

From Disturbance to Measurement: Application of Coriolis Meter for Pattern Identification of Gas Bubbles

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Abstract

Entrained gas has been regarded as disturbance to measurements based on Coriolis meters, since measurement accuracy can be degraded because of this disturbance. Recent research from Endress+Hauser has discovered that different types of gas bubbles, namely free bubbles and suspended bubbles, have various impact on the meter measurement performance. It is crucial to identify the bubble pattern in the measuring tube of a Coriolis meter to make a diagnosis and reduce the negative influence of the disturbance accordingly. For free bubbles that typically cause inhomogeneity of a medium, the fluctuation of the resonance frequency of the measuring tube in a Coriolis meter is directly correlated to the existence of this type of bubbles, since this medium under a flowing condition causes density fluctuation to the meter as gas density is typically much lower than that of a liquid. For homogenous suspended bubbles that lead to a significantly increased compressibility of a medium, the innovative Multi-Frequency Technology in Promass Q sensor offers the means to qualitatively detect the existence of this type of bubbles and quantitatively calculate the volume fraction of the gas phase, based on its ability to derive the speed of sound in a medium containing such bubbles. Identification of the type of bubbles helps not only for crediting the measurement reliability, but also for obtaining more detailed medium properties, and in turn a better process insight, with which a process optimization can be enabled to improve the quality of production.

1. Introduction

In recent decades, Coriolis Mass Flowmeters (CMFs) have been widely used in industry for mass flow and density measurements. The measuring technique has reached a high degree of acceptance and new fields of applications emerge every year. Together with this high acceptance, Coriolis meters are utilized as a multivariable sensor with not only mass flow and density, but also temperature and viscosity measurements [1]. There is a trend to use those additional measured parameters, for example density and viscosity, for monitoring product quality.

Figure 1 shows a typical Coriolis meter, which consists of two parallel measuring tubes, a housing that protects the inner part as well as other components adhering to the measuring tube such as a driver for exciting the tube and sensors for sensing the tube motion. The measuring tube, which in commercial designs can be of various shapes, is the core element of a Coriolis meter. In order to be energy efficient, the tube is continuously

excited at its natural frequency. This measured natural frequency is a function of the medium density in the tube, therefore, forms the basis of the density measurement. The induced tube vibration generates an angular velocity. Together with the mass flow of a medium inside the tube, Coriolis forces are generated, which causes an anti-symmetrically distortion of the tube. The magnitude of this distortion sensed by the sensors is directly proportional to the mass flow rate and forms the basis of the mass flow measurement.

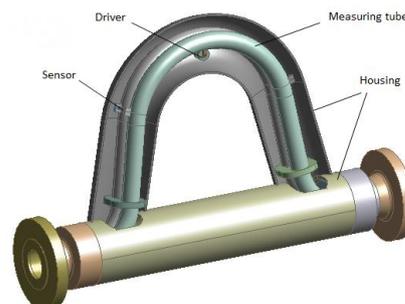


Figure 1: Typical structure of a Coriolis mass flow meter.

Similar to many other measuring principles, it is known that accuracy of a Coriolis meter can be affected by the existence of entrained gas in a liquid flow. A number of research activities have been carried out in the past to understand the error mechanisms of Coriolis metering under two-phase conditions, which is summarized in [2]. According to the effects on Coriolis metering, gas bubbles in liquid flows are classified as “free bubble” and “suspended bubble” that lead to “bubble effect” and “resonator effect”, respectively [3]. Therefore, it is important to detect the existence of entrained gas and identify the type of entrained bubbles that has relevance to the measurement reliability. Furthermore, very often entrained gas bubbles affect product quality in an adverse way, for example in chemical industry when a glue is produced. However, sometimes homogeneous suspended micro-bubbles are wanted as a product feature, for example in food industry when cream cheese is produced. But exactly for this product, big free bubbles are unwanted and regarded as being disadvantageous for product quality. In the meanwhile, the existence of big “free bubbles” also indicates a less optimal manufacturing process, in which the injected gas is not well mixed into the cream cheese for generating homogeneous micro-bubbles. Therefore, the detection of gas bubbles and the identification of the bubble types are crucial for product quality control and optimization of production process.

2. Identification of gas bubbles

2.1 Free bubble

The definition of free bubble is based on the “bubble effect” theory developed by Hemp et al [4]. According to the theory, a free bubble in the measuring tube of a Coriolis mass flowmeter does not strictly follow the oscillation of the surrounding liquid with the same amplitude because the liquid cannot “hold” the bubble well. The amplitude of the bubble is greater than that of the tube vibration. Based on the bubble effect theory, a holding coefficient is defined in Equation (1) to describe the degree of a bubble being “free” in a liquid subject to an oscillation [3].

$$\delta = \sqrt{\frac{\mu}{d^2 f \rho_l}}, \quad (1)$$

where μ , d , f and ρ_l are the viscosity of the liquid, the bubble diameter, the tube vibration frequency and the liquid density, respectively. Following this FLOMEKO 2019, Lisbon, Portugal

definition, the vibration amplitude ratio J between the gas bubble and the measuring tube can be calculated and only the result is given in Figure 2 below.

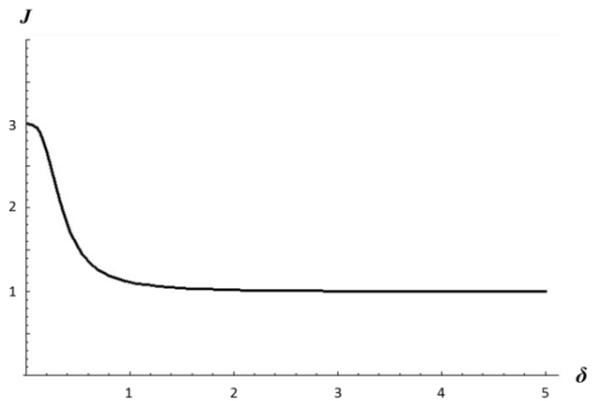


Figure 2: Amplitude ratio as a function of δ .

If the amplitude ratio is 3, the bubble is defined as “free bubble”, as it reaches its maximum vibration amplitude that is different to that of the measuring tube. Deviations for density and mass flow measurements occur due to this difference in vibration amplitude, which is named as “bubble effect”.

If the amplitude ratio is 1, the bubble is defined as “suspended bubble”, as it exactly follows the tube oscillation with the same amplitude and is therefore “held” by the surrounding liquid. Under such circumstance, there is no measurement deviations caused by the bubble effect. However, “resonator effect” that also leads to measurement deviations can become significant for homogeneously distributed suspended bubbles. This effect is discussed in the next subsection.

If the amplitude ratio is between 1 and 3, it is defined as the transition region that is typically of less importance for most practical applications.

It can be seen in Equation (1) that the bubble diameter is the most important parameter that almost dominates the holding coefficient, considering that the other parameters such as density and viscosity can only vary in a limited range for a certain application. Therefore, a free bubble is typically featured with a big diameter as a “big” bubble; while a suspended bubble usually has a small diameter and is known as “small” or “micro” bubble. It should be borne in mind that “big” and “small” here are relative. The precise definition of free or suspended bubble should follow the previously defined holding coefficient.

When practical application is concerned and the source of the generation of different bubble types is also considered, free bubbles are typically discrete and big in size, causing inhomogeneity to the process medium for density, as gas density is usually much smaller than that of a liquid even under a relatively high process pressure. A non-optimal process is very often the source of free bubbles, e.g. batching from empty, or insufficient liquid level such that the downstream pump sucks in air. To detect a medium containing free bubbles, the inhomogeneity of this medium can be used by a Coriolis meter that measures density. A simple density model for a Coriolis meter to measure fluid density is given by

$$\rho = c_0 + c_1 \frac{1}{f^2}, \quad (2)$$

where c_0 and c_1 are density coefficients that are determined by a density calibration and stored in the Coriolis device. The inhomogeneity of the flowing medium causes fluctuation of the density measurement of the meter over time. A derivative with respect to time can be built directly to the above equation, which in turn gives

$$\frac{\partial \rho}{\partial t} = c_1 \frac{-2 \partial f}{f^3 \partial t}. \quad (3)$$

Therefore, a derived parameter I_{FB} , as given in Equation (4), can be defined to indicate the existence of free bubbles.

$$I_{FB} = c_1 \frac{-2 \partial f}{\rho f^3 \partial t}. \quad (4)$$

As f is the resonance frequency of the measuring tube, $\partial f / \partial t$ can be obtained by building the standard deviation of the raw signal f over a certain period, for example, over a second, and ρ can take the average value over the same period.

For practical use, the parameter I_{FB} is actually not only related to gas bubbles, but also to the existence of a second phase that has a different density to the first carrier phase and leads to an inhomogeneous mixture status. A bigger this parameter is, a greater inhomogeneity the two-phase mixture has.

2.2 Suspended bubble

Homogeneous suspended small or micro bubbles are often seen in Food industry, for example in ice cream where gas is injected and well mixed in a form of micro bubble to increase the softness for a better taste of the product; or in Oil&Gas industry,

for example in a heavy oil where the viscosity is high and a lot of small or micro bubbles can be held. Because this type of bubbles is generated often as a product feature or due to the characteristics of the base liquid, the resulted two-phase mixture is usually homogeneous and does not really cause a significant density fluctuation to a Coriolis meter when it is flowing. Figure 3 shows two pictures of typical free bubbles and suspended bubbles.

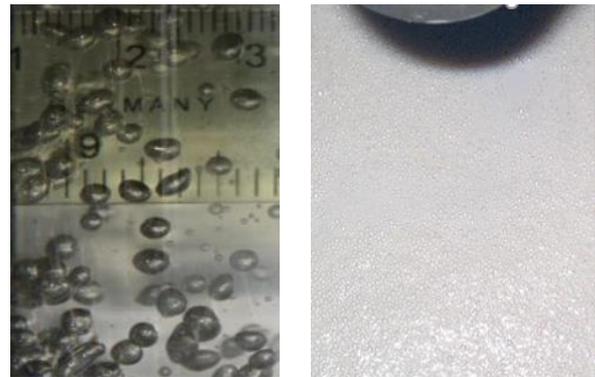


Figure 3: Typical inhomogeneous free bubbles (left) and homogeneous suspended bubbles (right)

Since a medium containing suspended small or micro bubbles is typically homogenous, the method provided in Section 2 is not able to detect such type of bubbles. However, the recently developed Multi-Frequency Technology (MFT) [3] in the Coriolis sensor, Promass Q, enables the possibility. This technology is invented to cope with the resonator effect that is related to the compressibility of a medium for a Coriolis meter. The detailed explanation of the resonator effect is given in [2]. For convenience, its basic theory is briefly presented again in this paper.

It has been known that speed of sound in a gas-liquid two-phase mixture is calculated by the following equation:

$$c = \left(\frac{\alpha}{c_g^2} + \frac{(1-\alpha)^2}{c_l^2} + \frac{\alpha(1-\alpha)\rho_l}{\gamma P} \right)^{-\frac{1}{2}}, \quad (5)$$

where c , α , ρ , P and γ are speed of sound, Gas Void Fraction (GVF), density, pressure and the adiabatic constant. The indices g and l represent gas phase and liquid phase, respectively. Equation (5) is plotted in the figure below. It can be seen that speed of sound decreases significantly even a small GVF is present. The lowest acoustic resonance frequency of a fluid in a tube f_0 is determined by

$$f_0 = c \frac{\lambda_1}{2\pi R_0}, \quad (6)$$

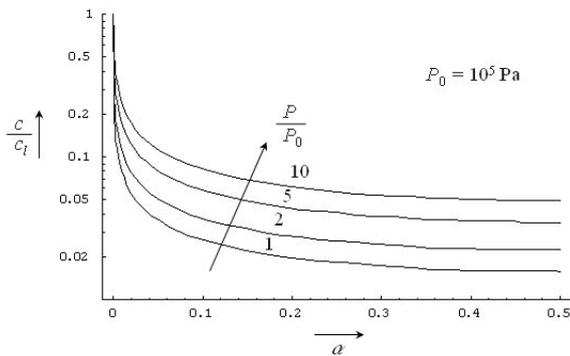


Figure 4: speed of sound as a function of GVF and pressure

where λ_1 is the lowest eigenvalue, and R_0 is the radius of the tube. Therefore, f_0 reduces with a reduced speed of sound when gas is present in a liquid. Typically, the speed of sound in a single-phase fluid is relatively high, such that the corresponding f_0 is also high, for example of the order of 10^4 Hz. Its distance to the tube resonance frequency f is too big to cause any noticeable deviation for Coriolis density measurement. However, it is not the case when GVF starts to increase from zero. The measurement deviation can be calculated by

$$\rho_a = \rho \left(r_0 + r_1 \frac{1}{1 - \frac{f^2}{f_0^2}} \right), \quad (7)$$

where ρ_a is the apparent density reading from the Coriolis meter, r_0 and r_1 are constants.

With MFT, the two measuring tubes in the meter are excited for the basic tube mode and a higher tube mode simultaneously, as depicted in Figures 5 and 6. It should be noted that the two modes have two different resonance frequencies. For each mode, an independent density measurement can be performed for the same medium inside the meter. Therefore, Equation (7) can be established twice, as given by

$$\rho_{ai} = \rho \left(r_0 + r_1 \frac{1}{1 - \frac{f_i^2}{f_0^2}} \right), \quad (8)$$

where $i = 1$ and 2 , corresponding to the basic mode and the higher mode, respectively. Combining the two equations of the modes leads to a solution of f_0 , and the true density of the two-phase mixture ρ . The latter is used as the output of the density FLOMEKO 2019, Lisbon, Portugal

measurement of Promass Q with MFT, instead of an apparent density reading without the correction for the resonator effect. It should be noted that mass flow measurement is also affected by suspended bubbles in a similar way. As a matter of fact, this influence on mass flow measurement is eliminated with the help of MFT in Promass Q, similar to that for density measurement.

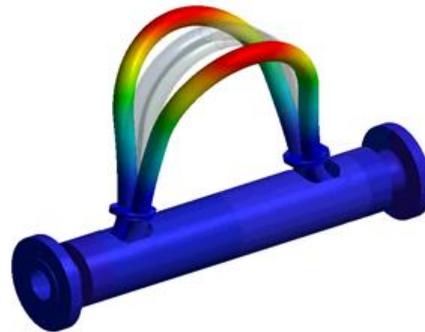


Figure 5: Modal shape of the basic tube mode in numerical simulation (shown in heightened form)

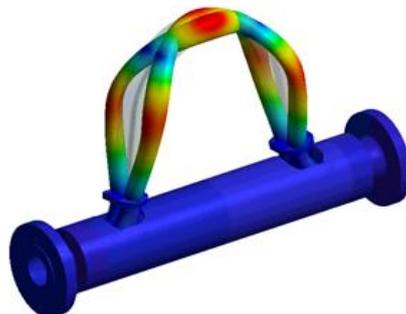


Figure 6: Modal shape of the higher tube mode in numerical simulation (shown in heightened form)

It is interesting to see that the measured apparent density can be different for the two modes, because of the different driving frequencies. Table 1 gives a calculation example of a DN50 meter for the measured apparent densities under the two tube modes of MFT. The tube radius is assumed to be 0.014 meter, and the medium density is 1000 kg/m^3 . The tube mode frequencies are fixed for the calculation for simplicity, although they can slightly vary for the two conditions, i.e. speed of sound 1400 m/s and 100 m/s respectively, in this example.

Table 1: Example of measured densities for the two modes of a DN50 meter

Medium density	f1	f2	c	f0	f1 mode apparent density	f2 mode apparent density
[kg/ m ³]	[Hz]	[Hz]	[m/s]	[Hz]	[kg/ m ³]	[kg/ m ³]
1000	200	1200	1400	29316	1000.04	1001.40
			100	2094	1007.71	1409.27

The calculated results show that for case 1, where speed of sound is 1400 m/s like in water, the Coriolis meter measures the density effect of the medium with only a deviation of 0.04 kg/m³ with the basic mode, which is the basic working mode of a Coriolis meter. It should be noted that this small density deviation is not shown in the final Coriolis density measurement because a factory calibration with a correction reference density already includes this effect and thus eliminates this influence. With the higher mode, the apparent density has a deviation of 1.40 kg/m³, which is still considerably small for such a single-phase medium. However, when entrained gas is present, the speed of sound can significantly drop, for example to 100 m/s as previously introduced, the Coriolis density measurement will show a deviation of 7.71 kg/m³ with the basic mode, and a deviation of 409.27 kg/m³ with the higher mode. The effect can be so strong for suspended bubbles that an indicator for the detection of such bubbles can be built based the measured density difference, as shown by

$$d\rho = \rho_{a2} - \rho_{a1}. \quad (9)$$

It has been proven by experimental data that $d\rho$ is a very sensitive indicator for homogeneous suspended bubbles. However, using $d\rho$ for the detection does not directly show how much gas content there is, and also normal users have no direct physical feeling with this parameter. Therefore, an intuitive indicator is of more practical use and has been developed.

It is shown by Equation (6) that the speed of sound c can be obtained with the help of the knowledge of f_0 , which is the outcome of Equation (8) with MFT. The GVF of the homogeneously distributed suspended bubbles can then be derived by using Equation (5). Certain simplification can be made to this equation to facilitate the GVF calculation. As explained, MFT directly outputs the true mixture density for a medium with suspended bubbles. It is known that a two-phase mixture density is calculated by

$$\begin{aligned} \rho &= \rho_l(1 - \alpha) + \rho_g\alpha \\ &\approx \rho_l(1 - \alpha). \end{aligned} \quad (10)$$

Therefore, Equation (5) can be rewritten as

$$c = \left[\frac{\alpha}{c_g^2} + \frac{(1 - \alpha)^2}{c_l^2} + \frac{\alpha\rho}{\gamma P} \right]^{-\frac{1}{2}}. \quad (11)$$

Equation (11) enables a solution of α , the gas content of suspended bubbles, based on the knowledge of the fluid properties of the gas and the liquid phases, together with the pressure in the measuring tube of the meter.

For the purpose of detection, the corresponding indicator can thus be defined as

$$I_{SB} = \alpha. \quad (12)$$

3. Application of the two indicators

To validate the two derived indicators, a field test was performed in one application in Chemical industry, where a chemical material in a big tank is processed and then pumped into smaller containers in small batches, as depicted in Figure 7. This product captures large amount of suspended micro bubbles during the manufacturing process because of its high viscosity. In the meanwhile, free bubbles can exist when the liquid level in the big tank is so low that the pump starts to suck in air. For the sake of product quality, entrained gas, no matter suspended bubbles or free bubbles, should be removed to a minimum level. Therefore, it is crucial to identify the bubble type, because the identification provides the process insight, enabling the possibility for process optimization based on this information. If certain amount of homogeneous suspended micro bubbles is detected, which is above the allowed threshold, a corresponding measure, for example more vacuum time in the tank to extract bubbles out of the liquid, should be applied to improve the product quality. On the other hand, the detection of free bubbles indicates an insufficient liquid level in the big tank and requires corresponding operations to handle this problem, for example, raising the liquid level in the tank.

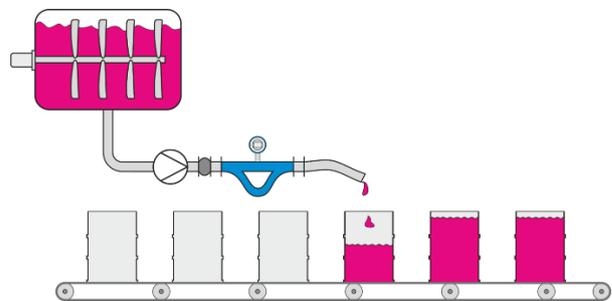


Figure 7: Production process

To generate unwanted process conditions that lead to bad product quality, two scenarios were created for the validation test: 1) low liquid level in the tank for some batches to generate free bubbles; 2) less vacuum time than the normal one applied in the tank

for some batches to generate suspended bubbles. The test results shown in Figures 8 and 9 clearly validated the ability of the two indicators for the detection of corresponding bubble pattern: the red markers represent the upset conditions, and the indicators accordingly gave high values than the others under normal conditions.

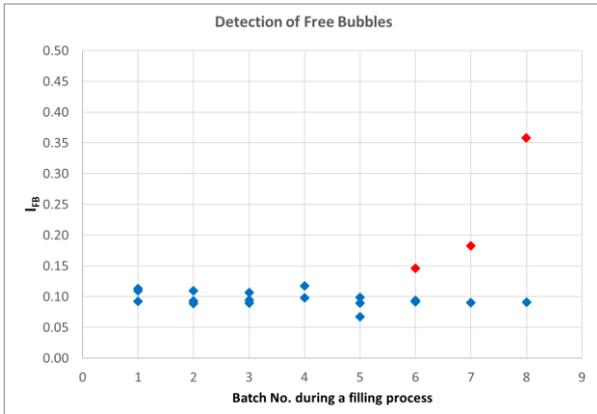


Figure 8: Detection of free bubbles (red: low liquid level)

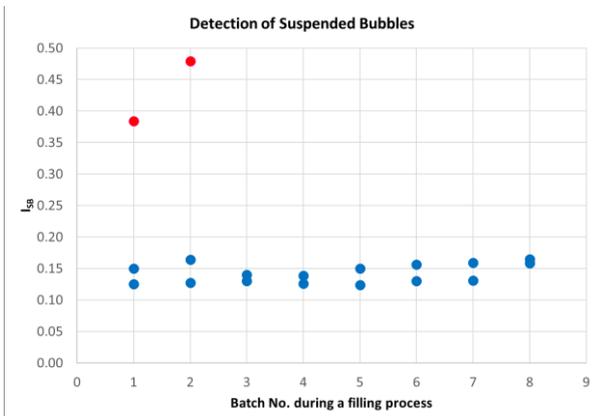


Figure 9: Detection of suspended bubbles (red: less vacuum time)

4. Conclusion

Free bubbles and suspended bubbles have different influence on Coriolis metering, and also cause the corresponding changes of different measurement signals. Free bubbles typically lead to an inhomogeneous density reading of a Coriolis meter when the medium is flowing, which can directly be used for the detection. A unique feature of MFT in Promass Q enables the quantitative calculation of the amount of suspended bubbles, although they are usually homogeneously distributed and show a constant medium density to the meter. Identification of the type of bubbles helps not only for crediting the measurement reliability, but also for obtaining more

detailed medium properties, and in turn a better process insight, with which a process optimization can be enabled to improve the quality of production.

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