

Vortex Shedding Tutorial

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Introduction

The vortex shedding flowmeter first emerged 25 to 30 years ago and has steadily grown in acceptance since then to be a major flow measurement technique. Its appeal is due, in part, to the fact that it has no moving parts yet produces a frequency output that varies linearly with flowrate over a wide range of Reynold's numbers. The vortex meter has a very simple construction, provides accuracy (1% or better) comparable to higher price and/or more maintenance intensive techniques and works equally well on liquids and gases. In addition it is powered primarily by the fluid and lends itself more readily than other linear flow devices to two-wire operation. Comparing the vortex shedding flowmeter to an orifice plate the former has higher accuracy and rangeability, does not require complex pressure impulse lines, is less sensitive to wear and, for volumetric flow measurement, does not require the need to compensate for fluid density.

Industrial vortex shedding flowmeters are normally available in pipe sizes ranging from ½" to 12", with some manufacturers offering sizes up to 16". Flow ranges covered depend on fluid properties and meter design. Typical ranges for a ½" meter are:

- Water at 70° F; 1 to 35 gallons per minute
- Air at 60° F and 14.7 psia; 140 to 2000 cubic feet per hour
- Dry saturated steam at 100 psig; 10 to 500 pounds per hour

Typical ranges for a 12" meter are:

- Water at 70° F; 85 to 8500 gallons per minute
- Air at 60° F and 14.7 psia; 20,000 to 1,600,000 cubic feet per hour
- Dry saturated steam at 100 psig; 2750 to 275,000 pounds per hour

Temperature capability ranges from cryogenic temperatures up to 800° F. Pressure capability as high as 3000 psig is available.

Principle of Operation

Probably the first time, ages ago, that anyone placed a blunt obstacle in a flowing fluid he or she observed the whirlpools or vortices that naturally form and shed downstream. In everyday life the examples of vortex shedding are numerous. The undulation of a flag is due to vortex shedding from the pole and the singing of telephone wires in a strong wind is due to shedding from the wires. Analysis by Theodore von Karman in 1911 described the stability criterion for the array of shed vortices. Consequently, when a stable array of vortices form downstream from an obstacle it is often referred to as the von Karman vortex street.

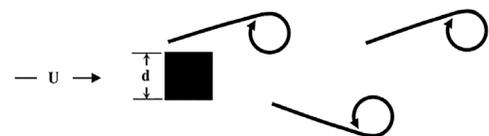


Figure 1. Von Karman Vortex Street

Very early on it was noted that, for a large class of obstacles, as the velocity increased the number of vortices shed in a given time, or frequency of vortex shedding, increased in direct proportion to the velocity. The dimensionless Strouhal number, St , is used to describe the relationship between vortex shedding frequency and fluid velocity and is given by:

$$St = \frac{f \times d}{U} \quad (1)$$

where;

f = vortex shedding frequency

d = width of shedding body

U = fluid velocity

Alternatively,

$$U = \frac{f \times d}{St} \quad (2)$$

Although early studies were done in unconfined flow, it was later observed that vortex shedding also occurred in confined flow such as exists in a pipe (see Figure 2). For this case the average fluid velocity, \bar{U} , and the meter Strouhal number, St' , replaces the fluid velocity and Strouhal number in (2), respectively:

$$\bar{U} = \frac{f \times d}{St'} \quad (3)$$

Since the cross sectional area, A , of the pipe is fixed it is possible to define a flowmeter K- factor, K , which relates the volumetric flowrate (Q) to the vortex shedding frequency.

Given that

$$Q = A \times \bar{U}$$

From Equation (3),

$$Q = \left(\frac{A \times d}{St'} \right) \times f$$

Defining

$$K = \frac{St'}{(A \times d)}$$

Results in:

$$Q = \frac{f}{K}$$

Vortex shedding frequencies range from less than 1 hertz to greater than 3000 hertz, the former being for large meters at low velocities and the latter for small meters at high velocities.

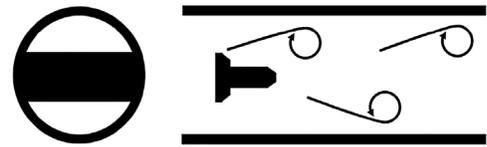


Figure 2. Vortex Shedding in a Pipe

For a vortex shedding flowmeter an obstacle is chosen that will produce a constant K-factor over a wide range of pipe Reynold's numbers. Thus simply counting the vortices that are shed in a given amount of time and dividing by the K-factor will give a measurement of the volumetric flowrate. A typical K-factor vs. Reynolds number curve is shown in Figure 3.

The variation in K factor over a specified Reynold's number range is sometimes referred to as Linearity. For the example in Figure 3 it can be seen that between Reynold's numbers from 15,000 to 2,000,000 the K-factor is the most linear. This is referred to as the linear range of the shedder. The wider the linear range a shedder exhibits the more suitable the device is as a flowmeter.

At Reynold's numbers below the linear range linearization is possible but flowmeter uncertainty may be degraded.

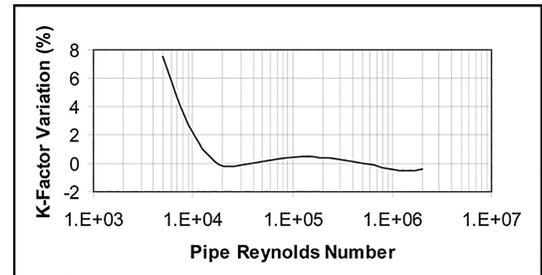


Figure 3. Typical K-factor Curve

Calculation of Mass Flow and Standard Volume

Although the vortex flowmeter is a volumetric flowmeter it is often combined with additional measurements to calculate or infer mass flow or standard volume.

To determine mass flow, M:

$$M = \rho_f \times Q = \rho_f \times \frac{f}{K}$$

Where,

ρ_f = fluid density at flowing conditions

Often it is desirable to know what the volumetric flowrate would be at standard process conditions with respect to pressure and temperature. This is referred to as standard volume. In different parts of the world and for different industries the standard temperature and pressure may be different. The fluid density at standard conditions is referred to as the base density, ρ_b .

To calculate standard volume, Q_v :

$$Q_v = \left(\frac{\rho_f}{\rho_b} \right) \times \frac{f}{K}$$

Flowmeter Construction

The vortex shedding flowmeter can be described as having two major components, the flowtube and the transmitter. Both are described below.

Flowtube

The flowtube is made up of three functional parts, the flowmeter body which contains the fluid and acts as a housing for the hydraulic components, the shedder which generates the vortices when the fluid passes by and the sensor(s) which by some transducing means detect the vortices and produce a usable electrical signal.

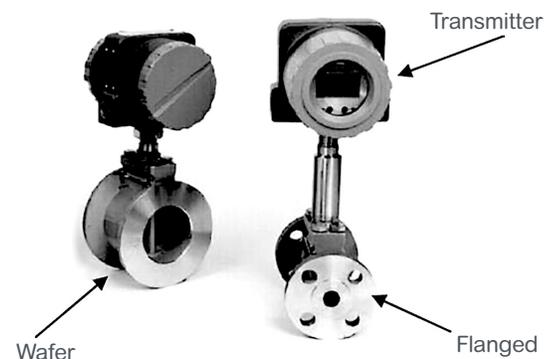


Figure 4. Vortex Flowmeter Construction

Flowmeter Body

The pressure-containing portion of the vortex flowmeter, sometimes referred to as the flowmeter body, is available in two forms, wafer or flanged (see Figure 4). The wafer design, which is sandwiched between flanges of adjacent pipe, is generally lower cost than the flanged design but often its use is limited by piping codes.

Shedder

The shedder spans the flowmeter body along the diameter and has a constant cross-section along its length. Typical cross-sections are shown in Figure 5.



Figure 5. Shedder Cross Sections

Sensors

When shedding is present both the pressure and velocity fields in the vicinity of the shedder will oscillate at the vortex shedding frequency. Pressure or velocity sensors are used to transform the oscillating fields to an electrical signal, current or voltage, from which the vortex shedding frequency can be extracted. Figure 6 shows an example of a piezoelectric differential pressure sensor located in the upper portion of the shedder, which converts into an electrical signal the oscillating differential pressure that exists between the two sides of the shedder. Some other sensing means utilized to detect vortex shedding are capacitive, thermal and ultrasonic. Often times the flowmeter electronics are mounted remotely from the flowtube. This may require a local pre-amplifier to power the sensor or boost its' signal strength.

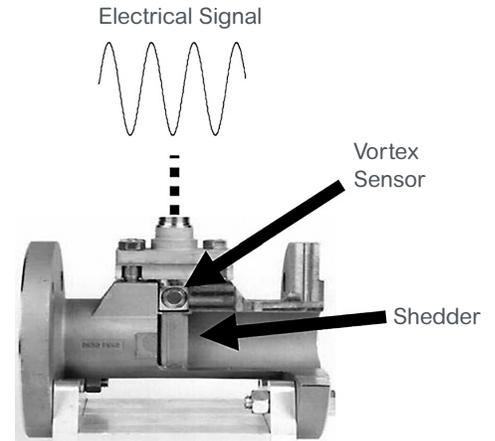


Figure 6. Example of Vortex Sensor

Since the sensor is the most likely mechanical component in a vortex flowmeter to fail most designs have a provision for replacement of the sensors. In some cases they can be replaced without removing the flowmeter from the pipeline. An example of an isolation manifold for sensor replacement under process conditions is shown in Figure 7.

Transmitter

Vortex flowmeter transmitters can be classified into two broad groups, analog and intelligent (or smart). Communication with the analog transmitter is carried out via local mechanical means, including switches and jumper wires. Communication with the newer intelligent device is carried out via digital electronic techniques. Both types of transmitters are two-wire devices. One of the more important features of the intelligent transmitter is that it allows application specific information to be loaded into the transmitter. This information is then used internally to automatically tailor the transmitter to the application, including calibration of the 4-20mA output. Before describing these devices, it will be useful to consider the three most common forms of flow measurement signals provided by vortex transmitters.

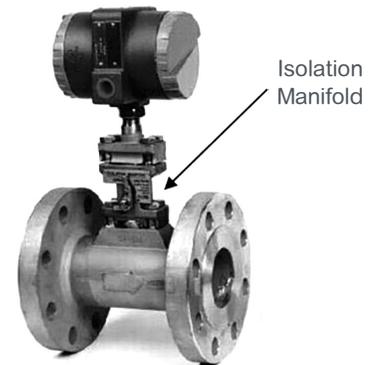


Figure 7. Isolation Manifold For Sensor Replacement

Measurement Output Signals

The three most common ways for a transmitter to communicate measurement information to the outside world are 4-20mA, digital, and pulse signals.

The 4-20mA signal is the dc current flowing in the power leads to the transmitter. This current is directly proportional to the vortex shedding frequency and, hence, is also linear with flow (see Figure 8). 4mA corresponds to zero flow and 20mA to the maximum flowrate, i.e., the upper range value (URV) of the meter. A frequency to analog converter in the analog meter and a digital to analog converter in the intelligent meter produce this output.

The digital signal is a digitized numeric value of the measured flowrate in engineering units transmitted over the two-wires powering the meter.

The pulse signal is a squared-up version of the raw vortex signal coming from the sensor (see Figure 9), and is accessible via a pair of electrical terminals inside the transmitter housing. The frequency of the pulse signal is either identical to the vortex shedding frequency (raw pulse) or some multiple thereof (scaled pulse). As discussed in the Principle of Operation section, in either case the frequency of the pulse signal is linearly proportional to flowrate going from zero to the frequency at the URV, f_{URV} (see Figure 8).

As shown in Figure 8, at a low but non-zero flowrate the frequency and mA signals drop to zero and 4mA, respectively. The flowrate at which this abrupt change takes place is normally referred to as the low flow cut-in, LFCI or cut-off. The reason for this forced zero is to avoid erroneous flow measurements at low flow which result from process noise, including hydrodynamic fluctuations, mechanical vibration, and electrical interference. The digital signal also drops to zero below the LFCI flowrate.

Analog Transmitter

Originally, analog transmitters were constructed totally of analog electronic components. Today, they may be built around a combination of analog and digital electronic components. In either case the measurement output is in the form of a raw pulse and/or a 4-20mA signal. Depending on the particular transmitter, one or more of the following functions are available for tailoring the device via mechanical means to the specific application:

a.) Signal Output Selection

If the transmitter provides both raw pulse and 4-20mA signals, but not simultaneously, a means is available for selecting the one desired.

b.) 4-20mA Calibration

Use of the 4-20mA signal requires that 20mA correspond to the desired URV. This is accomplished by inputting, via a signal or pulse generator, a periodic signal whose frequency corresponds to the upper range frequency (URF), and adjusting the output current until it reads 20mA. The URF, which is the frequency corresponding to the vortex shedding frequency at the desired URV, is calculated using the equation $URF = K \times URV$.

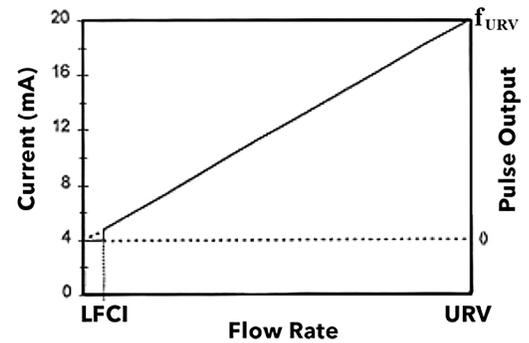


Figure 8. 4 – 20 Ma and Pulse Outputs

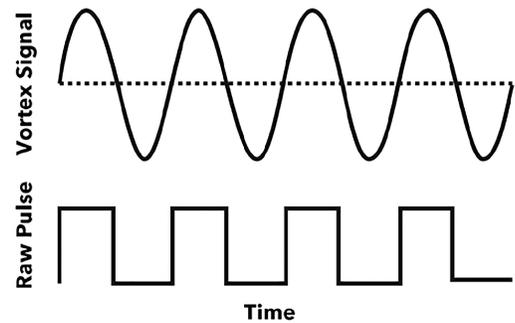


Figure 9. Raw Pulse Output

In order to achieve the accuracy specified by the manufacturer, the K used in the above calculation must be corrected for process temperature and piping effects according to the manufacturer's instructions. The temperature effect is a result of thermal expansion of the flowtube, and is described by:

$$\Delta K(\%) = -300 \times \alpha \times (T - T_0)$$

where α is the thermal expansion coefficient of the flowtube material and T_0 is the fluid temperature at which the meter was calibrated. If the shedder and meter body materials are different α must be replaced by $(2\alpha_1 + \alpha_2)/3$, where α_1 is the thermal expansion coefficient of the meter body material and α_2 that of the shedder.

Piping disturbances also affect the K-factor because they alter the flow profile within the flowtube. This will be discussed in more detail in the section titled "Adjacent Piping".

c.) Low Flow Cut-In

For optimum measurement performance the low flow cut-in should be set to fit the specific application. The goal is to set it as low as possible, while at the same time avoiding an erroneous flow measurement output.

d.) Filter Settings

To reduce noise present on the signal from the sensor, electronic filters are built into the transmitter. Normally, means are provided for adjusting these filters, that is setting the frequencies at which they become active. By attenuating frequencies outside the range of the vortex shedding frequency, which varies from one application to another, better measurement performance is achieved.

Intelligent Transmitters

Intelligent transmitters, which are microprocessor based digital electronic devices, have measurement outputs which usually include two or more of the following: raw pulse, scaled pulse, 4-20mA and digital. With regard to the digital output, there is at present no single, universally accepted protocol for digital communication, however, a number of proprietary and non-proprietary protocols exist.

The presence of a microprocessor in the intelligent transmitter allows for improved functionality and features compared to the analog transmitter, including:

- elimination of need for 4-20mA calibration
- automatic setting of low flow cut-in
- automatic setting of filters
- adaptive filtering (active filters that track the vortex frequency)
- digital signal conditioning
- K-factor correction for temperature and piping disturbances
 - correction for non-linearity of K-factor curve including the pronounced non-linearity at low Reynold's numbers (see Figure 3)
- integral flow totalization
- digital measurement output in desired engineering units

Configuring, i.e., tailoring the transmitter to a specific application is carried out by one or more of the following digital communicators:

- Local Configurator - a communicator, built into a transmitter, which has a display and keypad
- Hand Held Terminal - a palm size digital device programmed for configuration purposes
- PC Configurator - a personal computer containing configuration software
- System Configurator - a digital measurement and control system with imbedded configuration software

Using one of these configurators, the set of parameters that define the configuration can be modified to fit the application in question. The details of this data set vary depending on the specific transmitter, however, the general categories of information listed below apply.

- Flowtube Parameters (e.g., tube bore, K-factor, Serial No.)
- User Identification Parameters (e.g., Tag No., location)
- Transmitter Options (e.g., measurement units, function selections)
- Process Fluid Parameters (e.g., fluid density & viscosity, process temperature)
- Application Parameters (e.g., K-factor corrections, URV, LFCI level)
- Output Options (e.g., measurement output modes, damping, fail-safe state).

Application Considerations

Meter Selection

From a safety viewpoint, it is essential that the vortex flowmeter satisfy the appropriate electrical safety requirements and be compatible with the process, i.e., be able to withstand the temperature, pressure, and chemical nature of the process fluid. From a mechanical viewpoint, it must have the proper end connections and, if required, have a sensor that can be replaced without shutting down the process. Meter size and measurement output signal type are also two very important selection factors.

Size

Contrary to what one might expect, the required meter size is not always the same as the nominal size of the piping in which it is to be installed. In some applications, selecting the size based on adjacent piping will not allow the low end of the required flow range to be measured. The appropriate criteria for selecting meter size is that the meter provides a reliable and accurate measurement over the entire required flow range. This may dictate a meter size that is less than the adjacent piping.

Pressure drop is a competing criteria to that above for sizing. This drop is given by:

where C is a constant dependent on meter design, and D is the bore diameter of the flowtube. The tendency is to pick a flowtube with the same nominal diameter as the adjacent piping to eliminate the extra pressure drop introduced by a smaller size meter. However, in the majority of cases this added drop is of little consequence.

The meter manufacturer can provide the needed information for making the proper selection. In some cases sizing programs from manufacturers are available on the Internet in either an interactive or downloadable form.

Measurement Output Options

$$\Delta P = C \times \rho_f \times Q^2 / D^4$$

As mention in Sec. 3.2, three types of measurement outputs are in current use, a 4-20 mA analog signal, a pulse train, and a digital signal. Some vortex meters will provide all three of these outputs, but not always simultaneously. It is essential that the meter has the output(s) required by the application.

Meter Installation

The performance specifications of a vortex flowmeter are normally established under the following conditions: 1) the flowtube is installed in a pipeline running full with a single phase fluid, 2) the piping adjacent to the flowtube consists of straight sections of specified schedule pipe (normally Schedule 40) typically a minimum of 30 PD (pipe diameters) in length upstream and 5 PD downstream of the flowtube with no flow disturbing elements located within these sections, and 3) the meter is located in a vibration free and electrical interference free environment. As a consequence, certain constraints are placed on where and how the meter is installed in process piping if published performance specifications are to be achieved. These constraints are discussed below. Because meters from different suppliers differ in their sensitivity to the above influences, the statements made are of a qualitative nature. The specific manufacturer should be consulted for more quantitative information.

Location

The flowmeter should be located in a place where vibration and electrical interference levels are low. Both of these influences can decrease the signal-to-noise ratio at the input to the transmitter. This reduction can degrade the ability of the meter to measure low flows.

The meter should not be installed in a vertical line in which the fluid is flowing down since there is a good possibility that the pipe will not be full.

Adjacent Piping

Recommended practice is to mount the flowmeter in the process piping according to the manufacturer's stated upstream and downstream minimum straight length piping requirements. These are typically 15-30 PD and 5 PD, respectively. Piping elements such as elbows or reducers upstream of the meter normally affect its K-factor but not its linearity. This allows a bias correction to be applied to the K-factor. Many manufacturers provide bias factors for common upstream piping arrangements. Some who offer intelligent flowmeters make the corrections internally, once the user has selected the appropriate configuration from a picklist. For piping elements and arrangements where the bias correction is not available an in situ calibration should be run if the manufacturer's specified uncertainty is to be achieved. If this is not possible, calibration in a test facility with an identical configuration should be run.

The same situation as above applies if the pipe schedule adjacent to the meter differs from that under which the meter was calibrated.

To avoid disturbance to the flow, flange gaskets should never protrude into the process fluid.

The following recommendations apply if a control valve is to be situated near a vortex flowmeter. In liquid applications the control valve should be located a minimum of 5 PD downstream of the flowmeter. This not only prevents disturbance to the flow profile in the flowtube, but also aids in preventing flashing and cavitation (see below). In gas applications the control valve should be installed upstream of the meter, typically a minimum of 30 PD upstream of the meter to ensure an undisturbed flow profile. Having the pressure drop across the valve upstream of the meter results in a decreased density and subsequent increased velocity at the flowmeter. This helps in achieving good measurements at low flows. For condensable gases, such as steam, it also helps to reduce the amount of condensate that might otherwise be present at the flowmeter.

Orientation

In general, meter orientation is not an issue for vortex flowmeters, particularly for vertical pipe installations. However, for meters having electronics at the flowtube, it is recommended in high temperature horizontal pipe applications that the flowtube be oriented with the electronics beneath the meter. Although vortex flowmeters are not recommended for multiphase applications they do operate with somewhat degraded performance with dirty fluids (i.e. small amounts of gas bubbles in liquid, solid particles in liquid, or liquid droplets in gas). The degree of degradation in horizontal pipe applications depends to some extent on the specific meter design. Orienting the flowtube according to manufacturer's recommendations for the dirty fluid in question, if given, may help to alleviate this problem.

Pressure and Temperature Taps

The placement of pressure and temperature taps for determining gas densities, if required, is also an important consideration. Recommendations for location of these taps vary depending on manufacturer. The temperature probe is inserted typically 6 PD downstream of the flowtube. This prevents any flow disturbance in the meter, and at the same time gets the probe as close to the meter as possible. The pressure tap is made typically 4 PD downstream of the meter. Although a pressure tap does not significantly affect the flow, its placement is critical for achieving an accurate density measurement.

Process Conditions

Flashing and cavitation can occur in a liquid application just downstream of the shedder if the pressure drop across the meter results in the downstream pressure being below the vapor pressure of the liquid. These phenomenon lead to undefined measurement errors and possibly to structural damage, and hence should be avoided. This is usually accomplished by increasing the inlet pressure or inserting a back-pressure valve downstream of the meter. To avoid flashing and cavitation, the downstream pressure after recovery (approximately 5 PD downstream) must be equal to or greater than P_{dmin} , where

$$P_{dmin} = c_1 \times \Delta P + c_2 \times P_{vap}$$

and, P_{dmin} = minimum downstream pressure after recovery

P_{vap} = vapor pressure of the liquid at the flowing temperature

ΔP = overall pressure drop

c_1, c_2 = empirical constants for a specific meter (normally available from the meter manufacturer)

Pulsating flow can also in some circumstances lead to measurement errors. It is best to avoid placing the meter in process lines where noticeable pulsation exists.

Meter Configuration

It is important when installing an analog or intelligent vortex flowmeter that it be configured for the specific application. This is often done by the supplier prior to shipping if the user supplies the relevant information at the time the order is placed. If this is not the case, the user must carry out the configuration procedures provided by the manufacturer (see Transmitter).

Recent Developments

Recent efforts have been made to make the vortex flowmeter into a real-time mass flow measurement device. As was demonstrated in 'Principle of Operation', the output of the meter, based on the frequency of vortex shedding, is related to actual volumetric flow (see Equation 3). In intelligent transmitters the flowing density (the density at flowing conditions) and the base density can be entered into the transmitter's database. Based on these values mass flow or standard volumetric flow can be computed (see Equations 4 & 5). This procedure is valid if the flowing density does not vary in time. If this is not the case, an on-line real-time measure of the density must be provided. Two different approaches have been used. One employs sensors in addition to the vortex sensor, the other relies on additional information being extracted from the vortex shedding signal.

Multi-sensor

In this method, temperature and pressure measurements are made in addition to the vortex frequency. This approach is similar to that used in orifice-d/p mass flowmetering, in which case temperature and pressure ports are located in the pipe normally downstream of the orifice plate. However, in this case, the temperature and pressure sensors are incorporated into the flowmeter rather than located in the adjacent piping. Using these two additional measurements, the flowing density is calculated from the equation of state for the process fluid. This approach is similar to that used in orifice-d/p mass flowmetering, in which case temperature and pressure ports are located in the pipe normally downstream of the orifice plate.

Single-sensor

This approach takes advantage of the fact that, in principle, for a force or pressure based vortex shedding sensor, the amplitude of the vortex shedding signal is directly proportional to the density times the square of the fluid velocity, i.e.,

$$\text{signal amplitude} \propto \rho_f \times U^2$$

The fluid velocity can be determined from the vortex frequency, i.e.,

$$\text{frequency} \propto U$$

Hence,

$$\text{signal amplitude/ frequency} \propto \rho_f \times U \propto \text{massflow}$$

This approach, in principle, is independent of the process fluid, and requires no additional sensors.

Additional Reading

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January, 2016
Document Number FD-WP-002

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