how it **works**

NOT JUST FOR DRAINING BATHTUBS, THE CORIOLIS EFFECT BRINGS FLOW TO THE MASSES—AND VICE VERSA.

Going with the flow: A sensor that twists and shouts yields precision

By Bill Schweber, Executive Editor

MOST PEOPLE HAVE HEARD that bathtubs drain clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, due to the Coriolis force. This effect is hard to set up as a valid experiment, due to practical challenges (**Reference 1**). The same force is responsible for the curvature of the path of projectiles and rockets, as well as the rotational direction of hurricanes and swirling air currents in the Earth's atmosphere. Its effects can be large or subtle.

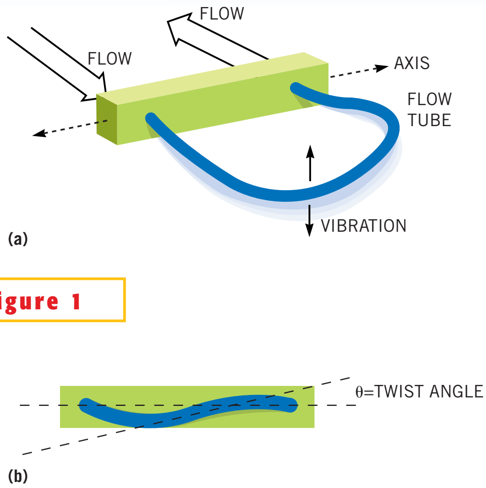
The force is named after French mathematician Gustave Gaspard Coriolis, who showed in the early 1800s that you must take into account an inertial force when you analyze the motion of bodies in a rotating frame of reference.

The Coriolis force, which is also called a gyroscopic force, has practical applications beyond drains and launch vehicles. With sophisticated engineering, you can use it to measure the flow of material, or mass flow, through tubes and pipes. Material flow (often specified in kilograms per second or pounds per second) is second to temperature as the most commonly measured variable in many industrial processes and lab experiments. Although mass flow is roughly analogous to electrical current, it is more difficult to accurately measure for two main reasons. First, the material itself presents a challenge: It can be water, liquid, slurry, or gas, and corrosive, homogenous, or mixed. Second, changes in material characteristics due to internal and external factors affect measurement.

Many flow-meter designs exist in industrial and lab use, and each brings virtues and weaknesses (**Reference 2** and **sidebar** "How do you go with the flow?"). All of them, however, measure the volume of material flowing rather than actual mass. You can, however, use this volume measurement to calculate the mass by plugging it into the simple equation, density=mass/volume. Unfortunately, temperature, pressure, viscosity, and uniformity affect volume and can result in overall errors of 5% or more, depending on the material, flow rate, and other circumstances.

The application of the Coriolis force offered a new way to solve the long-standing problem of measuring the flow of material (**Reference 3**). In 1977, Micro Motion Inc (www.emersonprocess.com/micromotion/) introduced an industrial flow meter based on the force. Because the measurement depends only on mass, such an instrument is a true mass flow meter and is unaffected by the issues that corrupt other flow-meter designs. Since Micro Motion's introduction, many other vendors have also developed flow meters based on the Coriolis force and refined them with new twists. A properly installed Coriolis flow meter can provide readings with errors of less than 0.1% and over a wide dynamic range; handling readings over such a range is a problem for most other flow-meter designs.

Figure 1



The basic Coriolis flow meter sends the fluid through a U-shaped tube that vibrates around a center axis (a). The twist, or angle, of deflection from the vibration plane is key to the measurement of mass flow rate (b).

LET THIS FORCE BE WITH YOU

The conceptual Coriolis flow meter uses a U-shaped tube through which the fluid you are measuring, which can be liquid or gas, flows (**Figure 1a**). The flow meter vibrates this tube at its resonant frequency using a capacitive, piezoelectric, or electromagnetic drive. The fluid travels through the tube, and the Coriolis force causes an angular deflection, or twisting, of the tube out its geometrical plane (**Figure 1b**). As the fluid travels into and out of the tube, its inertia alternately reinforces and resists the oscillations that are imposed in the tube to cause the twist. The amount of twisting is directly proportional to the mass flow.

If you are having trouble understanding how this effect happens, do this simple test: Take a garden hose, turn on the water, form a U-shaped loop between your hands, and then twist your wrists to make the end of the loop go up and down. You'll see the loop twist out of the flat plane of oscillation as the water flows. If you shut off the water flow, the loop doesn't twist as you make the same motions.

Vector physics can quantify the situation. The vector Coriolis force is: $\mathbf{F_c}=2m\boldsymbol{\omega}\times\mathbf{v}$, where m is the mass, $\boldsymbol{\omega}$ is the (vector) angular velocity of the rotation axis, $\times$ is the vector cross-product operation, and $\mathbf{v}$ is the (vector) particle velocity relative to the rotation axis. The mass flow rate, q, is then proportional to the twisting, or deflection angle, θ, of the tube and is inversely proportional to the angular velocity, ω, of the tube: $q=K_s\theta/(4\omega L\,r)$, where K_s is the angular spring constant of the tube, L is the effective length of the tube, and r is the distance between the tube and the central axis. You can determine the mass flow by measuring the resonant frequency and the twisting angle, for a given construction of the loop.

As an added benefit, the Coriolis design lets you determine the density of the fluid. Consider the vibrating system as a tube mass and a fluid mass with a natural spring-system frequency. If you continue the analysis, you'll find that the fluid mass flow is proportional to the fluid density, and the density determines the tube frequency. Therefore, by monitoring the change in resonant frequency of the tube, you can precisely determine the fluid density.

A practical Coriolis flow meter is more complicated than a conceptual one, of course. Most implementations use a pair of loops, called sensor tubes, which vibrate in opposite directions (**Figure 2a**). This design automatically nulls out some of the error sources, just as a differential circuit in electronics cancels many common-mode errors. The flow meter measures the angle of twist between the two sensor tubes. Some designs have a single sensor tube and compare the distorted twist of the tube when fluid is flowing with the no-flow position. Typical dual-tube flow-meter designs have a loop-vibration amplitude of a few millimeters at 75 to 100 Hz and cost several thousand dollars.

Another advantage of the Coriolis design is that there are no internal obstructions in the flow path, helping the design to avoid problems due to clogging, internal wear, and pressure drop. Still, the bent sensor loop causes some pressure drop and turbulence, so some Coriolis designs use an offset, straight pair of sensor tubes (**Figure 2b**). Another potential problem is that the fluid traps air or other gases (known as entrained gases) that affect the fluid mass and thus the flow rate. This two-phase situation occurs when the flow is not continuous but starts and stops in batch processes. To overcome this problem, a new flow meter from Invensys Foxboro (www.foxboro.com) uses multiple DSPs and advanced algorithms to compensate for any erratic vibration of the flow tubes.

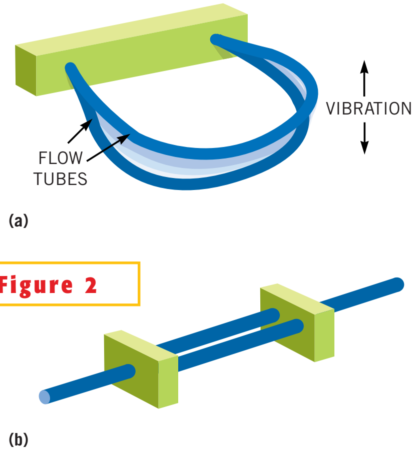


Figure 2

Most practical implementations use a pair of countervibrating tubes to cancel some common-mode error sources (a). To minimize changes to the fluid flow path, some implementations use offset straight tubes, which are sent into an antisymmetric vibrating motion that results in a twist angle (b).

The Coriolis flow meter has an advantage in another difficult fluid situation. Newtonian fluids, such as water and air, are well-behaved, with viscosity and flow characteristics that are constant; non-Newtonian fluids, such as some polymers and clays, for example, have viscosities that are functions of the fluid shear rate. The mass flow of non-Newtonian fluids can be difficult to accurately measure, but the Coriolis design can provide very good results even with this situation or even under these circumstances (**Reference 4**),

Although the basic Coriolis flow meter was designed for industrial applications and has a tube di-

HOW DO YOU GO WITH THE FLOW?

Measuring flow is simple in concept but harder in practice, and it's especially difficult in industrial applications. You can use both intrusive and nonintrusive methods. Various techniques include:

- magnetic flow meters, which are suitable only for conductive liquids; they use coils outside the pipe to generate a magnetic field into the pipe, which in turn induces a sensed voltage as the liquid flows through the field;
- ultrasonic flow meters, which are available in two versions—one measuring the transit times of a signal traveling with and against the fluid flow and the other measuring the Doppler shift that the flowing fluid creates;
- vortex flow meters, which deliberately create an internal vortex; the vortex frequency is proportional to the fluid velocity;
- differential-pressure flow meters, which measure the pressure drop as the fluid is forced across laminar flow plates; this difference is proportional to the fluid flow; and
- turbine meters, which employ a propeller blade in the pipe that rotates at a speed proportional to the flow rate; a tachometer or magnetic pickup senses the rotation.

Many of these flow meters sense fluid velocity or volume, which you must then convert to mass flow. The Coriolis approach is a direct mass measurement.

ameter of several inches, we're now living in a nanomaterial and MEMS (microelectromechanical-system) world. Accurately measuring fluid flow when the flow-tube diameters are a millimeter or less is difficult; it gets even more challenging when the tube diameter is on the order of microns, and atomic-scale effects start overwhelming macro-scale effects.

But that challenge is also an opportunity. Researchers have built micromachined Coriolis flow meters with silicon microtubes and a capacitive-detection technique to measure tube twist (**Reference 5**). The device has a mass-flow resolution of 2 μg/sec at a flow of about 1200 mg/sec and could resolve fluid-density resolution to 2 mg/cc.

The Coriolis force is not limited to measuring fluid flow, either. Recall that this force is a gyroscopic effect, and established vendors, applied-research labs, and universities are adapting it to MEMS-based gyros for angular-motion sensing. The structures they are using differ and include tuning-fork gyros, oscillating wheels, Foucault pendulums, and wine-glass resonators. You can find out more about these MEMS approaches to angular rate sensing via the Coriolis effect and who is using them in **Reference 6**.□

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