of the measuring tube are well defined within the meter and are not transmitted to flanges and process piping. This requirement is also a general rule to ensure a good zero-point stability.

Dual-Tube Meters

Designs with dual tubes offer the best performance for the decoupling of the measuring system from the process environment. Similar to a tuning fork, the two tubes vibrate in counterphase. While the oscillation is maintained, the forces at the fixation points of the two tubes are identical in absolute value but in counterphase directions. Ideally, this results in zero force acting on the flanges. The perfect symmetry of the two tubes is unaffected by changes in fluid density, temperature, pressure, viscosity, and so on.

The sensors shown in Figure 2.11b can be mounted between the two tubes and do not have to be supported by the housing. This results in maximum common-mode rejection and maximum suppression of externally induced vibrations. The mounting of the driver and sensors must be done in such a way that the overall mass balance of the tubes is maintained.

If the flow is not split completely symmetrically into the two measuring tubes, no additional error will occur, because the flow signal, which is due the Coriolis forces, is composed of the displacements of each tube separately and therefore is independent of the exact flow distribution. Thus, a well-defined flow profile is not a requirement for the design of a CMF. This also indicates that no special precautions are needed for installations near devices that may generate flow turbulences.

The majority of the commercially available CMFs use a double-tube design, because this offers the best performance with regard to accuracy and insensitivity to external disturbances. However, the dual-tube design requires flow splitters, which are not recommended for applications with fluids that are prone to plugging. Such fluids are often used in the food processing industry, where single-tube meters are required.

Single-Tube Meters

Generally, there are two different designs of single-tube flowmeters. In the first design, the tubes are bent to form a double loop. This design behaves similarly to the dual-tube flowmeter with the difference that the tubes are in series rather than parallel. Such single-tube flowmeters offer the same advantages as dual-tube meters, and they do not have the disadvantage of employing flow splitters. However, with this design, the tube length increases dramatically, which results in increased pressure loss. Furthermore, easy drainage of the instrument is impossible with this design. The second single-tube flowmeter design contains a straight, or fairly straight, single tube. From the customer's point of view, these designs are preferred, since they offer the best cleanability and the most prudent fluid handling. A challenge is to find a balancing mechanism for such flowmeters that allows accurate measurements for various process conditions and changing fluid densities. Nevertheless, straight (or fairly straight) single-tube CMFs are available that offer comparable performance to that of dual-tube flowmeters.

Tube Geometries

A variety of tube designs are currently available, a small selection of which is shown in Figure 2.11c. Most designs aim to magnify the effect of the Coriolis force by the geometrical form of the tubes. The larger the Coriolis effect

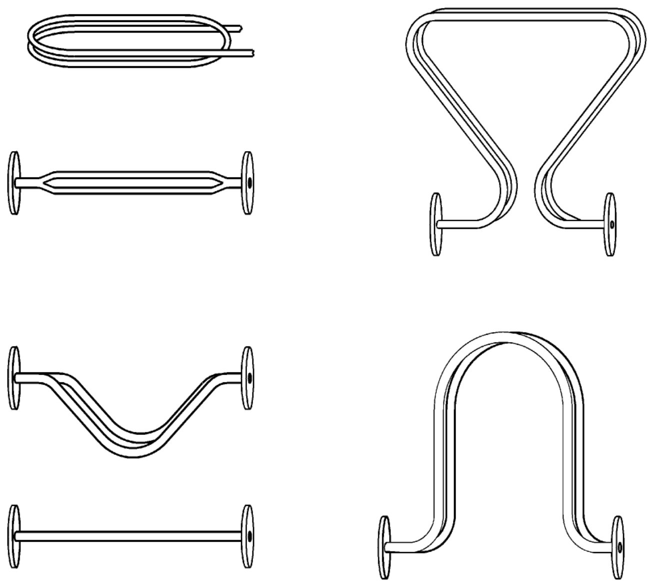


FIG. 2.11c
Selection of geometries of various Coriolis flowmeters.

becomes, the larger the time or phase difference between the flow sensors becomes, and the easier it is to determine the mass flow. Such magnifying geometrical forms often result in large tube loops that take up much space and have no advantage in zero-point stability, because external disturbances are also magnified. Thus, the signal-to-noise ratio remains the same. As electronics have become more and more efficient, the need for such geometrical magnification of the Coriolis effect has disappeared. Therefore, the large loops can be replaced by compact tube designs that require little space. An example of such a compact design is shown in Figure 2.11b. In addition, the compact design shortens the tube length, which results in higher oscillation frequencies of about 300 to 1100 Hz. Higher oscillation frequencies have the advantage of a better decoupling performance from pipeline vibrations and external disturbances, which are predominantly in the range of about 50 to 180 Hz.

For the dual-tube design, symmetry is the key factor, so a pair of tubes are chosen that are nearly identical in terms of mechanics. The two tubes have to be assembled in such a way that tube symmetry is not altered. Therefore, the production of these tube assemblies needs to be done very accurately, with a good understanding of the production process itself.

The main reason for using bent tubes is the thermal expansion of the measuring tube. While the fluid temperature may change by several hundred degrees Celsius, the temperature of the supporting structure changes much less, due to thermal transport, convection, and radiation. This can lead to large temperature differences between measuring tube and housing, which increase the axial forces of the tube. For a straight-tube CMF, the axial forces are largest and mainly depend on the expansion coefficient of the tube material. To prevent the tube from damage, the axial force must stay below a certain value, which depends on the material of the tube. By choosing a material with a low expansion coefficient, the axial forces can be kept below the critical value, even for straight tube CMF. Unfortunately, the rather high expansion coefficient of stainless steel, which is the most common material for measuring tubes, allows only a very restricted temperature range for a straight-tube design. Therefore, stainless steel tubes need to have a curved shape to reduce the maximum stress, since the tube can expand into the curve. All commercially available CMFs with straight tubes use titanium or zirconium for the measuring tubes, since these materials offer a small temperature expansion coefficient. With these materials, even great temperature differences between the measuring tube and the housing result in only small additional axial stress. Moreover, titanium offers higher stress limits than stainless steel. CMFs with single straight tubes are available for use up to 150°C.

With regard to corrosion, erosion, and pressure rating, the wall thickness of the measuring tubes should be as thick as possible. However, the sensitivity of the instrument to flow-induced Coriolis forces decreases with increasing wall thickness. Therefore, tube dimensions have to be optimized for several considerations, including the overall pressure loss. For a 1.5-in. (DN 40) dual-tube design, a typical size of the measuring tube is 1 in. (25 mm) inside diameter with a wall thickness of 1/16 in. (1.5 mm).

Flowmeters are commercially available with stainless steel, Hastelloy®, titanium, zirconium, and tantalum as tube material. Exotic materials such as glass or Tefzel®-lined tubes are also available for special purposes.

Sensors

As shown in Figure 2.11b, two motion sensors are needed to measure the displacement of the tube at the inlet and outlet sections. The phase difference or time lag between the two sensor signals is a measure of the mass flow. The sensor could be of any type that can represent the motion of the flow tubes, measuring position, velocity, or acceleration. At present, the most commonly used device is the electrodynamic sensor, in which a coil is mounted on one tube and a magnet on the other tube. The relative motion between the tubes induces a voltage in the coil, representing the differential velocity of the tubes. Electrodynamic sensors have the advantages of offering very good phase accuracy and high reliability.

Temperature Sensors

As described previously, mechanical properties change with temperature. This leads to axial stress and also changes the Young's modulus. An increase in temperature decreases the stiffness of the tube by lowering the Young's modulus. To compensate for the influence of thermal effects on CMF readings, each flowmeter needs to be equipped with at least one sensor to measure fluid temperature. Furthermore, because a temperature difference between the measuring tube and the housing results in an axial force, a second temperature sensor is needed to adjust the reading of the flowmeter for this effect. Instead of a second temperature sensor, the axial stress can also be detected by a strain gauge attached to the measuring tube.

Temperature sensors have uses beyond merely accounting for thermal effects. Because they measure the temperature of the fluid, temperature information is used as the third direct process signal of a CMF, in addition to mass flow and density.

Security

The oscillation amplitude of a CMF is very small (typically, 100 μm). Stress in the measuring tubes is limited to ensure reliable operation of the meter for many years and to protect the meter from damage due to tube oscillation.

The whole vibration system, including driver and sensors, is fixed in a solid housing, typically constructed of stainless steel. This housing can act as a secondary containment. The more compact the CMF, the smaller the housing can be and, possibly, the higher the pressure rating of the secondary containment. Housings with pressure ratings up to 1500 psi (100 bar) are available.

Because they employ a small excitation current, intrinsically safe CMF versions are available for use in hazardous areas. The electronics must be tested for electromagnetic compatibility (EMC), fulfilling general EMC requirements according to applicable guidelines.

Electronics

The drive circuit initiated the tube oscillation and maintains the oscillation at a certain amplitude. This circuit needs to be built to provide a fast response to changing fluid properties. Air bubbles, for example, cause a sudden increase in excitation power. This information has to be supplied to the driver quickly so as to keep the amplitude of the oscillation constant. The driver circuit also controls the excitation frequency.

The sensor signals are very small sinusoidal signals, which have to be amplified to make them processible in the succeeding signal processing stages of the electronics. These amplifiers need to have a very broad bandwidth to prevent the mass flow signal from containing additional zero-point errors.

The electronics can be mounted on the flowmeter directly, forming one compact flowmeter unit, or the flowmeter can be interfaced to the electronic via a cable. This permits the electronics to be located remotely from the sensor. The remote assembly may be necessary for high-temperature meters, or it may be convenient if the sensor is installed in a place that is not easily accessible.

Signal Processing

The sinusoidal signals from the two sensors are compared to determine either the time difference or phase shift between the two signals. The mass flow rate is calculated directly by multiplying the time difference or the phase shift with the calibration constant of the flowmeter. Furthermore, thermal effects on the mass flow and density reading have to be included as well. This is commonly done with a microprocessor. However, analog circuitry can also be used. Today, much analog circuitry is being replaced by digital signal processors, which offer powerful mathematical functions to allow, for example, filtering of the flow signals. With digital processing, the response time of a CMF becomes faster, and the reproducibility of the flow reading improves. Thus, with digital signal processors, CMFs become capable of controlling formidable applications such as rapid batching, where fast response and high accuracy are critical.

Communication/Output

The primary output from a CMF is mass flow. However, most electronic designs are also capable of providing temperature, density, and volumetric flow data. Furthermore, totalizers provide mass or volume totals.

Most electronics are equipped with configurable alarm outputs. Sophisticated relay functions are available whereby the CMF directly controls a valve in a batching process.

Many digital output protocols are supported (e.g., Profibus, FOUNDATION™ fieldbus, HART, Modbus, scaled pulse, and others), allowing a choice of communication solutions. However, current (4- to 20-mA) and frequency outputs for mass flow are still the preferred and most common output signal formats.

TECHNICAL DATA

Measuring Accuracy/Range

Figure 2.11d shows the excellent measuring accuracy and the large rangeability of CMF. During the 12-h test run, the zero point and the calibration factor remain stable and are well within the specification of the instrument. Note that the reading remains accurate even at low flow rates, even below 1/100 of the maximum flow rate specified for the CMF.

Pressure Drop

The pressure drop depends on tube design and mainly depends on the length of the tube and its inner diameter. For the pressure drop of CMF with dual tubes, the design of the flow splitter is also important. The lowest pressure drop occurs with single straight-tube flowmeters, where the inner diameter of the measuring tube is identical to that of the connected process pipe. Typical pressure drops at the maximum flow speeds specified by manufacturers are 7 to 20 PSIG (0.5 to 1.5 bar) referred to water. For the measurements shown in Figure 2.11d, the pressure drop at 80 in./sec (2 m/s) is only 0.4 PSIG (30 mbar).

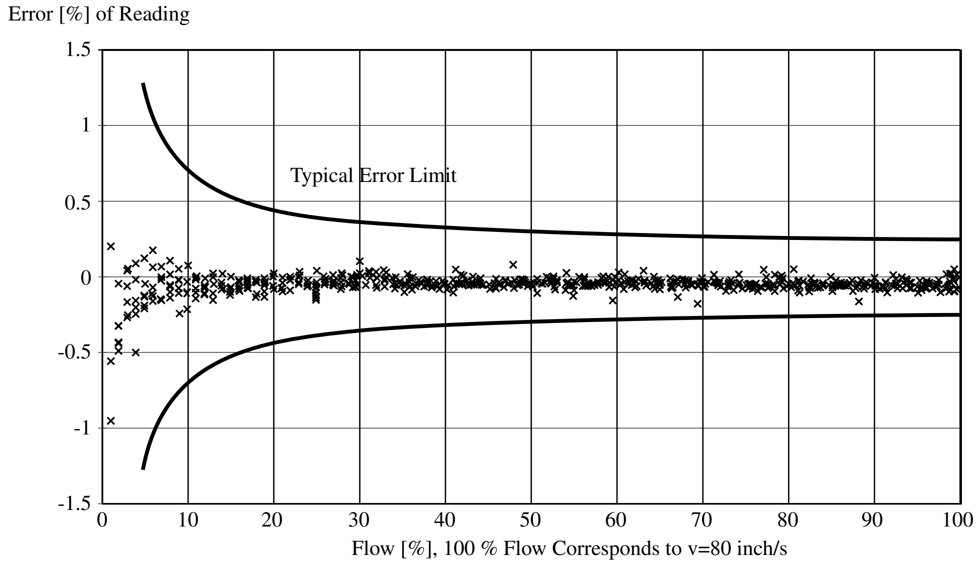


FIG. 2.11d
This figure shows the measuring uncertainty for a 1" (DN25) Coriolis flowmeter. The maximum flow speed is 80 in./s (2 m/s), which is 20% of the maximum specified flow speed of the flowmeter. The curves show the specified error limits.

Influences on the CMF Reading

While improving the accuracy of CMFs during the past decade, many effects, mostly secondary, can be identified that influence the performance of a CMF. These effects can be roughly separated into two groups.

1. Effects such as changing fluid temperature, for which CMF can directly account
2. Effects like external vibration, for which CMF cannot directly account

The latter effects are minimized by either the design layout or, if that is not possible, by special installation or correction instructions. In this section, we will briefly describe different effects.

Temperature As mentioned previously, changing fluid and housing temperatures will affect the elastic properties of the CMF and thus influence the mass flow and density readings. We can account for this effect directly by measuring the fluid and housing temperatures separately. On the other hand, temperature changes can also influence the zero offset and the performance of the electronic components to some degree. The drift in electronic components will usually lead to changes in the zero offset of the flowmeter. Both influences can be minimized by using a special design that does not require any further corrections or installation instructions.

In-Line Pressure With changing in-line pressure, the tube becomes slightly deformed, which influences the stiffness of the layout and thus can affect the reading of the CMF. With special designs, this effect can be minimized.

Mounting Pipe stress is introduced not only by in-line pressure and temperature, as described before, but also by different mounting conditions. These conditions may cause compression, tension, or shear forces to be applied to the flowmeter, which may affect the zero offset of the CMF. The influence of these effects has been greatly reduced during the last decade so that, today, a zero-point calibration is needed only for special applications as described below.

Vibration In most applications CMFs are exposed to some external vibrations. Such vibrations can occur as a result of the pumping system or nearby vibrating devices, or they may be flow induced as observed in pipeline systems. External vibrations typically occur at 50 to 180 Hz. As mentioned previously, CMFs are designed such that the effect of external influences is minimized. Therefore, external vibration plays a minor role and generally has no effect on the accuracy of the CMF reading. However, if the external vibration is close to the working frequency of the CMF, measurement errors will occur. It has been shown that pulsation is critical not only at the working frequency (f_E) of the CMF but also at frequencies $f = f_C - f_E$, where f_C is the Coriolis frequency.[3] Therefore, CMFs with high working frequencies are much less sensitive to pulsation and external vibrations than others. This is because both f_E and the difference $f_C - f_E$ are high; i.e., above roughly 200 Hz. For severely vibrating applications, where the low working frequency of the CMF might become critical, the influence of the external vibration can be greatly reduced by using flexible piping and vibration-isolating pipe supports.

Humidity Because CMFs are typically enclosed in sealed cases that are completely isolated from atmospheric conditions, external humidity has only a minor influence. Also, the flowmeter electronics are commonly enclosed in a housing that provides protection against external humidity. However, in CMFs with inadequate case seals or damaged housings, extremely humid environments can create condensation on the flow detector coils, which may lead to corrosion and component failure.

Fluid Velocity It is well known that the velocity of the fluid can slightly influence the accuracy of the CMF reading.[1] This is a minor effect, which is below the specified accuracy of most CMFs and does not necessarily require any correction. Nevertheless, given that the velocity of the fluid is known, a CMF can directly account for this effect.

Gas Measurements Only in recent years has it been shown that the compressibility of gas can affect the accuracy of the CMF reading.[4] Although this effect can be neglected for most fluids, it becomes relevant for gases in which the speed of sound is diminished. Knowledge about this effect allows us to correct the reading of CMF.

Two-Component Flow A CMF may be suitable for homogeneous two-phase (solid/liquid) flows and for heterogeneous flows. Such applications include many food processes, sand in water, pulverized coal in nitrogen, water in oil, and many others. To measure two-phase fluids, single-tube meters may be preferable.

Corrosion, Erosion Corrosion and erosion diminish the wall thickness and therefore change the stiffness of the tube, which can lead to faulty CMF readings. Since CMFs are available with different tube materials, corrosion can significantly be reduced by choosing the appropriate material for each application. To reduce erosion caused by highly abrasive media, it is necessary to keep the flow velocity low. Erosion also depends on the design of CMF and is smallest in straight, single tubes.

Reynolds Number Although the accuracy of a CMF generally does not depend on the flow profile, the sensitivity changes slightly from laminar flow to eddy flow. Knowledge of the Reynolds number allows us to determine the state of the flow regime and thus to account for it directly.

Installation

Some general recommendations for installations are applicable to all CMFs. The measuring tubes should remain full of the process fluid. Mixtures of gas and liquid should be avoided. For gas measurements, the tubes should be filled with gas only, with no fluid droplets present.

The preferred installation orientation is vertical, with an upward flow direction. With this orientation, entrained solids can sink downward, and gases can escape upward, when the medium is not flowing. This also allows the measuring tubes to be completely drained and protects them from solid build up.

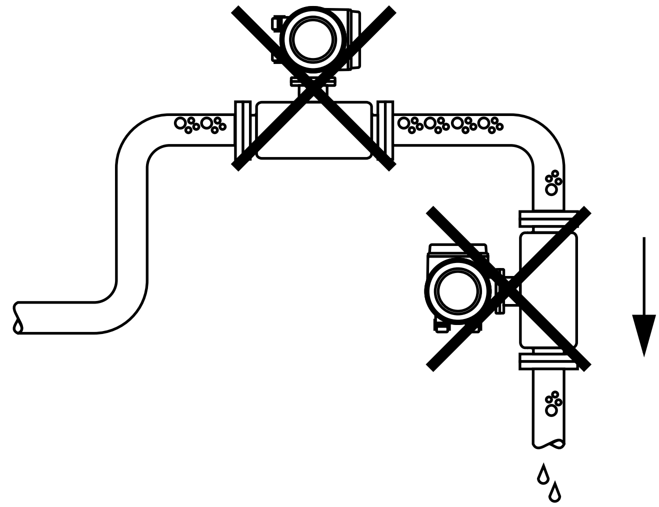


FIG. 2.11e
Not recommended mounting location of a CMF.

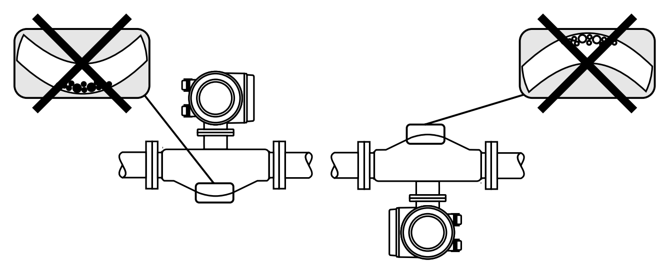


FIG. 2.11f
Orientation of CMF with curved tubes; the orientation shown in the left panel is not suitable for fluids with solids content; the orientation shown in the right panel is not suitable for outgassing fluids.

When measuring liquids, the CMF should not be installed at the highest point of the system, because gas may accumulate in the flowmeter as shown in Figure 2.11e. Installation in a vertical pipeline directly upstream of a free pipe outlet should also be avoided.

With curved tubes, the CMF orientation should be adapted to type of fluid used. Figure 2.11f illustrates problems with outgassing fluids and with fluids containing solid particles.

Mechanical Installation Modern CMFs offer good balance in the vibration system and therefore have no specific installation requirements. The CMF can be installed easily in a pipeline. When heavy CMFs are used, mechanical support of the pipeline has to be considered. Pipeline supports should not be attached directly to the sensor, and the CMF should not be used to support process piping directly.

TABLE 2.11g
Examples of Common Coriolis Flowmeter Applications

Food and Beverage	*Chemical and Petrochemical*		*Petroleum Products*
Beer, soda	Adhesives	Hydrogen peroxide	Asphalt
Chocolate	Alcohol	Latex	Bunker C
Fruit juice	Ammonia	Nitric acid	Crude oil
Honey	Catalysts	Phosgene	Diesel fuel
Ice cream	Caustic	Phosphoric acid	Fuel oil
Margarine	Cyclohexane	Polyol	Gasoline
Milk	Ethylene	Propylene	Hydraulic oil
Molasses	Formaldehyde	Resins	Jet fuel
Peanut butter	Freon®	Solvents	Kerosene
Pet food	Glycerine	Styrene	Lube oil blending
Tomato paste	Glycol	Sulfuric acid	Oil/water emulsion
Animal, vegetable fat	Hydrochloric acid	Toluene	Tar
Pharmaceutical	*Pulp and Paper*	*Other*	
Alcohols	Antifoaming agents	Compressed gases: nitrogen, helium, carbon dioxide, CNG	
IV bag filling	Black liquor	Dyes	
Palm oil	Cellulose slurry	Ink	
Perfume	Paper pulp	Liquefied gases: carbon dioxide, LPG, LNG	
Pill coatings	Red liquor	Magnetic tape coating	
Soap	Titanium dioxide	Paint	
Sodium methylate		Photographic emulsion	
Talcum powder		Wax	
Vitamins		Filling airbags (automobile industry)	

Zero-Point Adjustment (Static/Dynamic) After factory calibration of a CMF, the calibration factor and the zero point are stored in the electronics. CMFs that have good balance, and thus are decoupled from connected piping, are not affected by the installation into the process piping. As a result, the zero point will not change, and no special zero-point adjustment is necessary. Practical experience has shown that a zero-point calibration is required only in special cases; for example, to achieve the highest measuring accuracy possible in the presence of very slow flow rates or in the case of extreme process conditions such as very high fluid temperatures.

Zero-point calibration is carried out using completely filled measuring tubes with no mass flow. During the zero-point adjustment, care has to be taken that no gas or solids are present in the measuring tube. Keeping the in-line pressure high during the zero-point calibration reduces the risk of gas formation in the CMF and thus increases the accuracy of the zero-point calibration.

FIG. 2.11h
This picture illustrates a CMF installed into a compact space. The shown CMF is a single-tube Promass I. (Courtesy of Endress+Hauser Flowtec AG.)

APPLICATIONS

CMFs are currently used in many areas, including chemical, petroleum, petrochemical, pharmaceutical, food and beverage, and pulp and paper industries. Because of their versatility, CMFs are used for process control, batching, inventory, precision filling of containers, custody transfer, and other applications. An overview of some of them is presented in Table 2.11g. CMFs are suitable for many applications, because they can be very compact and do not have any upstream or downstream piping restrictions. An example of a compact application is shown in Figure 2.11h. The photo shows a single-tube CMF Promass I from Endress+Hauser Flowtec AG. Note that inlet and outlet parts are bent at a 90° angle and that the available room is very limited.

ADVANTAGES OF CMFs

1. One of most important advantages of CMFs is that mass flow is measured directly. This can be performed with high accuracy, typically with 0.1% error. High accuracy is also maintained over wide ranges of temperatures (typically from −50 to +200°C) and in-line pressures. Furthermore, CMFs are extremely linear over their entire flow range.
2. CMF rangeability is extremely high. Measurements can still be performed at low flow rates, 100 times lower than the maximum flow rate specified.
3. In addition to direct measurement of mass flow, temperature and density are measured directly. Knowledge about density allows us to convert mass flow data into volume flow data.
4. The measuring principle is independent of the flow profile of the fluid or gas. Therefore, no flow conditioner or special upstream or downstream pieces are required. A CMF can also be used with a pulsating flow.
5. The accuracy of a CMF is independent of fluid properties such as viscosity or density. Therefore, a CMF can measure all kinds of fluids, including Newtonian and non-Newtonian fluids, slurries, and gases.
6. CMFs do not have any moving parts that wear out and require replacement. This reduces the need for and the cost of maintenance.
7. Single-tube CMFs do not have internal obstructions that could be damaged or plugged.
8. CMFs are designed to measure forward and reverse flows with high accuracy.
9. Because CMFs are available based on different construction materials, they can be used for many different applications, including corrosive fluids.
10. The design of CMFs allow them to operate with low power requirements.

LIMITATIONS OF CMFs

1. CMF prices are rather high as compared to other measuring device types. However, to measure mass flow with a volumetric meter, it is often necessary to install an in-line densitometer, which brings the cost up to roughly the equivalent of a CMF alone.
2. There are no CMFs available for medium temperatures above 800°F (426°C).
3. CMFs cannot be used for liquids with any significant gas content. This effect can be reduced by increasing the in-line pressure.
4. CMFs are not available for large pipelines; the largest CMF has a maximum flow rate of 63,000 lb/min (28,300 kg/min) using flanges with 10-in. (25-cm) diameters. To measure higher flow rates, two or more CMFs must be mounted in parallel.
5. CMFs are not suitable for gas applications with low in-line pressure, since low-pressure gases have low densities. To generate enough mass flow to provide a sufficient Coriolis signal, the velocity of the gas must be quite high. This may lead to a large pressure drop across the meter.

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