UNDERSTANDING DIAGNOSTIC AND EXPERT SYSTEMS IN ULTRASONIC FLOW METERS

Marcel J.M. Vermeulen, Jan G. Drenthen, Hilko den Hollander
KROHNE Oil & Gas, CT Products

1 INTRODUCTION:

Custody transfer ultrasonic gas flow meters are the cash registers of the companies. These cash registers should measure fair and accurately. To determine the accuracy in most of the times only one aspect is taken into account:

- The calibration: The deviation of an ultrasonic flow meter to the national standards under ideal flowing conditions.

Viewing only to this item, all manufacturers show similar specifications, this despite the obvious differences in their designs:

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>≤ ±0.5% of measured value, un calibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤ ±0.2% of measured value, high-pressure flow calibrated (relative to calibration laboratories)</td>
</tr>
<tr>
<td></td>
<td>≤ ±0.1% of measured value, calibrated and linearized</td>
</tr>
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| Repeatability                       | ≤ ±0.1% |

**TABLE 1: TYPICAL SPECIFICATIONS (TIP OF THE ICEBERG)**

This specification however, shown in the table above, is only a small part of the whole story. As with an iceberg, the larger part concerning the accuracy is less easy to determine and as with the iceberg it lies below sea level and can be dangerous. That is why the specifications in the above table are called “iceberg specifications”. What is below the sea level are:

![Iceberg Specifications Diagram](image)

**FIGURE 1: THE ICEBERG SPECIFICATIONS**

1. The installation effects: The increase of uncertainty due to the “non-ideal” on-site installation, as described in the international standards like ISO17089 and OIML R137.
2. The change in uncertainty of the ultrasonic flow, while in operation.
   Examples: A limited amount of fouling on the bottom of the pipe can give an additional uncertainty of 0.2 - 0.6%. Other aspects like sever flow profile changes due to partly blockage
of a flow conditioner and high levels of ultrasonic noise also play an important role during the operational time of an ultrasonic flow meter.

To monitor the change in meter error over time, re-calibration is often used. However, by recalibration the meter is removed from the actual piping configurations, cleaned and presented with the same almost ideal flow velocity profile. As such it can only access the possible drift in the meter without any chance to make a correct prediction what the real behavior has been in the field. Also if there is a shift, it is also unclear at what moment in time the shift has occurred.

The true solution is 24/7 diagnostics. This provides a continuous monitoring on the performance of the meter and can detect fouling, severe flow profile distortions and high level of ultrasonic noise in an early stage. Corrective actions can be taken long before significant measurement errors occur.

Ultrasonic flow meters do have a large number of diagnostic parameters. The latest generation of meters is even equipped with ultrasonic paths that are not used for flow measurement at all, but are solely used to generate diagnostic information assuring the user that his billing is still ok.

The only drawback of this is, that with the growing number of diagnostic parameters, the relations between these and the process conditions are getting increasingly complex (see figure 2).

In addition to this, also the quality of a diagnostic parameter can vary largely with the process conditions. At the end, the user is faced with a system that, without additional intelligence, only a highly trained expert can understand.

To remedy this, diagnostic systems and expert systems have been developed, presenting the user not only a warning but also an easy understandable solution.

This paper describes the diagnostic parameters of the ultrasonic flow meter and gives understanding how these parameters are affected. The difference between a diagnostic system and an expert system is explained. Finally based on extensive fouling testing a model is created to develop an expert system. A summary of these fouling tests and the description of this expert system are also described in this paper.
2 DIAGNOSTIC TOOLS OF AN ULTRASONIC FLOW METER

2.1 WORKING PRINCIPLE OF AN ULTRASONIC FLOW METER

However the working principle of an ultrasonic flow meter is well known, for completeness it will be presented in this paragraph.

In a pipe section two transducers Trd 1A and Trd 1B create an acoustic path, L is its length. and the intersection with centre line of the pipe is its path angle φ. Both transducers are capable to transmit and receive an ultrasonic signal. The transit time of an ultrasonic signal along a measuring chord is influenced by the velocity of the gas flow (v).

- If the gas flow is zero the transit time from Trd A to Trd B is exactly the same as the transit time from Trd B to Trd A.
- When the gas is flowing with a velocity v and with c being the speed of sound in the gas: $v \cdot \cos(\phi)$ is the component of v in the direction of measurement chord.

The transit time from Trd A to Trd B ($t_{AB}$) is:

$$t_{AB} = \frac{L}{c + v \cdot \cos \phi}$$

(1)

In opposite direction (from Trd B to Trd A) the transit time ($t_{BA}$) becomes:

$$t_{BA} = \frac{L}{c - v \cdot \cos \phi}$$

(2)

The velocity of gas is derived from formula (1) and (2) as :

$$v = \frac{L}{2 \cdot \cos \phi} \cdot \left( \frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right)$$

(3)

An important feature of this method is that the calculated gas velocity does not depend on the speed of sound in the gas. As a result the measurement is totally independent of the gas properties,
temperature and pressure (therefore, the ultrasonic flow meter is one of the few meters whereby the calibration is valid for all the different pressures and temperatures). The gas velocity as calculated is only a function of the measured transit times \( t_{AB} \) and \( t_{BA} \), the length of the chord and the path angle. In custody transfer applications, ultrasonic flow meters with multiple paths are used.

As a “bonus” the speed of sound in the gas can also be derived from formula (1) and (2) as:

\[
c = \frac{L}{2} \left( \frac{1}{t_{AB}} + \frac{1}{t_{BA}} \right)
\]

(4)

This gives a measured speed of sound value, a valuable tool for diagnostic purposes, as it can be compared with data from other sources.

Besides the speed of sound other pulse specific parameters are measured like:
- The amplification of the received pulse to a certain norm level, often called Gain.
- The Signal to Noise ratio of the pulse.

All this information; velocity, Speed of sound, Gain and Signal to noise can be used for diagnostic evaluation.

### 2.2 Diagnostic Parameters

The primary parameter of an ultrasonic flow meter is of course Flow. Next to this the ultrasonic flow meter produces a huge amount of diagnostic parameters such as:

- The velocity of each individual path,
- The speed of sound of each individual path,
- The pulse acceptance of each individual path,
- The amplification (gain) of a received acoustic pulse at each transducer,
- The signal to noise of a received acoustic pulse at each transducer.

#### 2.2.1 Path Velocity

**2.2.1.1 Path layout**

As mentioned in paragraph 2.1 the custody transfer ultrasonic flow meters have multiple paths.

In figure 4 different path lay outs are presented as used by current ultrasonic flow manufacturers. In each path the velocity will be measured. It is clear that each meter will respond differently to a flow profile distortion. As a result each flow meter has its own algorithm to determine, based on path velocities, the overall velocity.
The basic objective of every manufacturer is to position the paths in such a way to have an optimal solution for compensating for Reynolds and flow profile distortions. In this case the path at chord 0.5 becomes important. In general it is seen that the velocity at chord 0.5 remains stable. This is true for Reynolds behavior and in lesser extent also applicable for flow profile distortions. Therefor it is important to use path positions in and outside the chord 0.5 position. Distortion outside chord 0.5 will be compensated by readings inside chord 0.5. Path lay out A, B & C of figure 4 uses this concept whereby path lay out A also the stable chord position of 0.5 uses.

2.2.1.2 Reflective and non-reflective technology
The path configurations as presented in figure 4 are direct paths (B, C & D) and/or a reflective path (A & E whereby A also has a direct path option). Each type has its distinctive advantage and disadvantage.

The advantage of an reflective path is the ability to eliminate swirl in plane. If direct paths are used than compensation is only possible if two paths are placed at the same pipe position, crosswise (doubling the number of transducers). Another advantage of reflection, which is not applicable for
the above mentioned crosswise construction, is the ability to interrogate the pipe wall and as such
detect fouling.
A disadvantage of reflective paths (and as such an advantage of direct paths) is that due to a longer
path length the signal strength is lower and as such for low pressure application not so beneficial. An
often incorrect used dis advantage of reflection is that reflection is strongly influenced by roughness.
In paragraph 2.2.3.2 this item will be specifically addressed

2.2.1.3 Flow profile factor
Because in each measuring plane the velocity is measured the shape of the flow profile can be
monitored. Often a flow profile factor, a ratio of individual path velocities, is used to quantify the
shape of the profile. Of course due to the different path positions of each manufacturer the flow
profile factors are different but these flow profile factor should remain stable over time and as such
can be used as a diagnostic tool.

The profile factor is often used to determine roughness or fouling off the pipe. The basic idea is that
due to roughness or fouling the gas flow is moved away from the wall and the flow profile becomes
sharper as such the flow profile factor changes. To measure this accurately, it is important to have a
path positioned close to the wall. The profile factor can indeed detect fouling and changes in the
wall roughness, but its sensitivity is limited. Here the reflection technology offers a direct
measurement and with that even the smallest changes can easily be detected (see paragraph 2.2.2.1)

2.2.2 SPEED OF SOUND

2.2.2.1 Fouling
As shown in paragraph 2.1, an ultrasonic flow meter also measures the speed of sound using the set
path length and the measured time of flight. Especially with reflecting technique a small layer of
fouling at the pipe wall has an immediate impact in the measured speed of sound. Due to the fouling
the time of flight decreases and as such the speed of sound (“set path length divided by the measured
time of flight”) increases (see figure 6).

As can be seen in the example below a layer of fouling of only 0.03125” in a 6” ultrasonic flow meter
gives an easily detectable speed of sound change of 6 ft/s
Example:

\[
\begin{align*}
\text{Internal diameter: } D_{\text{int}} &= 6” (152.4 \text{ mm}) \\
\text{Path angle: } \varphi &= 70^\circ \\
\text{Path length (reflective path through center): } L &= 12.770” (324.36 \text{ mm}) \\
\text{Fouling layer: } d &= 0.03125” (0.79 \text{ mm}) \\
\text{Path length change: } \Delta L &= 0.058” (1.48 \text{ mm}) \\
\text{Relative change: } 0.46\% \\
\text{SoS change: } 1300 \text{ ft/s} &> 1306 \text{ ft/s}
\end{align*}
\]
If the fouling is regarded as a flat surface laying at the bottom of the pipe the change in cross sectional area ("A-foul" in figure 6) is 0.06%, giving an over reading in the flow of 0.06%. If the fouling however is due to an evenly fouling of the whole pipe wall the over reading becomes 2.1%.

2.2.2.2 Mach effect
As can be seen if formula 4 of paragraph 2.1, the speed of sound measurement seems to be independent of the velocity. Still a velocity dependent behavior on the speed of sound is present. Imagine an archer who is trying to hit a target with its arrow with strong side wind. The archer would not aim on the center of its target but slightly in the opposite direction of the wind. The arrow will now follow a bend path and as such the path length will become slightly longer and the measured time of flight will be longer.

For ultrasonic flow meters similar things occurring. At high velocity (strong side wind) the acoustic pulse that is transmitted slightly off center will reach the other transducer. Its path is bended and so it takes a slightly longer time to reach the other transducer. As such its speed of sound slightly decreases. This effect is the so-called Mach effect. In general ultrasonic flow meters compensate for this Mach effect. At even higher velocities a secondary Mach effect will occur as well but these deviation are although still detectable and of no consequence (a few hundredth of a percentage).

2.2.2.3 Stratification
Another effect detectable by the speed of sound measurement is temperature stratification. In normal operating conditions the temperature of the gas in the pipe is constant. Under low flowing conditions and sunny and warm weather conditions the temperature at the top of pipe can be higher than the temperature at the bottom of the pipe. The warmer the gas the higher the speed of sound. These vertical speed of sound deviation due to temperature stratification is easily detectable. When reviewing the individual speed of sound and the speed of sound decrease in value from top to bottom than temperature stratification is present. Here multi parallel path meter designs are in the advantage by presenting the operator vital information whether stratification occurs and as a consequence whether his temperature measurement is ok.

2.2.2.4 Temperature, pressure and Gas chromatograph
As presented the speed of sound is a powerful and accurate tool. Especially for fouling detection it is very useful. It is also possible to check the health status of your temperature, pressure and your gas chromatograph (including sampling). In multipath ultrasonic flow meters the speed of sound of each path, if operating correctly, should be identical within a narrow tolerance of 1-2 feet/second.
A second way of determining the speed of sound is the use of temperature, pressure and a gas composition. Based on AGA10 the speed of sound can be calculated. Comparing the calculated speed of sound (T, P, GC) with the measured speed of sound (UFM) the health status of both can be checked.
If all paths have identical speed of sound and each path deviates from the calculated values in a similar way, probably there is something wrong with the temperature, pressure or PGC. If however some paths are similar to the calculated values and some are not, a failure within the UFM seems to be more likely.
2.2.3 **PULSE ACCEPTANCE**

2.2.3.1 *Rejection of pulses*
An ultrasonic flow meter receives and transmits acoustic pulses. The arrival time of an acoustic pulse should be measured accurately and correctly. The pulse shape of such an acoustic pulse is important. A distorted pulse shape may give an incorrect arrival time. Many ultrasonic flow meter manufacturers check the shape of the pulse prior to determining the time of flight. If a pulse does not satisfy certain criteria, a pulse is rejected and not used for time measurement. The percentage of the number of pulses transmitted to the number of pulse rejected is called pulse acceptance (also performance is used). Especially at higher flow rates the pulse acceptance may drop slightly due to the higher turbulence at higher velocity. As such this is not alarming. Pulse acceptances down to even 20% can still give acceptable flow measurement results.

2.2.3.2 *Pulse acceptance and roughness*
Especially using reflective techniques the perception is that roughness strongly influences the acoustic pulses and so the ultrasonic flow meter reading. The operating frequency of the transducer is in the range of 100 to 300 kHz. Taking into account a speed of sound of about 1300 ft/s the wavelength of an acoustic pulse is in the range of 0.156” - 0.052” (4.0 – 1.3 mm). The roughness of piping is much smaller and as such the reflective surface is “mirror-like”. Only in situations of severe fouling where those dimensions become applicable the pulse acceptance may decrease.

2.2.4 **GAIN**
Within the electronics the acoustic pulse received at the transducer is transferred in an electrical signal and this electrical signal is amplified to a certain norm level. The amount of amplification is called gain. The gain is a useful tool for diagnostics.

2.2.4.1 *Shape of the Acoustic bundle*
The transmission and receive of acoustical pulses is often visualized as a single pulse which is traveling between transducers (figure 3). A more realistic visualization is the traveling of a wave front between transducers as shown figure 7 often also addressed as an acoustic bundle.

![Figure 7: Traveling of an acoustic wave front (Acoustic bundle)](image)

The intensity of the wave front is the highest in the center. Left and right of this center point the wave is still present but in lower intensity (according to a first order Bessel function). At zero flow the center of the acoustic wave will reach the opposite sensor but at higher flow rates the acoustic...
bundle is blown away and such waves with lower intensity arrive at the receiving transducer. The signal will be smaller, the amplification will be larger and so the gain will increase. This means that the gain will change as a function of the velocity.

2.2.4.2 Gain and reflection (roughness)
As explained in paragraph 2.2.3.2 the roughness of a pipe does not influence the pulse acceptance as long as the roughness has smaller dimensions than its wave length. Tests have been done with different reflectors with different roughness’s (see paragraph 5.3.3.1). The pulse acceptance remained unchanged but a small deviation in gain was observed.

2.2.4.3 Gain and process conditions
For diagnostic evaluation it is useful to have diagnostic parameters which specifically give information on the ultrasonic flow meter and are process independent. Unfortunately gain is very process dependent. When changes in gas composition or pressure occur gain can change significantly. Of course, general gain limits for each UFM are present but to state that an increase in gain is due to a failure of an UFM is difficult without taking the process values into account.

2.2.5 S2N
Together with the pulse related value gain (amplification factor) also the signal to noise is measured. It is clear that the signal should always be greater than the noise (S2N > 1) but in general a factor 3 to 10 is often used. This is required to have a correct time measurement. The time measurement is based on a zero crossing of the pulse. It is clear that noise can change this zero crossing of the pulse. However if the noise is truly non correlated noise than the effect will average out.

A useful diagnostic feature of the signal to noise is the noise itself. Comparing noise measurement of different transducers gives information where the noise source is located and how severe this noise source is. The S2N should always be checked together with the gain while a high gain often creates a low signal to noise.

2.3 Diagnostic values
Above mentioned diagnostic parameters are available after each measuring cycle, which is typical about 10 – 20 times per second. An ultrasonic flow meter, in general, will present this data only once a second.

For stable diagnostic evaluation it is useful to use averaged values over a time frame of about 100 seconds or more. Within this time frame also the observed minimum, maximum and standard deviation can be used for diagnosis.

For each of the above described diagnostic parameters the following values are available:
   a. Average,
   b. Standard deviation,
   c. Minimum & Maximum
3 **DIAGNOSTIC MONITORING.**

For diagnosis the diagnostic parameters that are mentioned in chapter 0, needs to be continuously monitored and checked. The monitoring can be done in different ways.

3.1 **ABSOLUTE MONITORING.**

The first type of monitoring is absolute monitoring. A value of a parameter is checked to a certain warning and alarm limit. If the value is lower (or higher) than its limits, a warning or alarm is given.

In figure 8 an example is given of an absolute monitoring type. In this case the Pulse Acceptance (paragraph 2.2.3) of path 6 (diagnostic path) is monitored over time. For Pulse Acceptance the applicable absolute warning and alarm limits are 40% and 20%.

![Absolute Monitoring (Trend)](image)

Due to passing of a slug of liquid the Pulse Acceptance drops to almost 0% (see figure 8). As a result the alarm will be active. After a few minutes the Pulse Acceptance increases up to around 40%. The alarm will become inactive and a warning will be given.

3.2 **MONITORING RELATIVE TO THE PATHS.**

Another way of monitoring a value of parameter is relative to the paths.

![Relative to paths monitoring](image)
In figure 9 the gain (paragraph 2.2.4) of path 6 is presented over time. High gain indicates low signal strength, low gain values indicate a high signal strength. figure 9 shows that path 6 had a gain of about 55 dB at a certain moment the gain increased significantly passing a warning level of 70 dB. The conclusion could be a failure on path 6.

![Relative to paths monitoring](image)

**FIGURE 10: EXAMPLE RELATIVE TO PATH MONITORING (ALL PATHS)**

However if all paths are evaluated (as presented in figure 10) all paths seems to behave similar. The initial conclusion, failure on path 6, seems to be incorrect. All paths have a problem (unlikely) or another effect has caused this behavior. In this case the increase was due to a pressure drop in the system.

Instead of monitoring these values in an absolute way the gain can be presented in a relative way whereby the differences between the paths are observed. A new parameter could be the ratio of the path gains or in this case the difference of the gains (logarithmic scale, dB).

![Relative to paths monitoring](image)

**FIGURE 11: EXAMPLE relative TO PATH MONITORING**

In figure 11 the difference of the gain of path 1 & 5, 2 & 4 and 3 & 6 including the warning and alarm limits (warning limit difference between paths = 2 dB). The choice for this combination of paths is because these paths are similar positioned within this ultrasonic flow meter. For other vendors different path combinations need to be used. The difference between similar paths should lie close to zero and if not changing the conclusion can be made that the meter is functioning correctly.
3.3 **MONITORING RELATIVE TO THE VELOCITY**

A number of diagnostic parameters will change if the velocity changes. It is known that for example the flow profile changes. The change of this profile has an effect on the individual velocity readings of the paths. This velocity dependency is application specific.

![Figure 12: Velocity Dependant Monitoring](image)

In figure 12 a not so obvious parameter, the standard deviation of the speed of sound, is shown as function of the velocity. By setting warning and alarm bandwidths around the presented curve this parameter can be used for diagnostic.

3.4 **APPLICATION DEPENDENT MONITORING.**

Because an ultrasonic flow meter is based on time of flight also the speed of sound can be measured. In natural gas applications, gas chromatographs (GC) and temperature and pressure sensors are used to calculate the energy and compressibility of the gas. The same information, gas composition, temperature and pressure can also be used to calculate the speed of sound.

![Figure 13: Application Dependent Monitoring (SoS)](image)

Comparing the calculated speed of sound to the measured speed of sound gives a powerful diagnostic feature. This feature is used to check the ultrasonic flow meter but can also check the gas chromatograph, temperature and pressure sensor. In a situation that a deviation between measured and calculated speed of sound is present and all the speed of sound measurements of the individual
path are identical to each other, it is advisable to first check the temperature, pressure, gas composition and the sampling system.

4 Setting up a diagnostic system

To create a diagnostic system the parameters as mentioned chapter 0 and the different monitoring types as mentioned in chapter 3 needs to be combined. The gain as discussed in paragraph 3.2 was monitored in an absolute way (gain < 70 dB) and in a relative way (difference gain 1 & 5 < 2 dB). Each type of monitoring of a parameter is called a CHECK. Each CHECK can have three statuses; Good (Green), Warning (Orange) and Alarm (red). In figure 14 the used CHECK’s of one diagnostic system is presented in detail.

![Figure 14: Checks of a diagnostic system](image)

The discussed CHECK’s “gain absolute” and “gain difference 1 & 5” (paragraph 3.2) are separately emphasized in figure 14.

By combining different CHECK’s, a STATUS is created. As such a more condensed presentation of the health status of an ultrasonic flow meter, can be given.

![Figure 15: Status’s of a diagnostic system](image)

In figure 15 the results of the CHECK’s are condensed to path STATUS’s (path 1 to 6) and parameter STATUS’s (speed of sound, velocity, signal acceptance and signal quality). Finally an overall health STATUS is required. This Master status will be a single marker. If colored green, the meter operates correctly. If colored orange some failures have occurred but the ultrasonic flow meter is still operating within its custody transfer limits, corrective actions should be planned. If colored red, a serious failure has occurred and immediate action is required. The master status can be found in the top left corner of figure 15 and will also be visible at the start up screen of the on-board web page as presented in figure 37.
Other software packages are available which use similar alarm and warning checks and statuses with color coding as described above (see figure 16).

![Figure 16: Diagnostic Software Different Vendors](image)

**Figure 16:** Diagnostic Software Different Vendors
5 CREATING EXPERT SYSTEM

5.1 INTRODUCTION

To create an expert system it is important to test the response of an ultrasonic flow meter to multiple process distortions.

To check the response of the meter to extreme flow profile distortions, for example, a deliberately blockage of flow conditioner plate can give some information. Or, by inserting swirl plates the effect to swirl can be reviewed and the response of the individual paths can be reviewed. Also the standard flow profile distortion tests as described in ISO 17089 and OIML R137 give sufficient diagnostic data. The AGA9-2 is less specific in this aspect and proposed only some suggestions in Annex D).

Another important issue of an expert system is recognizing different types of fouling. Extensive tests have been done on the effect of fouling on to the ultrasonic flow meter. A paper and presentation on this topic has been given at the AGA Operation Conference in Nashville 2011. This paper is the base to the developed expert diagnostic system. Because of its importance for the topic of this paper, a short summary is presented in this paragraph.

5.2 TYPES OF FOULING

Looking at fouling, one of the main problems of it is the variety in its manifestations. Fouling can be classified into 5 categories; each of them affects the measurement in a different way.

These categories are:
1. Fouling as a small flow on the bottom of the pipe.
2. Fouling intermittently sticking to the pipe wall.
3. Fouling which is as an evenly distributed coating on the inside of the pipe.
4. Fouling as dirt build-up on the transducers (especially on those transducers facing upstream).
5. Fouling as liquid build-up in the transducer pockets.

For ultrasonic flow meters, the major effects of fouling on the measurement are:
- A reduction of the cross sectional area.
- An increased wall roughness.
- The shortening of the acoustic path length.
- The attenuation of the acoustic signal through the reduction of the reflection coefficient.
- The absorbance of the ultrasonic signal due to the layer of fouling on the transducer.
- Increased cross talk when liquid is present in the transducer pockets.

5.3 TESTING AT LINTORF

In July 2010 extensive testing on fouling have been done at the E-ON Ruhrgas test facility in Lintorf using two 6” ultrasonic flow meters in series (see figure 17). Beside the in paragraph 5.2 described types of fouling also the following effects were tested:
6. Reflection on rough (corroded) surfaces
7. Honed and corroded upstream pipes
The different types of fouling were simulated and the response of the meter, the error curve but also the responses of the diagnostic parameters were monitored and analyzed.

5.3.1 FOULING ON THE BOTTOM OF THE PIPE
To simulate the bottom fouling and to test the sensitivity of the diagnostic detection, an approximately 4 to 6 cm wide and relatively thin layer of “never-seize regular grade anti-seize and lubricating compound” - further to be referred to as “grease” - was applied over the whole length of both the inlet spool and the meter.

Measuring the thickness proved not to be an easy task and an assessment was made using calipers and by weighing the amount of grease applied. Based on these the thickness was estimated as an average layer of about 0.02” (0.5 mm) with peaks of 0.08” (2 mm, see figure 18).

5.3.1.1 Velocity profile
The flow velocity profile is presented in figure 19. The fouling in this orientation is on the right side. Reviewing this, it is evident that the change in the flow velocity profile is negligible and absolutely not enough to be used as an indicator. As such the flow profile factor as discussed in paragraph 2.2.1.3, would not detect this type of fouling. Maybe an ultrasonic flow meter with a path closer to the wall could detect this by flow profile distortion. But all other manufacturers have the outer path
further from the wall than the flow meter tested. In the case of extreme fouling than the flow profile factor can be a useful tool.

**Figure 19**, Flow Velocity Profile with and without Fouling (Fouling on the Right Side)

5.3.1.2 *Signal strength or gain*

The second indicator is the reflection coefficient, measured as a change in the signal strength. This is presented in figure 20.

**Figure 20**, Change in the Reflection Coefficient

Although stable, the change in the reflection coefficient on such a small layer of grease is less than 1 dB. The same change in signal strength also occurs when the pressure changes some 10%. On itself this is insufficient to draw conclusions from and this parameter is therefore only to be used in combination with other parameters.
5.3.1.3 *Speed of Sound (standard deviation)*

The change in standard deviation in the flow velocity and that of the SOS are useful parameters for indicating changes in the hydraulic roughness. With fluid contamination on the bottom, this occurs when the fluid surface changes from smooth to wavy. In figure 21 the standard deviation is shown of both the path reflecting at the bottom (path 6) and that on the side, which is unaffected by the fouling on the bottom (path 3).

![Figure 21, Standard deviation of path 3 & 6](image)

In this picture can be seen, that ripples are formed at higher flow velocities leading to a larger fluctuation in the SOS. Also, the thickness of the layer as well as its viscosity will impact the result. Again: on itself this parameter alone is insufficient to draw conclusions from but can be very useful in combination with other parameters.

5.3.1.4 *Speed of Sound (average)*

Clearly in this case, the absolute value of the speed of sound is the most important and direct parameter. In figure 22, the speed of sound ratios of all the acoustic paths are shown.

![Figure 22, Speed of sound ratios](image)

In this figure it can be seen that the speed of sound of path 6, the diagnostic path reflecting on the bottom of the pipe has shifted approximately 0.2 % in respect to the other paths. Calculated on the shift in the speed of sound, the average thickness of the bottom layer was 0.01” (0.3 mm); somewhat lower than assessed by the mechanical measurement. As a first order correction, based on the
blockage of the cross sectional area, such a layer results in a total reduction of the cross sectional area of 0.12%.

In figure 23, the calibration results of both the “clean” meter as well as that with bottom fouling are shown. From these, it is clear that the first order correction is in close agreement with the measured offset.

5.3.2 Other Types of Fouling

Other types of fouling were simulated and the response of the meter, the error curve and the diagnostic parameters were analyzed in the same way as presented in paragraph 5.3.1. The different types of simulated fouling are presented in the next few pictures.
5.3.3 ADDITIONAL TESTING

Next to the tests on fouling also the effect from roughness variations of reflection point and the change in roughness of inlet pipe were tested.

5.3.3.1 Roughness reflection point

In figure 28 a photo is presented from three reflectors with different roughness. As explained in paragraph 2.2.3.2 the wave length of an acoustic pulse in the 300 kHz range is 0.052” (1.3 mm).
The roughness applied was much smaller. As a result the Pulse Acceptance remained high.

Despite the huge differences roughness, the meter functioned flawless showing no impact of the added roughness of the reflector. As expected, see paragraph 2.2.4.2 the gain could be influenced. Both the medium and high roughness reflectors required some more gain in the order of 1.5 to 3 dB, but the quality of the flow measurement was not affected in any way (see figure 29).

5.3.3.2 Honed versus corroded inlet spools.

Unless specific attention is paid to the inlet spools, the roughness of the spools can vary widely and other meters such as orifice meters are extremely vulnerable for this.

In contrast, for ultrasonic meters this seems not the case. Looking at the requirements for the connected piping, both the ISO 17089 as well as the AGA 9 do not make any statement regarding the roughness of the upstream piping. Reasons for this were amongst other the tests done by Wilsack & Dane, finding no shifts even when very corroded or smooth pipes were used [5]. With these tests done at an older design it was decided to repeat these tests (courtesy of Eon-Ruhrgas). In figure 30 the test results from the corroded pipe as well as the honed pipe are shown.
Despite large differences in the upstream piping, the calibration curves were not affected at all (see figure 31).

5.4 CONCLUSION: RELATIONAL DIAGRAM (EXPERT SYSTEM)

The outcome of all the performed tests showed that a typical type of fouling influences the diagnostic parameter differently. A relational diagram could be made as presented in figure 32 which shows which parameters are affected by which type of fouling.

![Relational Diagram](image)

**FIGURE 32: RELATIONAL DIAGNOSTIC DIAGRAM**

It is this relational diagram which makes it possible to convert a diagnostic system to an expert system.
6 SETTING UP AN EXPERT SYSTEM

6.1 FROM DIAGNOSTIC SYSTEM TO EXPERT SYSTEM

In chapter 4 the diagnostic systems are presented. Multiple CHECKS compare the values to the predefined warning and alarm limits. The outcome of chapter 5 resulted in a relational diagram which can transfer diagnostic alarm into understandable failure recognition. Until now only a specialist can, based on the CHECKS and STATUSES, deduct the problem and advice corrective actions. For an expert system, based on the outcome of chapter 5 this advice can be given by the system itself.

![Diagram showing transition from diagnostic system to expert system]

The right side of figure 33 shows the condensed information of all the CHECK’s into clear understandable advice. At the top, the ultrasonic flow meter and its paths are visualized. Below that, different causes are presented with their likelihood of occurrences.

![Visualisation of failures]

In figure 34 different examples are given on the visualization of failure modes. The failure type, warning or alarm, is presented with different colors. The orange color of the profile distortion in the bottom-left corner of figure 34 indicates that the flow profile is distorted but still within acceptable (custody transfer) limits. In the bottom-right corner of figure 34 multiple failures are given. The likelihood of occurrences of these failures will give more background information.
The likelihood of occurrences (status details) of the situation in the bottom-right corner of figure 34 can be seen in figure 35. The failure of path 2 is likely due to fouling. Wall fouling gives a likelihood of 35% which is just above the warning level. Advice in this case would be to clean path 2. While cleaning path 2 check the inside of the pipe for fouling. Some fouling may be present but it is expected that the wall fouling warning is also caused by the fouling alarm of path 2.

6.2 APPLICATION DEPENDENT OPTIMIZATION OF THE EXPERT SYSTEM

An expert system with basic settings is always available. These settings are based on the dry calibration (FAT) and, if applicable, on the flow calibration. To further optimize the expert system application specific settings should be added.

In paragraph 3.3 the velocity dependent monitoring was presented and the changing velocity profile as a function of the velocity was discussed. The flow profile is however not only velocity dependent but also application dependent. To optimize the expert system, this application specific behavior should be registered. For this an auto-commissioning function can be used.

During commissioning of an ultrasonic flow meter it is preferred to test the meter under pressure and over its full operating range. In practice commissioning is done mostly under non-flowing and pressurized conditions. Sometimes, a flow can be given but never over a full flow range. To fully optimize an expert system this information is required. During the startup phase of the ultrasonic flow meter, different flows will pass through it. By using the Auto-commissioning of the expert system these flows and its related parameters will be stored automatically. This information will not be used immediately while it cannot be guaranteed that the information stored is done under normal, clean and non-failure conditions. After confirmation of the correctness of the data, the velocity dependent data will be implemented in a reference file. This reference file will check all the velocity dependent parameters. The expert system is now optimized to the customer’s application.
6.3 **IMPORTANT FEATURE OF USE ON AN EXPERT SYSTEM**

Some important features for diagnostics and expert systems are discussed in this chapter.

6.3.1 **REMOTE OR WEB BASED MONITORING**

With the number of applications growing and with installation in difficult reachable installation like unmanned platforms it is preferred that diagnostic systems are remotely accessible. The use of internet can be a powerful tool. A fully web based system is a good solution. From any laptop or personal computer via internet the ultrasonic flow meter can be checked by typing its IP-address into a web browser.

![Figure 36: Overview screen of web based expert system](image)

In figure 36 the overview (start) screen of a web based expert system is presented. On the top-right side the overall master STATUS is presented. Below the overall master STATUS bars are presented for indicating the actual flow, velocity, Speed of Sound, Pulse Acceptance, temperature and pressure. Left from the master STATUS a graph presents the master status value over the past few days. Below this graph the audit and alarm log is presented. Also the visualization of the ultrasonic flow meter as presented in paragraph 6.1 is present. Below this, general information of the application is presented together with the totals. On the left side, a tree is present to navigate through the different screens.

The next two pages are presented in figure 37. The in paragraph 4 and 5.2 discussed CHECK’s and STATUS’s are shown on these pages.

![Figure 37: Expert & Diagnostic page](image)
Of course next to the diagnostic data also live data should be reviewed remotely (via internet).

In figure 38 the parameters like Gain, Signal to Noise, Pulse Acceptance, Velocity and Speed of Sound can be presented in multiple ways; bar, column, line and spider graphs. Also trend charts are present for different selectable parameters. In the middle a visualization of the skewness and sharpness of the profile is shown. In figure 39 this detail is in detail presented.

The skewness of the flow profile is presented the angle of the base line. The left side picture of figure 39 shows a correct flow profile. The base line is horizontal. The right side picture of figure 39 shows the baseline under an angle, indicating that the flow profile is skewed. A second feature is the sharpness of the flow profile. The length of the line between center of the profile and the baseline is an indication of the sharpness. A sharper profile shows a longer length. As long the center of the flow profile is within the dotted line region. The flow profile is acceptable. If the center is outside this region a warning is generated and the color of the flow profile changes from green (left side picture) to red (right side picture).

6.3.2 REPORTING
For audit trail purposes reporting of current status of a flow meter is important. Also it is preferred that the reporting can be done remotely.
Within the web-based environment, a report needs to be generated from the actual status but also historical data of the past days, weeks, or even months can be presented in two pages as shown in Figure 40. The report can be checked, undersigned, and stored for audit trail purposes.

6.3.3 DATA STORAGE AND TRANSFER

6.3.3.1 Data Storage

For traceability, it is preferred to store sufficient data locally. The storage should be live data but also event-based. Especially in standalone situations, it is preferred to store all relevant details prior to and after an alarm or status change.

The data that should be stored includes:

- **Live data:** The actual parameters and diagnostic parameters including CHECK’s and STATUS’s should be stored using averaging. It is preferable to store averages every minute, 15 minutes, hour, and day. Using 2 GB of memory storage, easily 10 years of daily data, and 365 days of hourly data, 100 days over quarterly hour data and 24 hours of minute data can be stored.
- **The event-based storage stores data based on different triggers.**
  - The trigger can be a STATUS change or an Alarm. When triggered, the diagnostic data and 30 seconds of live data before and after the trigger are stored. As such, the Alarm or STATUS change can be reviewed afterwards.
  - Another event-based storage is the discussed auto commissioning function (par. 6.2). For optimization, this data needs to be retrieved. This data transfer can be done web-based.
6.3.3.2 Data Transfer
To store the data locally (par. 6.3.3.1) is an important feature. Still it would be useful to transport this data to a laptop or PC as backup or for further analysis. Especially the event based data storage during the commissioning phase needs to be reviewed for optimization of the expert system. This should be done remotely (web based).

![Figure 41: Web based data transfer](image)

A data transfer routine is required (figure 41) which gives the ability to upload the type of data (event, log, commissioning and/or GC data), but also the ability to do this for a certain time frame. Via remote communication (like internet) the data is transferred from the ultrasonic flow meter to the laptop or PC.

6.3.4 Historical Review
Aside from the above discussed use of “data transfer for further review”, the historical data analysis should also be done directly via internet. In figure 42 the web based daily averaged path statuses are presented of a demo unit from 10 December 2011 until 23 April 2012. This demo unit is situated in the R&D facility in the Netherlands and errors were deliberately created as part of a long term test.

![Figure 42: Path status from 10 December 2011 to 23 April 2012](image)
Within the same time frame the Parameter Status’s (SoS, Signal, Velocity & Pulse acceptance) can be checked as well as the Expert Status’s (wall fouling, bottom fouling, Noise levels, flow profile distortion).

Other ways of reviewing the stored data is by:

- State Histogram: How often in a certain time frame was a parameter in alarm, warning of correct operating mode for a specific path (see figure 44)
- Historical trend line: A trend graph of a specific parameter in a certain time frame including Standard deviations, minimum and maximum values reached.
- And more ...... like graphs to review velocity and pressure dependent historical behavior.

These web based historical review options gives powerful tools to do remote review without the need to transfer the data to a local PC (par. 6.3.3).
7 FLOW COMPUTER FUNCTIONALITY

One of the diagnostic tools of the expert system was to check the measured Speed of Sound to a calculated speed of sound (see par. 3.4) as such the requirement to connect to a GC, Temperature and Pressure sensor was present. Because AGA 8 SoS calculations require a certain arrhythmic. This required calculation power can easily be extended to other flow computer calculations. The expert system communicates through Modbus with a gas chromatograph. Temperature and pressure sensors could be read by HART or analogue inputs. The energy and compressibility can be calculated based on different methods / standards and the normalized flow can be determined and normalized totalizers are available.

![Diagram of Expert System with Flow Computer Functionality](image)

**FIGURE 45: EXPERT SYSTEM WITH FLOW COMPUTER FUNCTIONALITY (T, P AND GC INPUT)**

8 CONCLUSION

To continuously guarantee the correctness of your cash register a continuously monitoring system is required. Ultrasonic flow meters have a significant amount of diagnostic parameters which can be used for continuously diagnosis of the ultrasonic flow meter. A diagnostic system only tells you if certain parameters are outside its limits, it does not tell you what the problem is. An expert system does. It should be an easy to use, remote accessible (e.g. web based) expert system if possible with flow computer functionality which makes continuously monitoring of an ultrasonic flow meter easy to understand.
9 REFERENCES:


