6.5 Oscillating Coriolis Densitometer
(Gas, Liquid, and Slurry Services)


Density Range: 0.0 to 5.0 g/cm³ (0 to 5000 kg/m³); can also measure mass flow, volumetric flow, and temperature

Sizes (Diameter): 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, compressed gases, liquified gases (not suited for gas-liquid mixtures)

Output Signal: Linear frequency, analog, digital serial protocols, display, Highway Addressable Remote Transducer (HART), Profibus, Foundation Fieldbus, Modbus, scaled pulse, display, alarm outputs, manufacturer specified protocols.

Detector Types: Electromagnetic, optical, and capacitive

Operating Pressure: Depends upon tube size and flange rating; 1400 PSIG (100 bars) is the typical standard; 5000 PSIG (345 bars) is a typical high pressure. At 650°F temperature, the maximum operating pressure is 1160 PSIG (80 bars).

Required Pressure Drop: From under 10 PSIG (0.7 bar) to over 100 PSIG (6.9 bars)

Operating Temperature: Depends upon design: −400 to 400°F (−240 to 204°C) is the standard rating; 32 to 800°F (0 to 426°C) is the rating of high temperature units. Special low temperature designs can also be used on cryogenic applications from −40 to 140°F (−40 to 60°C). Temperature ratings can be affected by hazardous area classification.

Materials of Construction: 304/316L/316 Stainless steels, high alloy Ferritic Stainless 17-7PH, Hastelloy C, titanium, Ni-Span C as standard; tantalum, zirconium, Tefzel-lined as special

Inaccuracy: ±0.0002 to 0.05 g/cc, depending upon design; typical is ±0.002 g/cm³ over a 0.3- to 3.0-g/cm³ range

Repeatability: ±0.0001 to 0.01 g/cm³, depending upon design; typical is ±0.001 g/cm³ over a 0.3- to 3.0-g/cm³ range.

Digital Communications: Most manufacturers provide electronics, which are equipped with digital communications that support RS232/RS422 or RS485 physical interfaces and/or protocols such as ModBus. Other electronic transmitters support a variety of other digital communications protocols such as HART as well as FOUNDATION Fieldbus, DeviceNet, and Profibus-PA/DP.

Costs: 1/25th in. (1.0 mm), $5000; typical 1 in. (25 mm) meter, with full-scale flow rate of 400 to 1000 lb/min (180 to 450 kg/min), $7000; typical 3 in. (75 mm) meter, with full-scale flow rate and FOUNDATION Fieldbus transmitter, with full-scale flow of 9800 to 39,500 lb/h (4500 to 18,000 kg/h), $13,500; 6 in. (150 mm), $27,500.
Density Measurement

Partial List of Suppliers:
- ABB Inc. ([www.abb.com](http://www.abb.com))
- Bopp & Reuther ([www.burhm.com](http://www.burhm.com))
- Brooks Instrument, a Unit of Emerson Process Management ([www.emersonprocess.com/brooks](http://www.emersonprocess.com/brooks))
- Danfoss A/S (Denmark) ([www.danfoss.com](http://www.danfoss.com))
- Endress & Hauser Inc. ([www.us.endress.com](http://www.us.endress.com))
- Fischer and Porter, a Unit of ABB ([www.us.abb.com](http://www.us.abb.com))
- Foxboro-Invensys ([www.foxboro.com](http://www.foxboro.com))
- Heinrichs GmbH & Co. ([www.heinrichs-mt.com](http://www.heinrichs-mt.com))
- Krohne ([www.krohne.com](http://www.krohne.com))
- Oval ([www.oval.co.jp](http://www.oval.co.jp))
- Rheonik ([www.rheonik.de](http://www.rheonik.de))
- Schlumberger Industries ([www.slb.com](http://www.slb.com))
- Smith Meter Inc. ([www.fmcenergysystems.com](http://www.fmcenergysystems.com))
- Yokogawa ([www.yokogawa.com](http://www.yokogawa.com))

INTRODUCTION

It requires the least amount of energy to cause an object to go into natural frequency vibration. This frequency is a function of the mass of the object. In case of a Coriolis densitometer, the mass of the vibrating object is the sum of the pipe, the fluid within the pipe, and the mass of the driver and sensors (Figure 6.5a). Therefore, since the masses of the pipe, driver, and sensors are constant, a change in natural frequency is a direct indication of a change in the density of the process fluid.

A unique feature of the Coriolis flowmeter is its ability to determine, in addition to its flow rate, the density of the process fluid. This ability can be used even when the measurement of the fluid flow rate is of no interest. The density measurement requires the main components illustrated in Figure 6.5a.

THE SENSOR

One design of a Coriolis densitometer is shown in Figure 6.5b. This density sensor is comprised of either one or two flow tubes (usually two), a driving mechanism for oscillating the flow tubes, detectors for the measurement of natural frequency, and a temperature-measuring device.

The process fluid stream is split into two and flows through the flow tubes. A coil-and-magnet driver is used to oscillate the flow tubes in opposition at their natural frequency. The oscillation of the tubes causes the flow detectors to output a sinusoidal voltage signal that reflects this motion. The frequency of the sinusoidal voltage from the flow detectors represents the natural frequency of the tube vibration. Typically, the flow detectors are electromagnetic sensors, although capacity detectors and optical sensors are also used.

Changes in the density of the process fluid will cause the mass of the fluid-filled flow tube system to change. This in turn will change the natural frequency of the sensor. This change will cause the frequency of the sinusoidal voltage from the flow detectors to change. By measuring the frequency of the sinusoidal voltage developed by the Coriolis detector, the density of the process fluid is determined.

Temperature Correction

The temperature of the tube affects its natural frequency of vibration. If the tube temperature increases, the tube becomes more elastic, which causes the natural frequency to decrease.
even though the mass of the system has not changed. The measurement of the tube’s temperature is used to correct the natural frequency for changes in the elastic modulus of the flow tube material. A resistance temperature detector is typically used to measure the tube temperature.

**THEORY OF OPERATION**

The natural frequency of vibration is described by the equation:

\[ \omega_n = \sqrt{\frac{k}{m}} \]  
6.5(1)

where

- \( \omega_n \) = natural frequency, rad/s
- \( k \) = spring constant, pound-force/in. or \( \text{lb/s}^2 \) (N/m or kg/s^2)
- \( m \) = mass of the system, lb (kg)

For the Coriolis meter, the mass of the system is the combined mass of the fluid and the flow tube assembly and can be expressed by the following relationship:

\[ m = \rho_f A_t l_i + \rho_t A_l l_t \]  
6.5(2)

where

- \( \rho_f \) = fluid density, \( \text{lb/ft}^3 \) (g/cc)
- \( \rho_t \) = tube material density, \( \text{lb/ft}^3 \) (g/cc)
- \( A_t \) = tube internal area, in.\(^2 \) (cm^2)
- \( A_l \) = tube cross-sectional area, in.\(^2 \) (cm^2)
- \( l_i \) = tube length, in. (cm)

The spring constant \( (k) \), from Equation 6.5(1), is a function of geometry and material properties and is determined from the following equation:

\[ k = \frac{\text{MEI}}{l_i^4} \]  
6.5(3)

where

- \( \text{M} \) = modal constant
- \( E \) = modulus of elasticity, pound-force/in.\(^2 \) (kPa)
- \( I \) = moment of inertia, in.\(^4 \) (cm^4)

The natural frequency (\( \omega_n \)), from Equation 6.5(1), can also be expressed by the following equivalent relationships:

\[ \omega_n = 2\pi f = \frac{2\pi}{T} \]  
6.5(4)

where

- \( f \) = oscillation frequency, cycles/s
- \( T \) = tube period, s (time for one cycle of oscillation)

Substituting Equations 6.5(2), 6.5(3), and 6.5(4) into Equation 6.5(1) and solving for \( \rho_f \) gives the following relationships:

\[ \rho_f = \left( \frac{\text{MEI}}{4\pi^2 l_i^4 A_l} \right) T^2 - \frac{\rho_t A_l}{A_t} \]  
6.5(5)

**The Calibration Constant**

The variables that depend upon the tube geometry and materials properties can be combined to obtain the calibration constants, such as: \( K_1 = (\text{MI})/4\pi^2 l_i^4 A_l \) and \( K_2 = (\rho_t A_l)/A_t \). A correction factor \( C_f \) is used to compensate for changes in the material modulus of elasticity \( (E) \) with temperature. Equation 6.5(5) can then be rewritten as:

\[ \rho_f = K_1 C_f T^2 - K_2 \]  
6.5(6)

Values for the calibration constants are determined by measuring the period of oscillation of the tube at two known fluid densities. With the two fluid densities and their respective tube periods, two simultaneous equations with two unknowns can be solved to obtain \( K_1 \) and \( K_2 \). Any two fluids of known density can be used to determine the calibration constant.

Calibration fluids should be so selected as to have sufficiently different densities to minimize the amount of error associated with the calibration constants \( K_1 \) and \( K_2 \). Air and water are commonly used as the calibration fluids. The value of \( C_f \) depends upon the material of the flow tube and is determined by the manufacturer from experimental data.

**ELECTRONICS**

A typical block diagram of the density measurement electronics is shown in Figure 6.5c. The electronics is comprised of interfaces to the sensor, signal-processing components, and outputs to external devices. The interfaces between the sensor and the electronics include the flow detectors, the drive mechanism, and the temperature detector.

The electronics vibrates the tubes at their natural frequency by minimizing the amount of energy input into the driver while maintaining sufficient tube displacement to produce the forces required to measure the fluid flow rate. The electronics applies an alternating current to the drive coil that is mounted on one of the flow tubes. This alternating current generates an alternating magnetic field in the coil. The alternating magnetic field causes the fixed magnet mounted on the other tube to be repelled and attracted, forcing the tubes alternately away from and toward one another at their natural frequency. The flow detectors generate a sinusoidal voltage signal that reflects the oscillation of the flow tubes.
The sinusoidal voltage signal from one of the flow detectors is input into a counter that detects the start and end of each tube cycle. The tube cycles are gated by the counter, which triggers the counter to make a time measurement over the duration of the tube cycle. The time or period over which the tube cycle occurred is obtained from a precision crystal oscillator. The microprocessor reads the counter time measurement and uses this value along with the tube temperature and calibration constants, $K_1$ and $K_2$, to calculate the fluid density using Equation 6.5(6).

### Output Options

Electronics are available to provide several different output options. The most common output is an analog (4 to 20 mA) output, which can be scaled to represent the desired density range. Some manufacturers provide a scalable frequency output that can also be used to represent the fluid density. Many of the meters are equipped with built-in displays that can be used to directly display the density of the process fluid (or any other process variable acquired by the meter including volumetric flow, mass flow, temperature, and total flow). The user can select a variety of units for the density display, such as g/cc, lb/ft$^3$, °API, °Baumé, etc.

Most manufacturers provide electronics that are equipped with digital communications that support RS232/RS422 or RS485 physical interfaces and/or protocols such as ModBus. Other electronic transmitters support a variety of other digital communications protocols, such as Highway Addressable Remote Transducer (HART), as well as FOUNDATION Fieldbus, DeviceNet, and Profibus-PA/DP. The latter two can provide high-speed transmission of all sensor process variables back to the host distributed control system (DCS) for display and/or control purposes.

A density output is occasionally optional on some devices. A typical Coriolis flowmeter comes standard with one pulse or frequency output that usually represents flow rate and another output that can represent density. Two analog outputs can be configurable for a choice of flow rate, density, or temperature; a local display can be purchased which is independent of the other outputs. Digital discrete outputs are also normally standard issue including alarm outputs. Several data communications options are available including basic RS-232/422/485 physical links, ModBus, and HART. Other optional multivariable transmitters can provide fieldbus serial digital data communication outputs such as FOUNDATION Fieldbus, DeviceNet, and Profibus-PA/DP, and can send many process variables (flow rate [mass or volumetric], density, temperature, and flow total) back to a host DCS. The number and type of outputs, both standard and optional, vary from one manufacturer to another.

### APPLICATIONS

A Coriolis meter can measure the density and the flow rate of a wide variety of process fluids. In addition to indicating density, the electronics can be configured to provide additional information such as the concentration of one or more components in a mixture.
Microprocessors can be programmed to determine the composition of mixtures. Common options that are provided allow for the determination and monitoring of % solids by mass or volume, °Brix, % fructose, % alcohol, and % solids in black liquor. Many of these relationships are temperature-dependent, and the temperature reading from the flow tube is used to correct for the variations in fluid temperature.

Since the flow rate is measured by the Coriolis meter, the net flow rate of one or more components in a multicomponent mixture can also be determined. An example of this is the ability to determine the flow rate of oil in an oil-water emulsion.

**DEVELOPMENTS AND TRENDS**

In addition to monitoring several variables, the newer systems allow the transfer of calibration and diagnostic related information to and from the host DCS. Some Coriolis meters not only support the use of many different density units, such as °Baume, °Balling, °Plato, but are also able to convert their readings into specialized units as required by the particular industry. For example, in the hydraulic well fracturing process of the oil and gas industry, the sand added per cubic meter of liquid can be monitored.

Two- and three-dimensional polynomial calculations can yield relationships between concentration and reference density or can correlate relationships between concentration, density, and temperature. The Coriolis electronics can support up to four detector assemblies and can provide high precision under widely variable operating conditions. For example, it can detect the density within an error of ±0.0005 g/cm³ over a range of 0.001 to 1.8 g/cm³, while the temperature varies from 5 to 80°C.

The Coriolis meter is a multivariable sensor. It is hoped that in the future it might become capable of measuring even more variables, possibly including viscosity.

**Bibliography**


