

Part 3: Multivariable Mass Vortex

Core Technology White Paper Series 3 of 4



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Publication Date: July 2009
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About:

This white paper, part 3 of our core technology series, explores the mechanics and science that make up a multivariable vortex meter by showing the evolution from the original idea of a vortex shedding flow meter to its current generation. This paper also explores the reasons why a multivariable mass vortex flow meter technology is more reliable and beneficial to the end-user by presenting easy-to-understand descriptions of the principles of operation.

Introduction: Multivariable Mass Vortex

In 1997, Sierra Instruments took proven vortex shedding technology to the next level with the launch of the Innova-Mass[®] Model 240 & Model 241 Multivariable Mass Vortex Flow Meter. Sierra was the first to offer this unique solution for measuring the mass flow of gases, liquids and steam.

Vortex shedding flow meters have been in use for many years. The typical device is a flanged in-line unit. Most vortex meters measure only one variable (the velocity of the flowing fluid). Effectively, this makes the typical vortex meter a volumetric unit. While mass flow can be calculated for a constant density fluid, it becomes problematic for gases and steam. A multivariable mass vortex meter builds upon the current generation and offers improved accuracy, lower installed cost, and enhanced functionality, including multiple outputs of process conditions. These features reduce total cost of ownership and provide a reliable, accurate instrument for monitoring mass flow rate and other process variables.

The multivariable mass vortex monitors mass flow rate by directly measuring three variables: fluid velocity (**v**), temperature (**T**), and pressure (**P**). The built-in flow computer calculates mass flow rate (**\dot{m}**), density (**ρ**) and volumetric flow rate (**Q**) based on these three direct measurements (see Figure 1).



Three 4-20 mA
analog signals
for a choice of:
 \dot{m} , Q, T, P or ρ

Figure 1 Multivariable Mass Vortex Flow meter

The velocity-temperature-pressure “VTP” sensing head in Figure 1 is built into the body of the meter. To measure fluid velocity, the flow meter incorporates a bluff body (shedder bar) in the flow stream and measures the frequency of vortices created by the shedder bar. A platinum resistance temperature detector (PRTD) measures temperature. Pressure measurement is achieved using a solid-state pressure transducer.

Born in Germany

Velocity measurement is based on the phenomenon of vortex shedding. A vortex is an eddy, or swirl, of fluid. Around the turn of the century, German scientist Theodore Von Karman investigated the vortex-shedding phenomenon, which was later exploited to form the basis for vortex-shedding flow meters. Von Karman demonstrated that when a fluid flows past a non-streamlined body (called a “bluff body” or “shedder bar”) an alternating series of vortices is shed from each side of the body. This alternating series of vortices is termed a “Von Karman Street” (see Figure 3.)

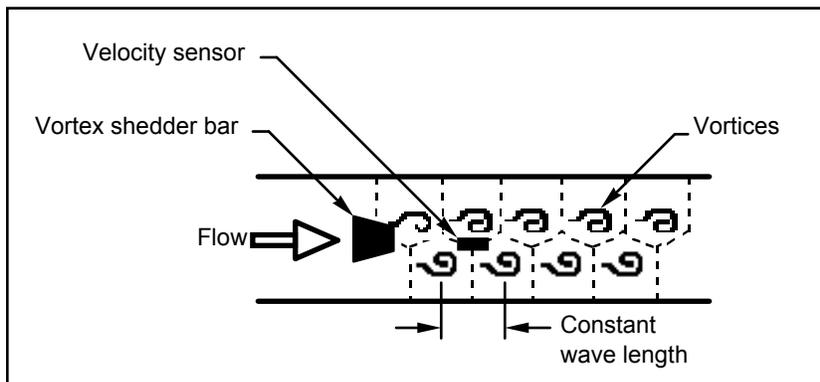


Figure 3: The Von Karman Vortex Street

Various flow meter manufacturers have different shapes of shedder bars. Their common trait is sharp corners, which enhance the strength, or energy, of the vortices and ensure boundary-layer separation at two defined points: the two sharp corners. This feature is responsible for the extra-ordinary linearity of the frequency of vortex shedding over a wide velocity range. Multivariable mass vortex flow meters are available in two configurations:

- In-line flow meter (replaces a section of the pipeline)
- Insertion flow meter (requires a “cold” tap or a “hot” tap into an existing pipeline) Sierra Instruments is the only manufacturer of this configuration.



In-line



Insertion

Both the in-line and insertion configurations are similar in that they both use identical electronics and have similar sensor heads. Besides installation differences, the main difference between an in-line flow meter and an insertion flow meter is their method of measurement.

For an in-line meter, the shedder bar is located across the entire diameter of the flow body. Thus, the entire pipeline flow is included in the vortex formation and measurement. The sensing head, which directly measures velocity is located just downstream of the shedder bar.

An insertion flow meter has its sensing head at the end of a 0.750 inch diameter tubular stem. The stem is inserted into the pipe until the sensing head is properly located in the pipe's cross section. The sensing head fits through any entry port with a 1.875 inch minimum internal diameter.

How It Works: Inside Sierra's Innova-Mass[®] In-line

In the Innova-Mass[®] In-line, the shedder bar is located across the flow meter's diameter, as shown in Figure 4. The vortex velocity sensor is located just downstream of the shedder bar. Von Karman vortices form downstream of the shedder bar into two distinct wakes. The vortices of one wake rotate clockwise, while those of the other wake rotate counterclockwise. Vortices form one at a time, alternating from the left side to the right side of the shedder bar.

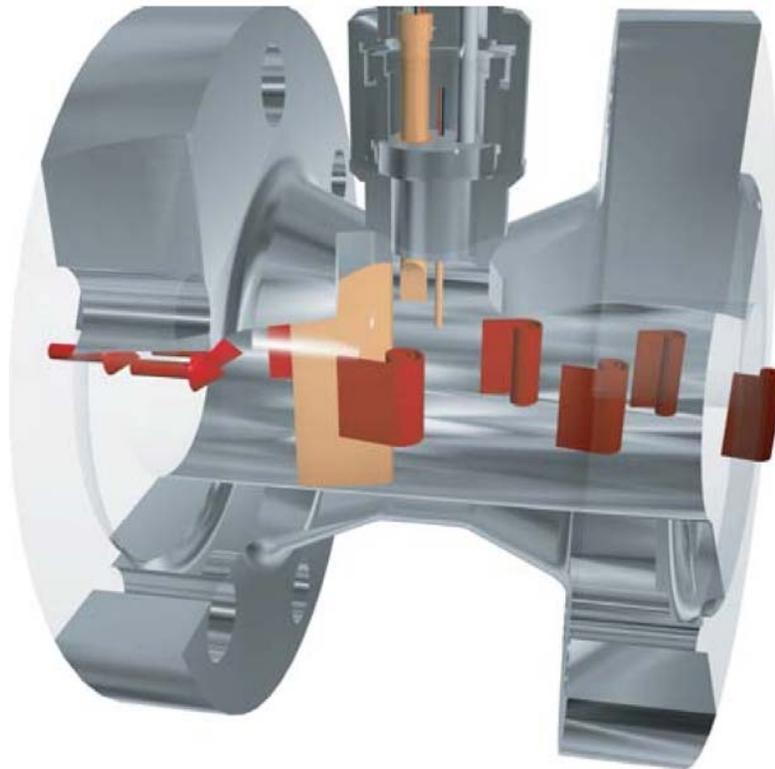


Figure 4: Innova-Mass[®] In-Line Flow Meter with Von Karman Street

They interact with their surrounding space and overpower every other nearby swirl on the verge of development. Thus, the volume encompassed by each vortex remains constant. By sensing the number of vortices per unit time passing (the vortex shedding frequency **f**) by the velocity sensor, the flow meter is able to compute the fluid's velocity **V**. Thus **f** is proportional to **V**. This is the fundamental principal by which a vortex flow meter operates.

Von Karman discovered that the distance between vortices, or the wavelength, is constant for higher Reynolds numbers. The Reynolds number is a parameter used to describe fluid flow. It encompasses the fluid's velocity, density, and viscosity and the pipe's diameter. The Reynolds number is the ratio of the inertial forces to the viscous forces in a flowing fluid and is defined by Equation 1 as follows:

$$(1) \quad Re = (\rho V D) / \mu$$

Where:

Re = Reynolds Number.

ρ = mass density of the fluid being measured.

V = velocity of the fluid being measured.

D = internal diameter of the flow channel.

μ = viscosity of the fluid being measured.

Strouhal, another German scientist, expanded on Von Karman's findings. He discovered that the frequency of the vortices times the width of the shedder bar divided by the velocity of the vortex street was constant for higher Reynolds numbers. The Strouhal number is defined is defined by **Equation 2** as follows:

$$(2) \quad St = (f d)/v$$

Where:

St = Strouhal number.

f = frequency of vortex shedding.

d = shedder bar width.

V = fluid velocity.

As shown in Figure 5, Innova-Mass[®] flow meters exhibit a constant Strouhal number across a large range of Reynolds numbers, indicating a consistent linear output over a wide range of flows and fluid types. Below this linear range, the intelligent electronics in the Innova-Mass[®] automatically corrects for the variation in the Strouhal number. The smart electronics correct for this non-linearity by calculating the

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Reynolds number based on constant values of the fluid's density and viscosity stored in the instrument's memory. Innova-Mass[®] flow meters automatically correct down to a Reynolds number of 5,000.

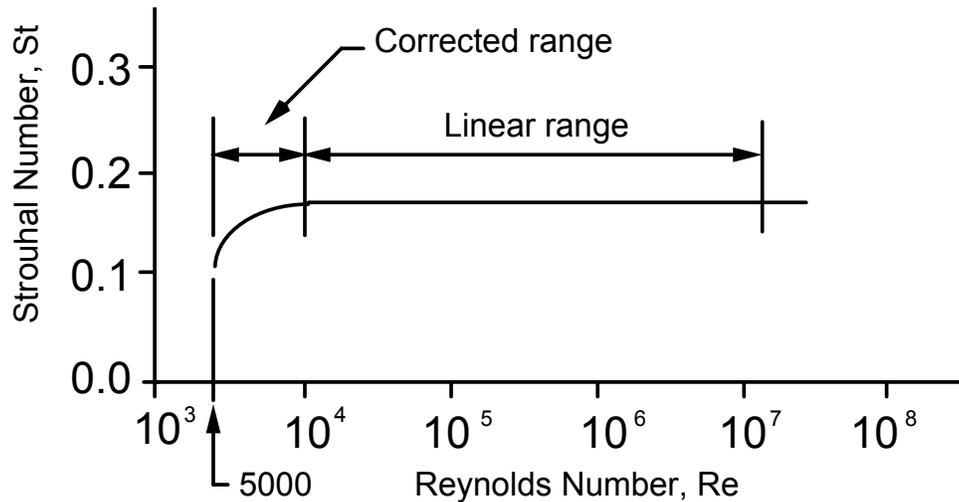


Figure 5: The Relationship between Reynolds number and Strouhal number

The Seven Calculations Performed

1. The sensing head of the flow meter directly measures the fluid's velocity (**V**), temperature (**T**), and pressure (**P**). Then, in real time, the built-in flow computer calculates the following:
2. The fluid density, ρ , using the **P** and **T** measurements and the fluid's equation of state, which is stored in memory. For incompressible fluids (liquids), only **T** is needed for this calculation.
3. The fluid viscosity, μ , using **T** and an onboard equation.
4. The Reynolds number from ρ , μ , and the pipe's inside diameter, **D**, which is stored in memory.
5. A Reynolds number correction factor for low-velocity fluids.
6. The volumetric flow rate, **Q**, from **V** and the pipe's cross-sectional area and the mass flow rate \dot{m} using ρ and **Q**.
7. Three 4-20 mA output signals for the user's choice of three of five variables: \dot{m} , **Q**, **T**, **P**, or ρ .

Multivariable: Measuring V, T & P

As previously discussed, the velocity-temperature-pressure “VTP” sensing head in every multivariable mass vortex flow meter is built into the body of the meter. The following section discussed these measurements in more detail.

Velocity

The velocity sensor in the multivariable mass vortex flow meter consists of a fin immersed in the flow behind the shedder bar. The alternating lift forces created by the vortices cause the fin to deflect back and forth at the exact frequency of the vortices. The fin in the vortex mass flow meter is mechanically connected to piezoelectric elements.

Many techniques have been applied to sense the passage of vortices, including pressure sensors, ultrasonic sensors, capacitance-based sensors, heated thermistors, and strain gauges. Strain-gauge velocity sensors based on the piezoelectric effect have the highest sensitivity and range-ability.

When piezoelectric elements are strained, they produce an electric charge, which is converted to a current. Thus, the output of the velocity sensor is a sinusoidal current with a frequency equal to that of the vortices. Since frequency is the basic output of the velocity sensor, vortex flow meters have zero drift, in contrast to other flow meters with analog sensors.

The fin frequency (pulses/second) is divided by that particular meter’s calibration factor (pulses/cubic foot) and the cross-sectional area (square feet) of the opening to yield the fluid velocity (feet/second).

The insertion Innova-Mass[®] vortex flow meters have the velocity sensor embedded in the shedder bar itself, while the in-line Innova-Mass[®] has its lightweight fin located just behind the shedder bar where the strength of the vortices is highest.

Most real-world industrial pipelines experience vibration caused by pumps, machinery, and flow- induced oscillations. The velocity sensors in traditional vortex flow meters are designed for maximum sensitivity and often pick up the spurious signals generated by pipeline vibrations. The resulting noise creates erroneous vortex frequency signals, which degrade the meter’s accuracy.

Sierra’s Innova-Mass[®] eliminates this problem using a patented “low mass” sensor and sophisticated digital signal processing (DSP). The low mass sensor makes it very sensitive to the vortices formed and less sensitive to heavy vibration while the DSP conditions and filters the signal. The overall result is greater accuracy and reliability, particularly at lower flow rates.

Temperature

An error in measuring the temperature of flowing fluids is another annoying problem in real- world industrial mass flow monitoring systems. Conventional vortex and turbine meter systems and orifice-based systems of either the traditional or multivariable-transmitter variety measure fluid temperature with

a resistance temperature detector (RTD) or thermocouple temperature sensor separately mounted in a heavy-walled thermowell for protection.

Such temperature sensors have high stem conduction and therefore measure a value of flowing fluid temperature that lies somewhere between the actual fluid temperature and the temperature of the pipe's wall. This problem is not so severe in applications where the convective heat-transfer coefficient is high, such as liquid flows and flows at high velocity. On the other hand, the problem is exacerbated in gas and steam flows, especially at lower velocities and at higher temperatures.

The design of the temperature sensor in the Innova-Mass[®] solves this problem. The temperature-sensing element is a 1,000-ohm PRTD—a highly accurate temperature measurement device. This temperature sensor has low intrinsic stem conduction. The result is fast time response and superb accuracy (within 1°C). It is ideal for steam flow and other low-velocity, high-temperature fluid measurements.

Pressure

The Innova-Mass[®] incorporates a solid-state pressure transducer isolated by a 316 stainless steel diaphragm. The transducer itself is micro-machined silicon, fabricated using integrated-circuit-processing technology. A multipoint pressure/temperature calibration is performed on every sensor. Digital compensation allows these transducers to operate within a 0.4% of full-scale accuracy band within the entire ambient temperature range of –20° to +60°C (–4° to +140°F). Thermal isolation of the pressure transducer ensures the same accuracy across the allowable process fluid temperature range of –40° to +400°C (–40° to +750°F).

Why Multivariable?

Some conventional vortex flow meters accept inputs from external temperature and pressure transmitters thereby providing an inferred mass flow rate output. In these conventional inferential mass flow devices, temperature and pressure sensors are located somewhere in the pipeline either upstream or downstream of the vortex flow meter, but typically not at the same location in the pipeline.

This causes errors in calculating fluid density from the temperature and pressure measurements resulting in mass flow rate errors. Extensive testing has revealed that the only acceptable location for accurate temperature and pressure monitoring is just downstream of the shedder bar adjacent to the velocity sensor.

In the Sierra Innova-Mass[®] for example, all three sensors—velocity, temperature, and pressure—are located adjacent to each other in a single sensing head. This integrated multivariable design concept ensures accurate direct mass flow monitoring.

Big Advantages Over Orifice Plates

Every multivariable mass vortex simplifies process measurement because it provides output signals for five parameters: mass flow rate, volumetric flow rate, temperature, pressure, and density. It does this with only one break in the pipeline.

Multivariable mass vortex flow meters combine a differential pressure transducer, absolute pressure transducer, temperature-sensor electronics, and flow computer in one package. Traditional mass flow systems using vortex provide a standard flow measurement, but they require a separate temperature sensor, four invasions of the pipeline, and the installation of tubing, valves, and manifolds.

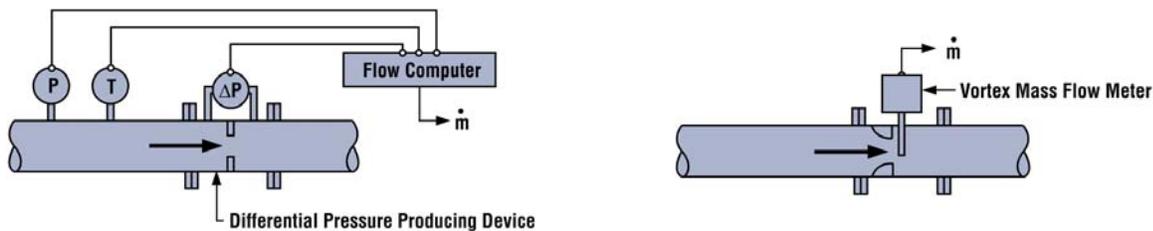


Figure 6. A single device reduces flow meter installation labor and maintenance costs.

When factoring in the cost of installing electrical conduit and wiring and the associated engineering and equipment costs, the Innova-Mass[®] clearly exhibits the lowest total cost of ownership (see Table 1). Accuracy figures are included in Table 1 also.

Cost Element ¹	Traditional Mass Flow System ²	Multivariable Transmitter ²	Innova-Mass [®]
Initial cost			
Flow meter	\$1,200	\$2,500	\$2,500
Flow computer	300	Included	Included
Pressure transmitter	200	Included	Included
Temperature	300	300	Included
Total initial cost	\$2,000	\$2,800	\$2,500
Installation cost			
Flow meter	\$1,500	\$1,500	\$1,000
Flow computer	750	Included	Included
Pressure transmitter	750	Included	Included
Temperature	750	750	Included
Total installation	\$3,750	\$2,250	\$1,000

Annual maintenance costs			
Flow meter	\$200	\$200	\$200
Flow computer	200	Included	Included
Pressure transmitter	200	Included	Included
Temperature	200	100	Included
Total annual	\$800	\$300	\$200
Total cost of	\$6.550	\$5.350	\$3.700
Overall accuracy	+/- 4–5%	+/- 3–4%	+/- 1–1.5%

Notes: ¹Based on average 2008 list prices in U.S. dollars. ²Includes cost for orifice plate and flanges.

Table 1: Cost of Ownership

The Price of Accuracy

When specifying any mass flow meter for an application, the process control engineer must carefully weigh cost versus accuracy. In this deliberation, the proper cost to consider is the total cost of ownership over the flow meter’s lifetime. Therefore, the correct cost includes initial cost, installation cost, and maintenance costs. It also must include operating costs, such as the additional cost of electricity that pumps will require overcoming the flow meter’s permanent pressure loss.

The proper accuracy to select is the accuracy band that is appropriate for the application. Accuracy that is too low will result in unnecessary process costs. Accuracy that is too high means an unnecessarily expensive flow meter. The engineer must find the most cost-effective solution.

Table 2 compares the three major candidates for industrial mass flow meter applications. The table shows that a multivariable pressure transmitter mass flow system has the worst accuracy band (+/- 3–5%) and a moderate total cost of ownership. The Coriolis mass flow meter is the most accurate (+/- 0.2–0.5%) but has the highest total cost of ownership. This is due to its high initial cost and its associated high pressure drop. Coriolis meters trade pressure drop for accuracy. The Innova-Mass[®] has a good midrange accuracy band (+/- 1–1.5%) and a relatively low total cost of ownership. Since most industrial process control applications require an accuracy band of approximately +/- 1–2% of rate, the new flow meter is the most cost-effective solution in approximately 80% of all mass flow meter applications.

Attribute	Multivariable Pressure Transmitter System	Coriolis Mass Flow Meter	Innova-Mass[®]
Accuracy	+/- 3–5% of rate	+/- 0.2–0.5% of rate	+/- 1–1.5% of rate
Cost			
Initial (coriolis = 1)	1/3	1	1/2
Installation	High	Moderate	Low
Maintenance	High	Moderate	Low
Operating	Moderate	High	Low
Total cost	Moderate	High	Low

Table 2: A Look at Accuracy

More on the Innova-Mass® Model 240 and Model 241

As we mentioned in the introduction, Sierra Instruments has taken proven vortex technology and elevated it to the next level. Among the many innovations of the Innova-Mass®:

1. **Patented “low mass” sensor and sophisticated digital signal processing (DSP).** The low mass sensor makes it very sensitive to the vortices formed and less sensitive to heavy vibration while the DSP conditions and filters the signal.
2. **Multivariable:** Measures three process variables (velocity, temperature and pressure- VTP) through one process connection. This allows for the real time calculation of true mass flow. Since everything is calibrated together, system accuracy is very high. Cost of ownership and cost of accuracy is also very low.
3. **Insertion:** Because VTP is directly measured, the Reynolds number can be dynamically calculated and the flow profile effects in large pipes calculated in real time. This allows for reliable measurements in large pipes (up to 72”) where using an in line meter would be cost prohibitive.
4. **Loop powered:** The Innova-Mass® can be loop powered, with power in, programmable 4-20ma out and a superimposed HART signal riding on the same two wires.