

## How Coriolis Flowmeters Work

This discussion examines in depth how Coriolis flowmeters work. It begins with the answers to some questions from a visit I made to Emerson in 2022.

### Questions About How Coriolis Flowmeters Work

As part of the research for this book, I visited Emerson's Micro Motion group and met with Dr. Mark Bell, one of the top Micro Motion Coriolis theorists. He was kind enough to respond to several questions I (JY) had. Here are his (MB) responses:

JY: My main goal in visiting Micro Motion this time (I've been there before) is to better understand the operating principle of Coriolis flowmeters. I wrote about this in my book *New-Technology Flowmeters* (September 2022), but I still have several questions:

1. What is the relation between the Coriolis force and/or Coriolis effect and the operating principle of the Coriolis flowmeter?

**(MB)  $F = m \cdot A$ , Newton's Law**

**Coriolis effect is generally the particle acceleration (A) which is  $2 \omega \times V$ ,  $\omega$  is angular velocity and V is linear velocity**

**Coriolis force is Mass of fluid \* Coriolis Acceleration**

2. (JY) The Coriolis effect has to do with the behavior of objects on a rotating frame of reference. Is oscillation a form of rotation? I assume that if there is rotation, that it refers to the meter body, not to the fluid being measured

**(MB)  $\omega$  is the rotation of the tubes while vibrating, the fluid mass is also rotating with the tubes**

3. (JY) What is angular velocity and how is it calculated?

**(MB) Angular velocity is the rate of change of an angle, often measured in radians/second (degrees/second)**

**It is calculated by measuring the rate of change of an angle**

Dr. Bell goes on to explain that, in his view, the Coriolis force falls under Newton's law:

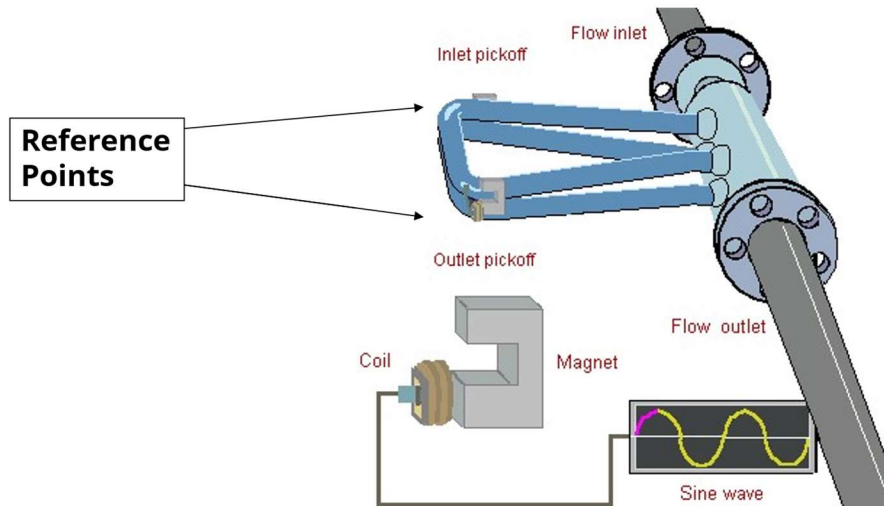
“The Coriolis force is then just the mass of the fluid times the Coriolis acceleration. That equals Newton's law. That's it. That's the only difference between the two, at least the way I think about it. You've got to make sure you're in the same coordinate systems and everything else. But yes, in general, forces are mass times acceleration. And this is how Coriolis meters work. And we apply that law in the non-rotating frame of reference. So, the fluid is rotating in the frame and we do mass times acceleration in a non-rotating frame.”

The drive coil of a Coriolis flowmeter is usually located in the middle of the flowtube. The drive coil is an electromagnetic coil that causes the flowtube to vibrate. The flowtube oscillates in its natural sinusoidal motion as a result of the tube's vibration. Vibration and oscillation are similar but different concepts. Vibration is what the drive coil does to the flowtube. Oscillation describes the tube's natural sinusoidal motion in response to the force of the drive coil.

The pickoff sensors that detect the motion of the flowtube as the fluid moves through it from inlet to outlet. Coriolis meters contain two pickoff sensors that are symmetrically located: one on the inlet side and one on the outlet side. These pickoff sensors contain a coil and a magnet. The magnet is attached to the flowtube.

## How a Coriolis meter works

- Measures mass flow rate and density of fluid using tubes oscillating on resonance
- Coriolis force causes “twist” which is measured as phase delay between two reference points



Source: [[www.micromotion.com](http://www.micromotion.com)]

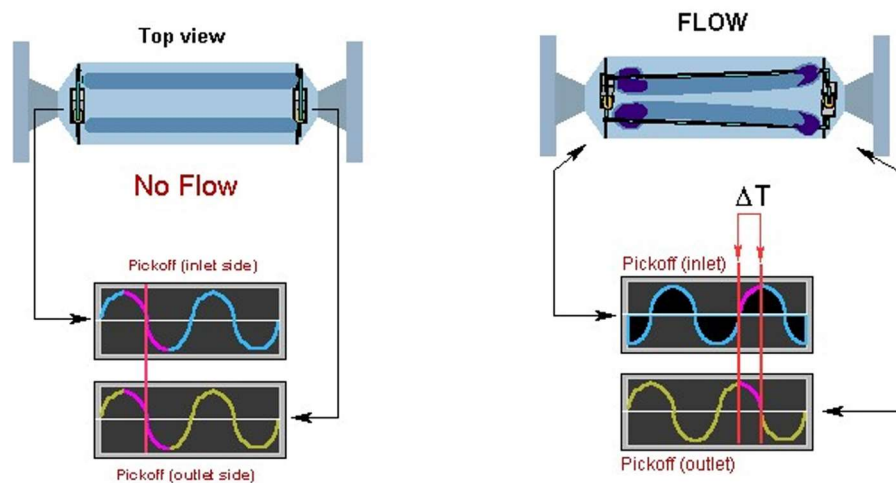
*Figure 3-1 Coriolis Flowmeter with inlet and outlet pickoffs;  
Courtesy of Emerson Micro Motion*

As the magnet in a pickoff sensor moves through the coil, the moving magnet creates a changing magnetic field that interacts with the electrons in the wire, pushing them and creating a voltage. The amount of voltage induced depends on the rate of change of the magnetic field (how fast the magnet is moved), the strength of the magnetic field, and the number of turns in the coil. Because the magnet is attached to the flowtube, the motions of the magnet capture the degree to which the oscillating flowtube is deflected by the flowing fluid.

The induced voltage varies sinusoidally with the motion of the tubes, resulting in a sine wave output. The phase difference (time delay) between the sine waves produced by the inlet and outlet sensors is directly proportional to the mass flowrate of the fluid. A larger time delay indicates a higher mass flowrate. The Coriolis transmitter analyzes the phase difference, or time delay, of the sine waves produced by the input and output sensors, and uses this value to compute mass flow. Mass flow is directly proportional to this phase difference or time delay.

## Mass flow measurement

- Coriolis force causes “twist” which is measured as phase delay between two reference points
- Phase delay is thus related to Coriolis force  $F_c = -2m\omega \times V$
- Therefore, mass flow rate is related to phase delay!



Source: [www.micromotion.com](http://www.micromotion.com)

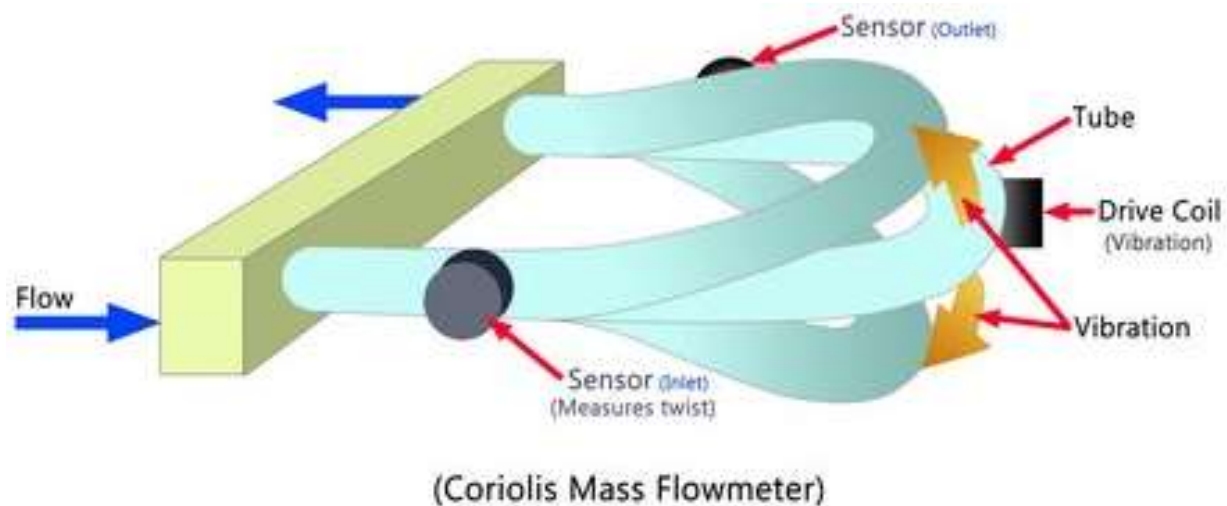
*Figure 3-2 How the sine waves are generated by the pickoff sensors;  
Courtesy Emerson Micro Motion*

As the flowtubes vibrate, the relative movement between the coil and magnet in each pickoff induces a voltage. The voltage signals from the pickoffs are processed by the meter's electronics. When there is no flow, the pickoff signals are in phase. When fluid flows, oscillatory forces cause the tubes to twist, resulting in a phase shift between the pickoff signals. The magnitude of this phase shift is directly proportional to the mass flowrate of the fluid.

Due to the oscillatory motion of the flowtubes and the interaction of magnets and coils within the meter, the voltage is generated as a sine wave. In Figure 6-2 on the left side, the sine waves from the inlet and outlet pickoff sensors are in phase, since there is no flow causing deflection in the flowtube. On the right side, where there is flow, the inlet and outlet sine waves are out of phase, and the difference between the two is shown as a phase difference, or  $\Delta t$ . This difference in time between the sine waves from the inlet tube and the sine waves from the outlet

tube is directly proportional to mass flowrate. The flowmeter transmitter uses this value to compute mass flow.

Figure 3-3 shows the inlet and outlet sensors at a different location from Figure 3-1, and also shows the action of the drive coil, which causes the flowtube to vibrate. The vibration of the flowtube results in the oscillation of the flowtube at its natural resonant frequency.



*Figure 3-3 A Coriolis flowmeter showing the inlet and outlet sensors, and the action of the drive coil*

### **The Coriolis Effect**

As we learned previously in this chapter, Coriolis flowmeters are named after Gaspard Gustave de Coriolis, a French mathematician and engineer. In 1835 he published a paper in which he described the behavior of objects in a rotating frame of reference. While this is sometimes called the Coriolis force, it is more accurately called the Coriolis effect, since it is not the result of a force acting directly on the object, but rather the perceived motion of a body moving in a straight line over a rotating body or frame of reference.

One common example given to illustrate the Coriolis effect is that of a ball propelled through the air a long distance in a straight line from the North Pole toward a target on the equator. When the ball arrives at the equator, it will not land at its target, because the earth will have rotated underneath the moving ball so that it will land a distance away from the perceived target on the

equator. The ball will appear to have curved from the perspective of the person standing where the ball is “thrown.”

A similar example is a person throwing a ball from the center of a rotating merry-go-round. If she throws the ball at a horse on the outside edge of the merry-go-round, she will not hit the horse she is aiming at but perhaps the one after it. By the time the ball reaches the edge of the merry-go-round the horse she aimed at will have moved to another location.

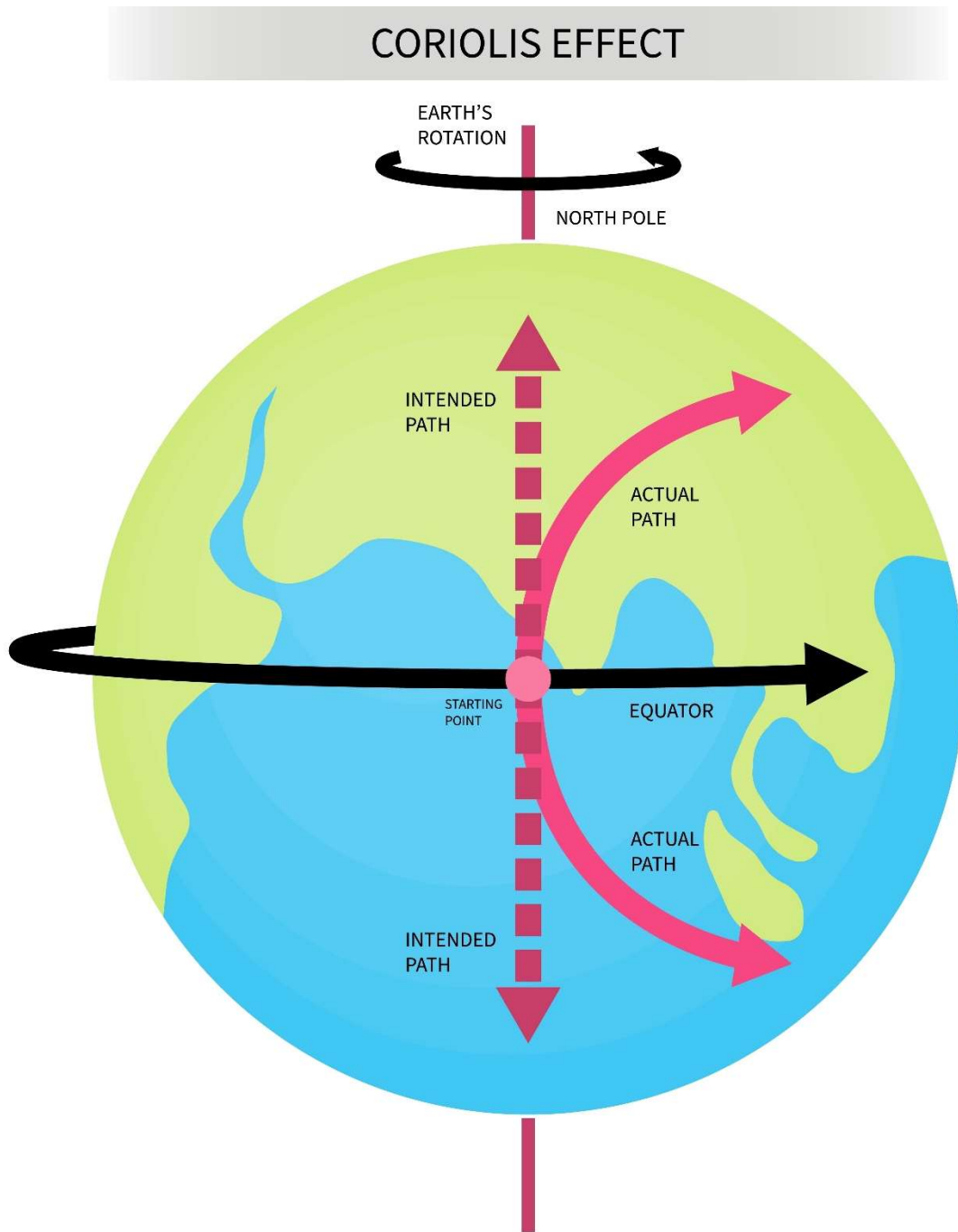
In both these cases, there is no force acting to push the ball in a curved direction. Instead, its motion will appear to be curved from the perspective of the ball-thrower because the frame of reference is moving underneath the ball. For this reason, the Coriolis “force” is more appropriately called the Coriolis effect. It refers to the apparent effect on the motion of an object passing over a rotating frame of reference when viewed from the point of origin of that moving object.

### **How the Coriolis Effect Occurs on the Earth**

The Coriolis effect occurs in rotating systems, such as the Earth, which rotates around its axis. In a rotating frame, an object moving in a straight line will appear to follow a curved path. This is due to the rotation of the reference frame itself. On Earth, this means that as air or water moves over the surface, it is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The Earth rotates from west to east, causing different points on its surface to move at different velocities. Points on the equator move faster than points near the poles. Objects moving across the rotating Earth retain their initial velocity relative to space. As the Earth rotates underneath them, their paths appear to curve. The Coriolis effect is stronger at the poles and weaker at the equator. This is because the rotational velocity of the Earth is greatest at the equator and zero at the poles.

The Coriolis effect influences wind patterns and the rotation of large-scale weather systems. For example, hurricanes in the northern Hemisphere rotate counterclockwise, while those in the Southern Hemisphere rotate clockwise. Ocean currents are also affected by the Coriolis effect, leading to the development of gyres, which are large circular current systems in the oceans. Pilots

and missile engineers must account for the Coriolis effect when plotting long-distance flights or missile trajectories, as it can cause significant deflection over large distances.



*Figure 3-4 The Coriolis Effect as it applies to the Earth*

## **The Coriolis Effect as Applied to Coriolis Flowmeters**

In the examples of the Coriolis effect commonly given, this occurs in rotating systems that are not attached to the frame of reference. In the case of planes and large-scale weather systems, they are traveling over the rotating Earth. If we hypothetically throw a ball from the North Pole to a target on the equator, the ball flies over the rotating earth and lands somewhere west of its target. While the ball is in flight, the Earth is rotating from west to east. The merry-go-round example is similar.

As a ball is thrown through the air from one side of a merry-go-round to the other, it will land somewhere beyond where the horse aimed it. This is because the merry-go-round is rotating underneath the flying ball.

In all these examples, the flying or thrown object is traveling above the rotating frame of reference; it is not part of the frame of reference. If the thrown object were part of the rotating frame, we would not experience the Coriolis effect because the thrown object would be moving with the rotating frame. For example, if we rolled a ball across the merry-go-round instead of throwing it through the air, chances are good that it would hit its target, since it would be moving along with the horse the ball is aimed at it. Likewise, we don't experience the Coriolis effect with cars traveling from south to north, since they simply rotate with the earth along with their target cities. Someone traveling from Boston, Massachusetts to Boothbay Harbor, Maine doesn't have to adjust for the Coriolis effect because the car, the road, and the town in Maine are all rotating with the Earth.

If this is the Coriolis effect, then it is difficult to see how it applies to a Coriolis flowmeter. The fluid traveling through an oscillating tube is not traveling over a rotating frame of reference; it is actually a part of the frame of reference it is traveling through. The fluid has inertia, and as the fluid with inertia encounters oscillation, it is accelerated back and forth with forces perpendicular to its direction of travel. However, the fluid becomes part of the oscillating frame of reference, since the tube oscillations create oscillations in the fluid. This example is not parallel to the usual examples of the Coriolis effect where an object travels above a frame of reference and does not travel with that frame of reference.

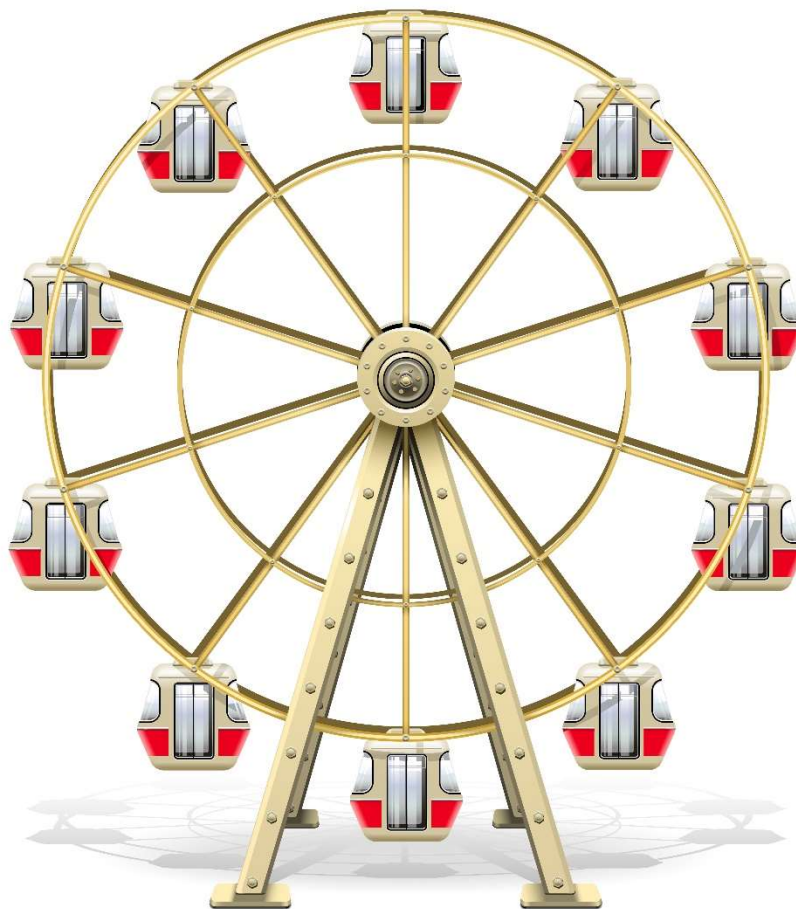
## Oscillation vs. Rotation: Are They the Same or Different?

Oscillation and rotation are distinct types of motion. Rotation involves movement in a circle around a central point or axis, while oscillation is a back-and-forth or to-and-fro movement around a central point or equilibrium position. Essentially, rotation is a circular motion, while oscillation is a repetitive, linear or curved back-and-forth motion.

The differences can be explained more clearly as follows.

### Rotation

- Involves a circular path around a fixed point or axis
- Can be non-uniform (changing speed) or uniform (constant speed)
- Examples include the Earth's rotation on its axis, a spinning top, a merry-go-round, or a Ferris wheel



*Figure 3-5 A Ferris wheel*

## Oscillation

- Involves repetitive movement back and forth or up and down
- Typically occurs around a central point of equilibrium
- Examples include a pendulum swinging, a vibrating string, or a spring bouncing



*Figure 3-6 An oscillating pendulum*

### Main Differences:

- **Direction:** Rotation maintains a consistent direction of circular movement, while oscillation involves reversing direction at the extremes of its movement.
- **Path:** Rotation follows a circular path, while oscillation follows a back-and-forth path.
- **Examples:** Rotation can be seen in the movement of a wheel, while oscillation is seen in the movement of a spring, a metronome, or the pendulum of a clock.

Some people say that oscillation and rotation are the same, or that oscillation is a form of rotation. From this point of view, going part of the way around a circle is rotating, and going the other way is rotating in a different direction. When the Coriolis tubes are moving apart, this tube is rotating that way and this tube is rotating that way. While this is one way to look at the situation, it involves stretching the meaning of the term ‘rotation’ to fit a theory. It’s not completely incorrect, but “oscillation” is a more accurate description of the situation than “rotation.” And we know that Coriolis flowmeters are all about accuracy – to within 0.05 percent!

### **What Happens to the Fluid Within the Tubes**

In a Coriolis flowmeter, the fluid flows through tubes that are vibrating perpendicular to the direction of fluid flow. These vibrations are typically sinusoidal and are driven by a drive coil. As the fluid moves through the oscillating tubes, each fluid particle is accelerated due to the vibration. The acceleration experienced by a fluid particle due to the vibration of the tubes in a Coriolis flowmeter is called centripetal acceleration. This type of acceleration occurs because the vibrating motion of the tubes forces the fluid particles to follow a curved path creating a centripetal force that acts toward the center of the curvature of the motion. The motion is essentially a repeated back and forth curvature of the path. The fluid particles must constantly change direction to follow the vibrating tube, and these changes in direction require centripetal acceleration.

As the fluid flows through the oscillating tube, a secondary vibration occurs in the tube. This secondary vibration is a twisting motion that occurs because the particles are trying to go in a straight line. As described above, inlet and outlet sensors detect this induced twisting motion as a phase shift between the inlet and outlet sensors. The magnitude of this phase shift is proportional to mass flowrate.

### **Fluid Inertia Plus Oscillating Forces Yield a Mass Inertial Effect**

While the Coriolis force is defined in the context of rotating frames, a similar inertial effect arises in oscillating systems like those in Coriolis flowmeters. This effect is due to the changing velocities and directions within the oscillating frame of the tubes. The twisting motion observed in Coriolis flowmeters is a result of those inertial effects, akin to the Coriolis effect, even though the tubes are not rotating continuously.

The traditional Coriolis force applies to objects in a rotating frame of reference, causing apparent deflection due to relative motion. Oscillating tubes in flowmeters generate inertial effects similar to the Coriolis force when fluid flows through them, resulting in a measurable twisting motion. The induced twist or phase shift in the tube caused by these inertial effects allows the flowmeter to determine the mass flowrate. Thus, the Coriolis flowmeter utilizes the principles of inertial forces arising from oscillatory motion to achieve a similar effect to the Coriolis force, enabling accurate flow measurement.

### An Alternative Understanding of the Coriolis Flowmeter

<b>Traditional View</b>	<b>Alternative View</b>
<p><b>(Coriolis explanation)</b></p> <p>In the traditional view, Coriolis flowmeters are explained using the Coriolis effect in a rotating frame of reference. As fluid flows through the oscillating tubes, it experiences Coriolis acceleration. This causes the tubes to twist. The resulting phase shift between the inlet and outlet sensors is proportional to mass flowrate.</p>	<p><b>Inertial Mass Explanation</b></p> <p>In the alternative view, the same tube twist is attributed to the inertial response of the flowing mass to the oscillating motion of the tubes. No rotating frame is required. Newton's second law (<math>F = ma</math>) is applied directly. The phase shift between the inlet and outlet sensors is still proportional to mass flowrate, but it is seen as a direct result of inertia — hence the name inertial mass meter.</p>

*“Instead of invoking the Coriolis effect in a rotating frame, I believe these meters work on a simpler, more direct principle: the inertial response of flowing mass to oscillating acceleration.”*

— Jesse Yoder, *Flow Control*, Nov. 2011

The vibrating tubes create centripetal acceleration, forcing fluid particles to follow the oscillatory motion. The fluid particles experience inertial forces due to the combination of their linear flow through the tubes and the oscillatory motion of the tubes. These inertial forces result in a secondary twisting motion in the vibrating tubes. This twist is a measure of the mass flowrate of the fluid. Inlet and outlet sensors detect the phase shift caused by the induced twisting motion. The phase difference detected by the inlet and outlet sensors is directly proportional to mass flowrate.

Note: This document is an early version of a discussion that appears in *Mass Flow Measurement* by Jesse Yoder, Taylor & Francis

In the context of a Coriolis flowmeter, the observed twisting motion is due to inertial effects arising from the interaction of fluid flow and tube oscillation. While these effects are similar to the Coriolis force, they do not strictly involve the Coriolis force as it applies to rotating frames.