A SEVA SENSOR - THE CORIOLIS MASS FLOW METER

M. P. HENRY.

Engineering Science Department, Oxford University, Oxford OX1 3PJ, UK.

Abstract. The SEVA approach to instrument validation (Henry and Clarke 1993) advocates exploiting the manufacturer’s knowledge of an instrument to detect faults internally, while describing the impact on each measurement in generic, device-independent terms (including the dynamic uncertainty). The Coriolis Mass Flow Meter is a sophisticated sensor, measuring the mass flow rate, density and temperature of the process. It is a resonant device, providing a rich set of internal signals ideal for an internal fault detection scheme. The coriolis meter is a challenging candidate for developing a SEVA instrument: on the one hand there are many internal signals providing diagnostic data; on the other, there is the need to assess the impact of any fault upon at least three measurements. This paper describes a prototype SEVA coriolis mass flow meter.

Keywords. Coriolis Meter, FDI, Sensor Fault Detection, Uncertainty, Sensor Validation.

1. INTRODUCTION

The SEVA approach to instrument validation (Henry and Clarke 1993) distinguishes between a sensor fault and the impact that the fault has upon the sensor’s measurements. It advocates exploiting the manufacturer’s knowledge of an instrument to detect faults internally, while describing the impact of each fault on each measurement in generic, device-independent terms (including the dynamic uncertainty). This contrasts with more conventional approaches, which are typically based outside of the sensor and which apply generic methods (e.g. model-based FDI) to measurement signals to detect device-specific faults.

The Coriolis Mass Flow Meter is one of the more sophisticated instruments for measuring physical parameters, and is used in the petrochemical, paper and food industries. Typically, it generates three measurements - mass flow, density and temperature, but additional parameters, such as volumetric flow and total flow, may also be provided. The principle of Coriolis acceleration is used to measure the mass flow of the process fluid directly, without the need for external pressure, temperature or specific gravity measurements. Particularly attractive features of coriolis meter technology are high accuracy (up to 0.2% of flow rate is claimed), and the ability to deal with 'difficult' fluids such as slurries and food products.

The coriolis meter is a resonant system, providing a rich set of signals (only some of which are directly related to the measurements) which may give indications of fault modes to an internal fault detection scheme. As virtually all commercial coriolis meters are microprocessor-based, such schemes are easily implemented, and self-diagnostics are becoming a common feature in 'intelligent' instruments.

The coriolis meter is an interesting and challenging candidate for developing a SEVA prototype: on the one hand there are many internal signals providing diagnostic data; on the other, there is the need to assess the impact of any fault upon at least three measurements.

This paper describes an on-line PC-based prototype system attached to a commercial coriolis meter which provides self-validating features. Two faults are presented. The first is the loss of the temperature signal, which is used to illustrate some of the basic SEVA concepts, and in particular how to assess the impact of a simple, single fault in a multi-measurement instrument. The second fault is the loss of a coriolis driver, which affects the mass flow measurement alone.

2. THE SEVA SENSOR

The starting point for the SEVA sensor is the state-of-the-art intelligent instrument with an embedded microprocessor (performing measurement calculations and diagnostics) and an interface to a digital communications system such as Fieldbus (Henry and Wood 1992).

A SEVA sensor employs self-diagnostics, but provides extra stages of processing. If a fault occurs its impact on each measurement is assessed, and the measurement is corrected if necessary. Validity indices are generated which describe the resulting quality of each
The definition of uncertainty is further extended to include the impact of any sensor faults on the measurement.

The standards provide a rule for calculating the uncertainty of arbitrary functions. Given the uncertainties of \(x\) and \(y\), say, we can calculate the uncertainty of \(R\), where \(R = f(x, y)\), using the following sum of squares formula:

\[
\delta_R^2 = \left(\frac{\partial R}{\partial x}\right)^2 \delta_x^2 + \left(\frac{\partial R}{\partial y}\right)^2 \delta_y^2
\]

For example, if \(x\) is volumetric flowrate, \(y\) is density, and \(R\) is mass flowrate, then \(R = xy\), and the uncertainty in \(R\) is given by \(\delta_R^2 = y^2 \delta_x^2 + x^2 \delta_y^2\). So, if vol. flowrate = \(2.0 \pm 0.04\) litres/s, and density = \(1000.0 \pm 30\) kg/m³, then the mass flowrate = \(2.0 \pm 0.072\) kg/s. Note that the uncertainty of \(R\) depends not only upon the uncertainties of \(x\) and \(y\), but will change dynamically with \(x\) and \(y\) themselves. Using this calculus it is possible to assess the uncertainty of any process or plant parameter which is inferred from sensor measurements.

The Validated Uncertainty provides the major indicator of the quality of the Validated Measurement Value. The VMV itself is a 'best estimate' of the current value of the measurand. Under normal conditions it is calculated using the latest data from the transducer, but this is not always the case. If a minor fault affects the sensor then a correction may be applied, and if a major fault occurs then the VMV may be calculated by projection from historical data. While the VU will increase to accommodate the reduced accuracy of such estimates, by itself it cannot indicate that the current VMV is, say, based on historical rather than live data. This information may be important to the control system, which would not wish to continue feedback control based only on historical data. A second, discrete, validity index is also generated with each VMV to inform the control system in effect 'how this VMV was calculated', and this parameter is called the Measurement Value Status.

2.2. Measurement Value Status

There are six possible values of the MV Status, corresponding to six different scenarios for how the VMV has been generated. The principal four values are named after a visual analogy:

- **CLEAR** indicates that there is no fault, and that the VMV has been calculated normally from the latest transducer data.
- **BLURRED** indicates that the measurement has been partially impaired by the presence of a sensor fault, and that a correction has been applied in the calculation of the VMV. The VU is increased appropriately to indicate the reduced accuracy of the estimate.
- **BLIND** indicates that a diagnosed fault has occurred which has a severe impact upon the measur-
ure, and so the current VMV is projected from historical data, not live transducer data. A BLIND measurement should never be used for feedback control.

- **DAZZLED** is a temporary status used when transducer data is clearly erroneous, but there is insufficient internal evidence to confirm that a substantial fault has occurred. The current VMV is projected from historical data, but the expectation is that the internal diagnosis will soon be resolved and that the status will then switch to one of the other values. DAZZLED is used to deal with the occurrence of temporary but severe effects such as a spike. It would, for example, be undesirable for a control loop to be switched to manual in response to the controlled measurement turning BLIND and then, only a few seconds later, the measurement were to return to CLEAR.

The two additional states are as follows:

- **SECURE** indicates that the VMV has been generated from redundant transducers or sensors, all of which are in nominal condition. This status is useful in critical applications where the user needs the reassurance that even if one transducer or sensor fails, CLEAR data will still be available.

- **UNVALIDATED** indicates that validation has not been in operation in the sensor which generated the measurement.

Note that it is not only sensor 'faults' which may have a detrimental impact upon a measurement. A self-test, for example, may for a short time have a partial or severe effect on the measurement. In such circumstances the strategies for calculating the VMV, VU and MV status are the same as if the underlying cause were a fault, for it is the quality of the measurements which matter to the control system, rather than the underlying cause of any degradation in quality.

### 2.3. Device Status

The Device Status is a generic, discrete value summarising the health of the sensor for maintenance purposes. Every sample one of the following values is generated:

- **GOOD**: the sensor is in nominal condition.

- **TESTING**: the sensor is performing diagnostic tests which may have caused any loss of measurement quality.

- **SUSPECT**: the sensor may have suffered an aberration; the condition has not yet been diagnosed.

- **IMPAIRED**: the sensor is suffering from a diagnosed fault which has a minor impact on performance, warranting a low priority maintenance call.

- **BAD**: the sensor is suffering from a diagnosed fault which has a major impact on performance, warranting a high priority maintenance call.

- **CRITICAL**: the sensor is in a potentially dangerous condition, requiring immediate attention.

It is stressed that that the (single) Device Status refers to the health of the sensor, whereas the MV Status refers to the quality of each (of one or more) measurement. Normally there will be some correlation between the Device Status and MV Status(es) - for example, if the principal measurement is BLURRED then the Device Status is likely to be IMPAIRED.

CRITICAL is used to indicate that the sensor is in a condition that may cause (or have caused) a hazard, such as a leak of the process fluid or a dangerous reagent, fire or explosion. This status refers only to hazards generated by the sensor itself, rather than by the process. Clearly not all types of sensor are capable of reaching a CRITICAL condition.

### 2.3. Implementation details

An essential aspect of the SEVA philosophy is that a sensor manufacturer should exploit all available knowledge of the device in the internal diagnostic software. Such knowledge is invariably proprietary and not available for publication. A SEVA implementation is described in general terms by Henry and Clarke (1993), but it is not possible to disclose devicespecific methods for fault detection and measurement correction. It is however possible to demonstrate how a SEVA device behaves in the presence of various faults, and to contrast this with the unvalidated instrument.

### 3. A PROTOTYPE SEVA CORIOLIS MASS FLOW METER

There are two ways of creating prototype SEVA instruments - by building a new transmitter, or by creating an add-on unit to an existing commercial meter. Both of these approaches have been followed at Oxford, resulting in SEVA prototypes based on the thermocouple and a Coriolis mass flow meter respectively.

Figure 2 shows a block diagram of the self-validating prototype of the coriolis meter. The conventional meter consists of the flowtube and transmitter, connected by a twelve-core cable. The flowtube has a thick-walled, single path configuration, with two driver coils and two velocity sensors. The principle of coriolis mass flow metering is well known. Electronics inside the transmitter keep the driver coils vibrating at a constant amplitude. The frequency of oscillation is used to calculate the density of the process fluid. Coriolis forces act to create a phase difference between the two arms of the flowtube directly proportional to mass flow. Temperature data is obtained from an RTD in the manifold of the flowtube. The transmitter has a microprocessor to perform all measurement calculations.

To validate the commercial instrument, several signals providing measurement and diagnostic information are picked up from the transmitter boards and are passed
through a signal-conditioning unit into a PC (see Fig. 2). The microprocessor is by-passed, so that in effect the PC becomes the transmitter's microprocessor, receiving data from and sending commands to the electronics in the transmitter and the flowtube. Using this hardware configuration, measurement, uncertainty and diagnostic calculations have been developed within the PC environment, and the resulting software package, called Siamese, provides user interface, data storage and hard copy facilities (Fig. 3).

3. EXPERIMENTAL RESULTS

3.1 Loss of the temperature input

A simple fault, the loss of the temperature input, can be used to illustrate some of the issues raised by a multi-measurement instrument, and to demonstrate how the SEVA philosophy responds to them. Figure 4 shows the response of the temperature, density and mass flow measurements to this fault, which may be caused by an aberration in the flowtube, transmitter or cabling. The graphs on the left show measurement behaviour without the validation feature. In the example at time 35s the temperature sensing circuit is disabled. The response of the temperature is predictably dramatic: it falls rapidly to about -118 degrees centigrade. However, the density and mass flow measurements are also affected, by about 22% and 7% respectively in this case, as they are both calculated using the process temperature. The impact this fault has on the density and mass flow will vary considerably with, amongst other factors, the particular values of these measurements prior to the fault. This demonstrates clearly that a single fault description, particularly an error code, would be entirely inadequate to describe the resulting quality of all three measurements.

The graphs on the right of Fig. 4 show the response to the fault with validation enabled. To the diagnostic software, the first indication that something has gone wrong is that the raw temperature measurement drops at a rate much faster than the process itself could generate. The raw temperature is therefore not credible, but in the absence of a firm diagnosis it is not clear whether this aberration is transitory - such as a spike - or permanent. The diagnostic software decides to set the temperature status to DAZZLED, and the VMV is set equal to a 'best estimate' of the true process temperature, based on recent pre-fault data. While the status indicates how the current best estimate is being generated, the increasing uncertainty provides a quantitative assessment of the reducing accuracy of this estimate.

Meanwhile, more data is being accumulated and diagnostic tests are carried out. A few samples later the loss of input fault is confirmed, and so the temperature status is set to BLIND. The temperature VMV and VU continue to be projected from historical data: as time goes by the long-term history of the measurement has an increasing influence on these estimates (as described by Henry and Clarke 1993).

Notice the effects on the density and mass flow. The erroneous raw temperature is not used to calculate their values, but the temperature VMV and VU are used instead. As a consequence, instead of experiencing the offsets of 22% and 7%, the density and mass flow remain approximately constant. However, the increased uncertainty of the temperature is propagated through into their own uncertainties, which grow accordingly. Once the loss of input fault is confirmed and the temperature status changes to BLIND, then the other two measurement statuses switch to BLURRED.

3.2 Loss of a Coriolis Drive Coil

Many commercial coriolis mass flow meters have only a single driver coil to maintain flowtube oscillation. The particular device used in the SEVA prototyping trials uses two driver coils, and thus has the potential to maintain operation even if one of the drives is lost. In coriolis applications a drive may be rendered inoperative by a wiring fault, a coil short or burnout, excessive vibration or mechanical shock.

Experimental investigation of the performance of the unvalidated device indicate that when a drive is lost oscillations do continue, but an error is induced in the mass flow measurement. The ability of the meter to continue operation may be seen as an advantage over a device with a single coil, which necessarily fail completely. However, the operational consequences of
an undiagnosed fault and a biased measurement may in practice prove be more serious. Ideally, the sensor should be able to detect the fault, continue operation, correct the mass flow measurement, and inform the operator and/or maintenance system of all these actions. This would enable an informed decision to be taken about whether to continue operation, and to issue a maintenance request at an appropriate priority level - even though the meter is still operational, the cause of one drive failure may rapidly effect a second.

The detection of driver loss is trivial, unambiguous, and instantaneous through the monitoring of internal signal levels. Of more interest is to determine how the fault affects the measurements, so that corrections can be applied. A very simple model suggests that a constant lag is introduced between each arm of the flow-tube, the leading arm having the still-functioning drive. This would translate itself into a phase lag between the velocity sensors, and hence a fixed offset in the mass flow measurement. There is an asymmetry between the
two sides: if the driver on one side fails this causes a positive offset, while the other driver results in a negative offset. Experiments confirm that this model is fairly accurate. Over the mass flow range of the instrument, the phase offset induced by the fault is fairly constant, equivalent to about 0.06kg/s. Validation features have been implemented accordingly.

Figure 5 shows the effect on a constant mass flow of the loss of drive 1, both with and without validation enabled. The double spike is a rare artefact of the fault, which is not severe enough to be distinguished from process behaviour, and so is replicated in the validated output. However, the constant negative bias is immediately corrected, the uncertainty increased (due to the limited accuracy with which the true bias is known), and the status is changed to BLURRED.

Figure 6 shows the effect on an increasing mass flow rate of the loss of drive 2. The fault occurs after about 40 seconds of the experiment, and induces a positive offset in the unvalidated measurement which is difficult to see given the much larger change in the process mass flow. However, with validation enabled the fault is successfully diagnosed, the measurement is corrected, the uncertainty increased (this is difficult to see due to scaling) and the status is changed to BLURRED.

4. CONCLUSIONS
This paper has described a prototype SEVA sensor based upon a commercial coriolis mass flowmeter, and demonstrated how it deals with two fault conditions.

5. ACKNOWLEDGEMENTS
The author gratefully acknowledges support from the SERC and the Foxboro Company.

5. REFERENCES