From Flowmeter to Advanced Process Analyzer

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Abstract
Flowmeter used to measure one process parameter: the flow rate of the fluid. Accuracy, robustness and interconnectivity have been a main focus of new developments in the past.
With the availability of enormously increased computation power the trend has shifted in the direction of diagnosing the industrial process in more detail rather than measuring the one flow parameter only. Flowmeter develop into important process analyzer and give a better knowledge of the process condition. For a specific application one chose in the past a flowmeter that was suitable according to the flow range and accuracy. With the possibility to get in addition diagnostics features the selection of the right flowmeter becomes a more important and challenging task. This paper presents flowmeters and their additional measurement possibilities.

1. Introduction and Motivation
In the last decade the process industry has seen a move away from single measurement devices towards those with extended functionality added on top of the primary measurement. The reason for this is twofold: On the one hand cost pressure forces companies to operate their equipment as efficient as possible. This means that the reliability of their sensors needs to be as high as possible, as malfunction or misreading lead to suboptimal operation. On the other hand added functionality allows to measure process parameters, which are not necessarily related to the primarily measured quantity, but still are of importance in order to control the process. A typical example is the minimization of downtimes. Maintenance or cleaning shutdowns should be avoided if not necessary. A predictive maintenance plan, based on the state of the facility and an asset management strategy is becoming more important. This requires the self monitoring of the devices for current or expected future malfunction or failure. But in addition the sensors can also predict malfunctions in other parts of the process, e.g., due to a coating of the pipes. This can be reached without the installation of additional sensors.
Diagnostic functionality has also been driven by customers namely in the NAMUR committee that writes the requirements for conform instrumentation devices [1]. The availability of enormously increased computation power on the device makes it possible to implement more advanced signal processing algorithms on the device. Detailed simulations allow a better understanding of the physical processes in the device and the process. This is necessary because the signals needed for diagnosing the process are mostly secondary effects that are often suppressed in conventional instruments to measure the primary process parameter.

2. Design Methods
Measuring more than flow rate can be achieved by adding more sensors to the flowmeter. Unfortunately this results in higher cost for the flowmeter and reduces the reliability. We will show methods to measure variables beside the primary variable flow rate without changing the primary sensing element.
The methods used for measuring more than one process variable are very individual. It is required that the sensor is well understood also under different operating conditions than those needed to measure only the primary variable. More powerful simulation means are an important part of the design process to find additional measures for the process. Based on measurements and simulations a device model can be derived that shows characteristics of secondary measurement values. The behavior are analyzed and modeled in the frequency domain with techniques like impedance spectroscopy or in the time domain like stochastic methods. Often it can even be a combination of the frequency and time domain. Depending on the computation power on the device the algorithms are based on statistical analysis or with more computation power even impedance tomography is used.
Using as example a magnetic flowmeter, a thermal mass flowmeter and a vortex flowmeter we will show how to achieve the measurement of more than one variable without adding sensors.

3. Process Control Based on Magnetic Flowmeter

The magnetic flowmeter principle is based on a magnetic field and the Lorentz force on a moving fluid in order to measure the velocity of the medium and determine from this the volume flow through a pipe. They are robust devices without any moving parts and can be used as long as the conductivity of the fluid is sufficiently large. Fig.1 shows the physical principle of the magnetic flowmeter.

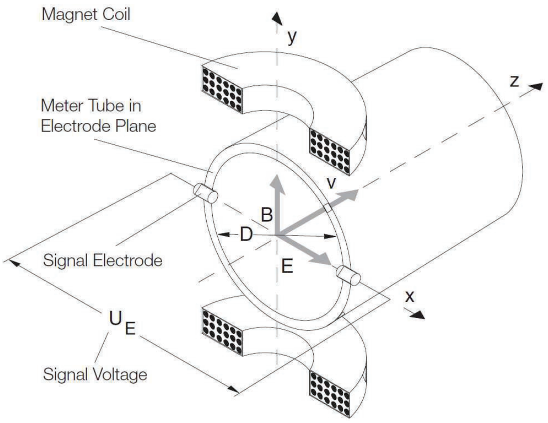

Fig. 1: Magnetic flowmeter measurement principle: The induced signal voltage U_E is directly proportional to the magnetic induction B, electrode spacing D and the fluid velocity v.

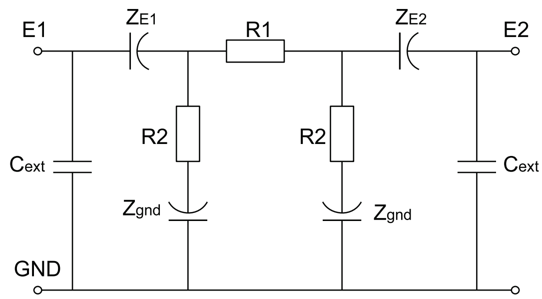

Fig. 2: Lumped diagram model for the transducer showing the bulk resistors of the fluid together with four CPE elements describing the electrode-electrolyte interfaces of the two measurement electrodes and ground. Also added are two external capacities coming from the measurement setup.

Diagnostics functionality can be applied to control the correct operation of the magnetic flowmeter, as well as, to determine additional process parameters. Two such functions have been developed and implemented [2] for the ABB process master flowmeter using as the basis the electric network build up by the two electrodes and the ground. Using electrical impedance spectroscopy the magnetic flowmeter transducer has been analyzed. The main components of the electrical circuits have been identified as the bulk resistances and the electrode-electrolyte boundaries, which were described by the phenomenological Constant Phase Element. A fit of the proposed lumped diagram (Fig. 2) and electromagnetic simulations confirmed this analysis. Based on this model it is possible to measure the conductivity of the fluid independent of electrode effects. For the coating detection changes of the electrode elements have been investigated. It has been seen that conductive and nonconductive coatings change the parameters of these elements and can therefore be used for detection.

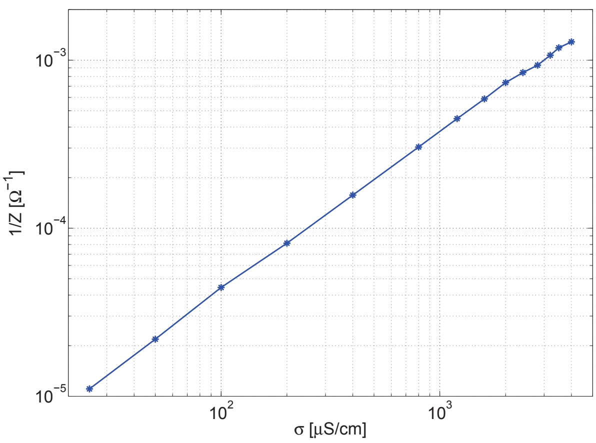

Fig. 3. The impedance value Z extracted from the flowmeter transducer is shown as a function of the conductivity of the medium. The almost linear behavior between the two can be used to determine the conductivity from the value of Z over a wide range.

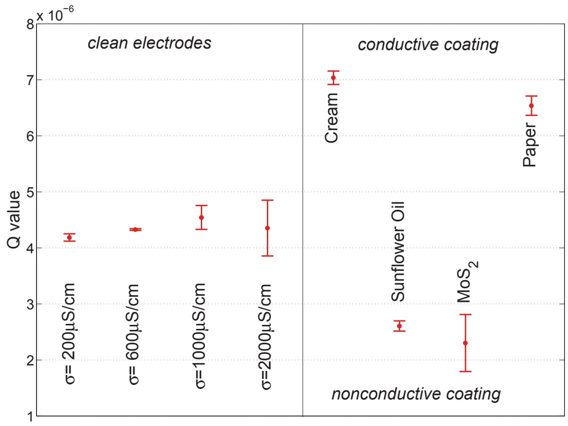

Fig. 4. Comparison of the parameter of the electrode model for different conductivities and coatings. Whereas the parameter is almost independent of the conductivity, nonconductive and conductive coatings can be distinguished

Magnetic flowmeter require for their operation a conductive medium. The determination of the conductivity of the medium to be able to signal a too low conductivity is therefore important. This prevents mismeasurement of the flow. But the conductivity can also be used as a process parameter, allowing the operator to distinguish between different fluids, for example, a process versus a cleaning fluid, or to monitor the fluid for changes in their properties, e.g., some salt concentration. Coating of either the electrodes or the liner is a problem in some applications. Nonconductive coating can cover the electrodes with a layer of low conductivity material, which ultimately interrupts the flow measurement. A conductive coating on the other hand covers the liner and leads ultimately to a short circuit between the two electrodes and ground. Detecting a coating is not only important for the self diagnostics. Coating does build up not only in the flowmeter, but will cover also other parts of the system and can then lead to a clogging of pipes. Therefore the detection of coating is of interest, e.g. to schedule maintenances even if it is not directly related to an error in the flow measurement.

Gas bubbles in liquid media are an important and searched-for indicator for the process quality. The reason for gas content in a liquid process can be a chemical reaction, cavitations at inlets or outlets or leakage due to the tubing. Another important area is the detection of air entrainment, e.g., when emptying storage containers, where air bubbles can damage or even destroy the pumps. The detection of such gas or alternatively also of solid particles in a flowing liquid is not possible with the classical instrumentation technology. The detection enables a fast stop of the process and saves cost immediately.

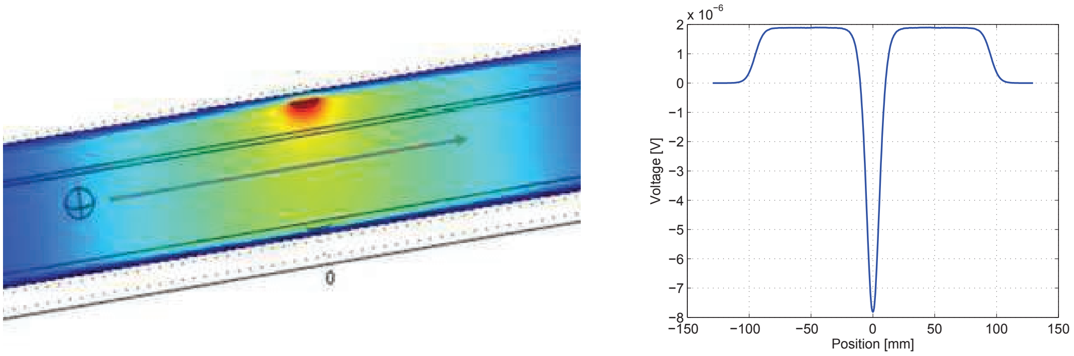

Fig. 5: The field distribution in a magnetic flowmeter is shown on the left together with an air bubble,. The moving gas bubble in the flow path influences the field in the flowmeter. The resulting electrode potential fluctuates as a function of the position of the gas bubble on the right.

It has been shown that the detection of gas bubbles based on statistical signal processing [3] and wavelet transform [4] is possible. The algorithm with the best performance to computational complexity has been selected and implemented on the ABB Process Master platform. First tests in the field successfully verify the high performance of the diagnostics feature. First products are being introduced to the market [5].

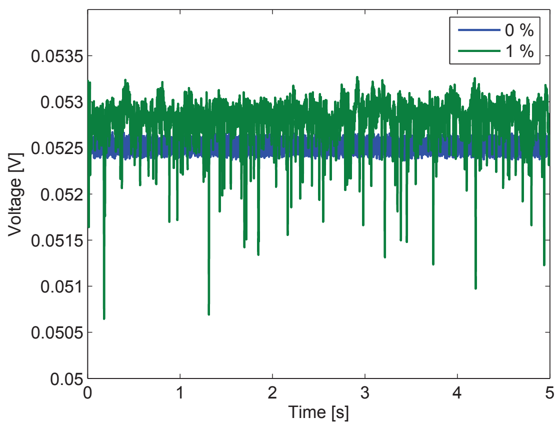

Fig. 6: Product demodulated signal on the second flowmeter electrode with a pure conductive liquid and with an addition of 1% of gas bubbles at a flow rate of 2.5m/s

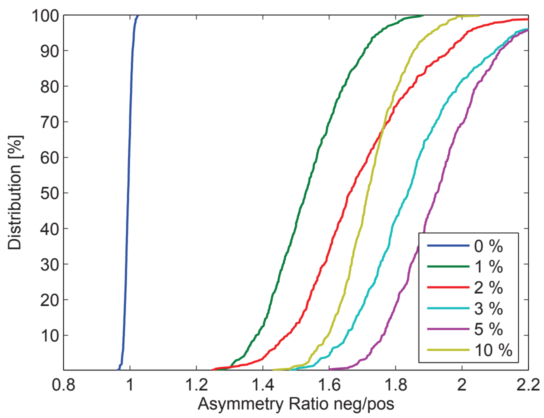

Fig 7: The cumulative distribution functions of the signal from the statistical signal processing, which is then used for a statistical test to distinguish between gas and no-gas content in the liquid

The basic measurement principle is shown in Fig. 5 with experimental results given in Fig. 6. Fig. 7 shows that the pure gas bubble detection with an algorithm that analyses the asymmetric behavior of the product demodulated signal according to [3] is very reliable. There is no overlap of the cumulative distribution functions for a pure liquid and a liquid with gas content. The measurement of the exact gas content on the other hand is difficult, seen also in the overlap of the distribution functions. The signal depends on the size of the gas bubbles which is defined by many parameters e.g. surface tension, viscosity, velocity and pressure.
Conventional magnetic flowmeter have two electrodes to measure the induced voltage and determine the flow rate. More advanced magnetic flowmeter make use of multiple electrodes. For example a “Top Electrode” is applied in addition to detect if the flowmeter is not completely filled, which indicates a mismeasurement of the flow but also a severe process failure.
The availability of multiple electrodes allows additionally to measure flow rate in partial filled pipes. This technique is commonly used in waste water applications, where the flow rate to be handled varies significantly. To measure at partial filling provides a better dynamic measurement range and especially high resolution at lower filling level which is the normal operating area of many waste water applications. Flow velocity and filling level can in addition be used to control the process. While flowmeter with two electrodes allow measuring the conductivity with a relative accuracy of up to 5%, four electrodes provide an even higher measurement accuracy. Multiple electrodes even allow measuring the flow profile of the liquid in the flowmeter. If the flow profile is not symmetric the measurement of flow rate can be disturbed. The reason for this can lie in a not correctly mounted flowmeter, coatings and fouling of the inner surface and obstacles or sedimentation in the flow path. Some patents and papers describe the use of multiple electrodes for measurement of viscosity. The trend to more computation performance will allow applying techniques like impedance tomography for measurement liquid level, flow profile and sediments in advanced magnetic flowmeter shown in [6].

4. Process Control with a Thermal Mass Flowmeter

Thermal mass flowmeters are widely used for applications in all industrial fields demanding fast and precise gas flow measurement [7], e.g. chemical, environmental and process engineering industries, food and beverages industries, or the automotive industry.
The measurement principle of the thermal mass flowmeter relies on a heated element in the fluid flow. The thermal impedance (ratio of over-temperature ΔT over required heating power P) of the heated element is a function of heat transfer coefficient, which is a function of the fluid flow. Beside the primary value mass flow rate the flowmeter provides temperature of the fluid, being an important value in many applications.
The flow measurement is strongly disturbed, if the flow medium causes coating on the sensor head. Examples in the industry are carbon-particulate emission (soot), condensed water or dust. Chemical aggressive gases or granules on the other hand can affect the surface of the sensor, e.g., by abrasion.

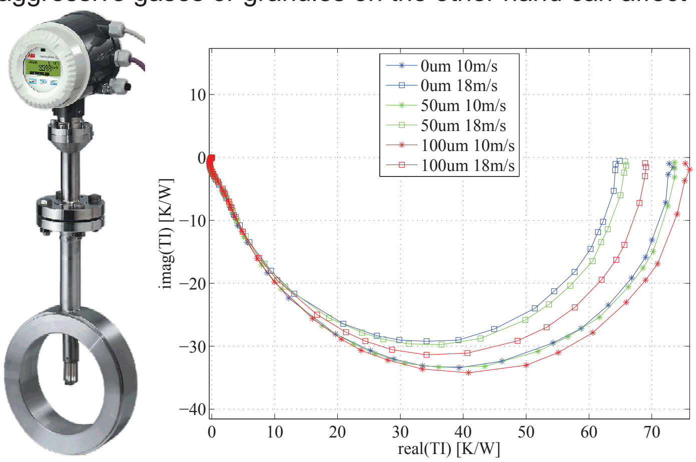

Fig. 8: Isolating coating on the surface of a thermal mass flowmeter can be measured. The effect of flow rate and fouling can be seen in the thermal impedance of the sensing element which is in this case a temperature dependant platinum resistor.

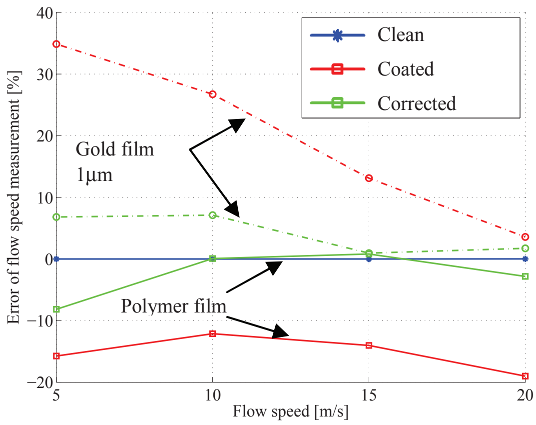

Fig. 9: Deviation of the thermal mass flowmeter for different coating layers with and without diagnostic algorithm.

It has been shown [8, 9] that the measurement of thickness of deposition on the sensing element is measurable with a thermal mass flowmeter without any additional sensors. A coating on the sensor causes a change of the heat transfer coefficient and therefore an error in the flow measurement. It can be shown [8, 9] that one of the dominant effects of coating is a change of the sensors heat capacity. This increase is visible through a change of the thermal impedance in the AC-domain seen in Fig. 8. Based on measurements and simulations, a simplified physical model has been developed. This model is able to separate the effect of coating from the effect of a flow rate change based on the thermal impedance at one single frequency. Using this model an algorithm that can detect the coating of the sensing element has been developed. With a known material the coating can be measured down to sub µm of deposition thicknesses, corresponding to a flow measurement error in the order of a few percent, as shown in Fig. 9. In addition a control algorithm was developed, which allows an undisturbed concurrent measurement of the fluid velocity while diagnosing the coating on the sensor surface.

5. Process Control with a Vortex Flowmeter

Vortex flowmeters have been successfully used as industrial flow rate sensors for roughly thirty years from now [10, 11]. Fig. 10 shows the measurement principle of a vortex flowmeter. When the fluid flows through the pipe and passes the bluff body vortices are generated that are measured with a sensor, which in this device is a piezo-sensor.

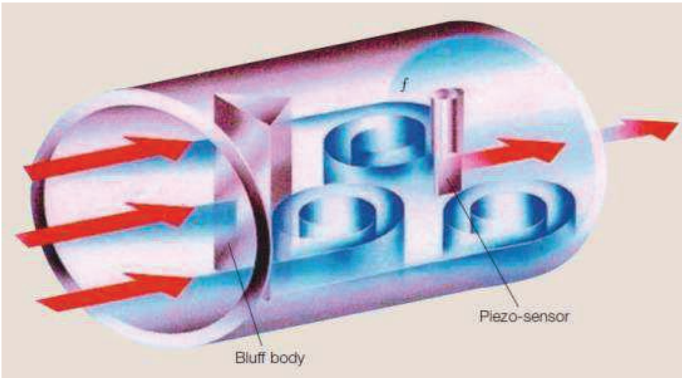

Fig. 10: A graphical illustration of the vortex flow measurement principle

The frequency f of vortex shedding is proportional to the flow velocity v and inversely proportional to the width of the solid body d:

$$f = St \times v / d$$

St, known as the Strouhal number, is a dimensionless number which has a decisive impact on the quality of vortex flow measurement. If the solid body is dimensioned appropriately, the Strouhal number St will be constant across a very wide range of the Reynolds number Re. Therefore vortex flowmeter measure volume flow rate independent of density and viscosity of the fluid.

Due to cross-sensitivities to vibrations the piezo-sensor measures not only the frequency of the vortices but also vibrations on the flowmeter which are often caused by pumps.

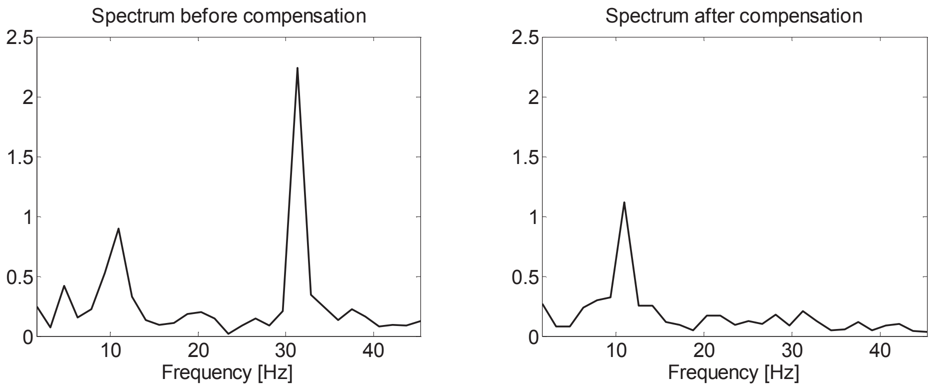

Fig. 11: Frequency spectrum of a vortex flowmeter piezo sensor with a pump vibration before and after compensation.

Pumps are used to transport liquids in continuous processes but due to abrasion and coatings they age over time. One indication of their upcoming failure is the increase of vibrations. It has been shown in [12] that a measurement of system vibration and their compensation using a vortex flowmeter is possible. The signal of vortices is different from the signals due to vibration because their phase is not constant over time and does intrinsically fluctuate. A compensation of the piezo signal is shown in Fig. 11. The information of vibration can be used to monitor the pump system. Additionally it has been shown in [13] that pressure fluctuations can be seen with a vortex flowmeter with an analysis of the frequency spectrum.

6. Summary and Conclusion

Flowmeter used to measure one process parameter: the flow rate of the fluid. With the availability of enormously increased computation power the trend has been shifted in direction of diagnosing the industrial process in more detail rather than measuring the one flow parameter only. Without adding additional sensors to the flowmeter but with signal processing in time domain and frequency domain it is possible to measure more process variables. The computation power enables the design of more complex algorithms based on device simulation and physical models describing the behavior also for secondary measurements. The measurement of more than one variable has been shown using as examples a magnetic flowmeter, a thermal mass flowmeter and a vortex flowmeter. A magnetic flowmeter enables to measure coating of the tubing, provides the conductivity of the liquid and detects gas bubbles in the fluid. Multiple electrode flowmeters can even measure liquid level and flow profiles. Thermal mass flowmeter could measure down to sub μm of deposition thicknesses. Vortex flowmeter would allow to measure vibrations on the tubing which could indicate a failure of a pump. First multivariable measurements based on more advanced signal analysis are being introduced to the market. Other techniques have been presented in papers. A trend from flowmeter to process analyzer becomes apparent.

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