How Diagnostics Improve Reliability and Quality of Clamp-on Ultrasonic Flow Meters

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1 INTRODUCTION

Ultrasonic clamp-on flow meters offer significant flexibility because they are non-invasive, mounted externally on pipes, and can be used across a wide range of applications.
Clamp-on Ultrasonic flow meters are often installed in challenging conditions as their invasive nature is very suitable for retrofitting on existing installations.
Their performance, however, is contingent upon accurate diagnostics that help in understanding and mitigating issues related to signal quality, flow disturbances, and transducer setup.
These existing installations have mostly not considered installation of flowmeters in the location of the clamp-on meter in their design and often face challenging piping conditions.

Clamp-on Ultrasonic Flowmeter inherently supports self-diagnosis during both setup and continuous operation. This is an essential differentiation to other intrusive methods of flow measurement, where diagnostics has limited use to optimize set-up during installation.

This paper outlines diagnostic strategies and evaluation methods, both device-based and user-driven.
It is recommended to combine these inherent diagnostics with pictures of the installation conditions and location for an overall assessment of installations.

2 Principle of Operation

Most of the Ultrasonic Clamp on flow meters in industrial applications utilize transit time technology.
This technology makes use of the fact that the travel time of an ultrasonic wave between an emitting and a receiving transducer is influenced by the flow rate of the fluid through which the wave propagates.
The upstream and downstream travel times relative to the flow direction are different. Consequently, the time difference between the upstream and downstream traveling ultrasonic pulses is directly proportional to the flow Velocity.

2.1 Configuration of an Ultrasonic Clamp-On Flow Meter

A clamp on flow meter uses transducers that are mounted on the outside of the pipe. A typical configuration is shown in Figure 1.

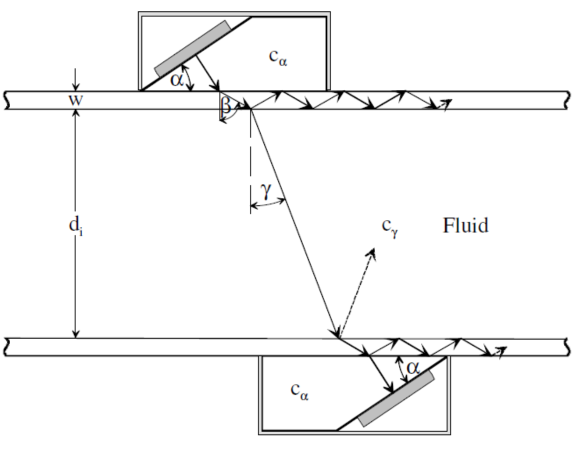

Figure 1 Ultrasonic Clamp on Configuration

For the Clamp on configuration shown in Figure 1 the flow velocity is given by:

$$v_l = k_\alpha \frac{\Delta t}{2\,t_F} \quad \text{with} \quad k_\alpha = \frac{c_\alpha}{\sin\alpha}$$

(1)

Where c_α is the speed of sound of the transducer, α the angel of propagation in the transducer and tF the traveling time of the ultrasonic pulse in the fluid to measure. k_α is the transducer constant. The fluid propagation time t_F is calculated as the difference of the traveling time from the emitting to the receiving transducer and the propagation times outside the fluid to measure. The out of fluid times are given by the transducer type and the pipe wall propagation time.

The propagation direction in the fluid, the pipe wall and in the transducer wedges are connected by the acoustical refraction law (Snell's law):

$$\frac{\sin\alpha}{c_\alpha} = \frac{\sin\beta}{c_\beta} = \frac{\sin\gamma}{c_\gamma}$$

(2)

As the characteristic values like speed of sound and geometry of the transducer are known by design, the propagation directions in the wall and the fluid can be derived. The transducer constant is defined by the transducer properties.

The acoustic coupling between the transducers and the pipe wall is typically realized by semi liquid couplants (grease, paste) or durable elastic coupling foils. The coupling material fills the always existing gap between the transducer and the pipe wall and compensates the roughness of the outer surface of the pipe.

2.2 Volume Flow

The flow velocity given by formula (1) results in a line average flow velocity along the propagation path of the ultrasonic signal v_l

$$v_l = \frac{1}{l}\int_{(l)} \mathbf{v}\cdot d\mathbf{l}$$

(3)

The volume flow rate Q is calculated from the product of the cross section area of the pipe A and the area averaged of the flow velocity V_A

$$Q = v_A \cdot A \quad \text{with} \quad v_A = \frac{1}{A}\iint_A \mathbf{v}\cdot d\mathbf{A}$$

(4)

To calculate the flow rate the area averaged flow velocity must be derived from the measured line averaged velocity by applying the fluid mechanical calibration factor k_{Re} which is defined by:

$$k_{\mathrm{Re}} = \frac{v_A}{v_l}$$

(5)

The fluid mechanical calibration factor k_{Re} is independent of the acoustic properties of the measurement configuration. In the case of a fully developed undisturbed flow profile the fluid mechanical calibration factor depends only on the Reynolds number

$$k_{\mathrm{Re}} = \frac{v_A}{v_l} \quad (6)$$

and the roughness of the inner surface of the pipe wall and is calculated by the meter for each measurement separately.

The flow profile can be assumed undisturbed if the distance between the measurement location and flow disturbers is long enough.

In the case of disturbed profiles, a correction model based on CFD, empiric measurements and profile measurements can be used to reduce uncertainty of the profile.

3 Evaluation of Ultrasonic Signals & Diagnostics

Signal clarity and strength are vital to achieve a reliable, stable and robust signal evaulation.

The performance and uncertainty of the calculation of the transit time difference is affected by signal amplitude and noise characteristics. Misinterpretation and instability of measurement quality can occur the signal evaluation is disturbed.

3.1 Diagnostics in ISO 24062

The ISO24062 has been released as ISO describing Clamp-on Ultrasonic Flow Meters for Liquid and Gases. Diagnostics are described in Section 6.9. as tool for verification of the installation.

Guidance of the meter manufacturer is referred to as no general rules for all meters exist.
Explicitly “Gain”, “Signal to Noise Ratio” and “Measured Sound Speed” are mentioned as most common diagnostics, but additional diagnostics are possible.

Following use cases are described for the 3 mentioned parameters:

“Fluid sound speed can be used to verify the geometry of installation, or assumptions on the fluid….”

“The presence or absence of a liner can often be deduced from the diagnostic facilities on the meter, for example poor signal strength readings or inconsistencies in the calculated sound speed.”

“Gain can be used for predictive maintenance.”

“A change of gain … If the fluid has not changed, this potentially indicates build up on the inner pipe wall, degradation of transducer coupling or even a degradation of the transducers.”

“Signal to noise ratio (SNR) can be used to verify the electrical installation.”

“An SNR below the expected value can indicate wrong or insufficient installation of electric shielding on the transducer cabling or the presence of strong electromagnetic disturbances. Another potential source of noise are control valves which are used in gas facilities”

3.2 Signal Amplitude or Gain

One basic requirement of reliable signal processing and stable transit time difference calculation is the detection of the measurement signal.

The relationship between Signal Amplitude A and Gain G is defined

$$A[\%] = \left(1 - \frac{G}{G_{\max}}\right) \cdot 100\% \quad (7)$$

Ultrasonic clamp on systems uses variable gain amplifiers to achieve an optimal signal level for the subsequent signal processing by amplifying the received signals. Practically speaking, the maximum gain is limited by the inherent noise of the amplifier. As a result, the attenuation of the ultrasonic signal cannot be fully compensated.

The transit time difference is not influenced by the actual gain.

But if the maximum gain is insufficient the measurement will fail as the ultrasonic signal cannotr be detected. The difference between the actual gain and the maximum gain can be considered as a reserve for more attenuation of the signal which is available for the application until the measurement drops in quality or even fails. If a sufficient reserve is available, the meters works safely and reliably even under changing application conditions like additional damping of small phase contamination or deposit build-up on the pipe wall over time. The operational reserve is higher as the base signal amplitude increases.

The amplitude of the ultrasonic signal is affected by the sound propagation through the whole acoustical path. The ultrasonic signal is attenuated by several influences during propagation.

As described in section 2.1, the sound is transmitted through several layers of materials (transducer, pipe, fluid). At each interface transmission as well as reflection occurs. This is connected to a loss of amplitude which is defined by the acoustic impedance (section 2.2).

This yields an unavoidable insertion loss for clamp on systems which is independent of Frequency used.

The amplitude is also influenced by the intermolecular and viscosity damping of the fluid which depends on frequency. To increase the operating margin of the amplitude the transducer working frequency can be reduced to reduce the damping of the fluid.

Increased gain over time might indicate build up, increased presence of a second phase in the fluid or issue with the transducer coupling (especially if non-permanent liquid or gel coupling is used).

Reducing the number of sound paths in the set up can decrease the gain required for receiving a valid signal.

3.3 Noise

One of the most important questions in reliable operation of meters is their sensitivity to disturbances, especially noise. The inherent diagnostic possibilities of ultrasonic clamp on meters allow a very detailed evaluation of the influence of several kinds of noise relative to the measurement result.

Noise that is superimposed on the ultrasonic signal can influence the ultrasonic flow measurement. A distinction can be made between noise which has a strong well-defined relationship to measurement process, correlated noise, and noise that has no relation to measurement process and random characteristics, uncorrelated or random noise.

If the source of the noise can be identified strategies to reduce it can be applied.

3.3.1 Correlated Noise

Correlated noise of ultrasonic clamp on flow meters is usually directly related to the transmission pulse of the emitting transducer. It is independent of the flow velocity of the fluid.

$$SCNR[dB] = 20 \cdot \log \frac{Signal\ Amplitude}{Correlated\, Noise\ Amplitue}$$

(8)

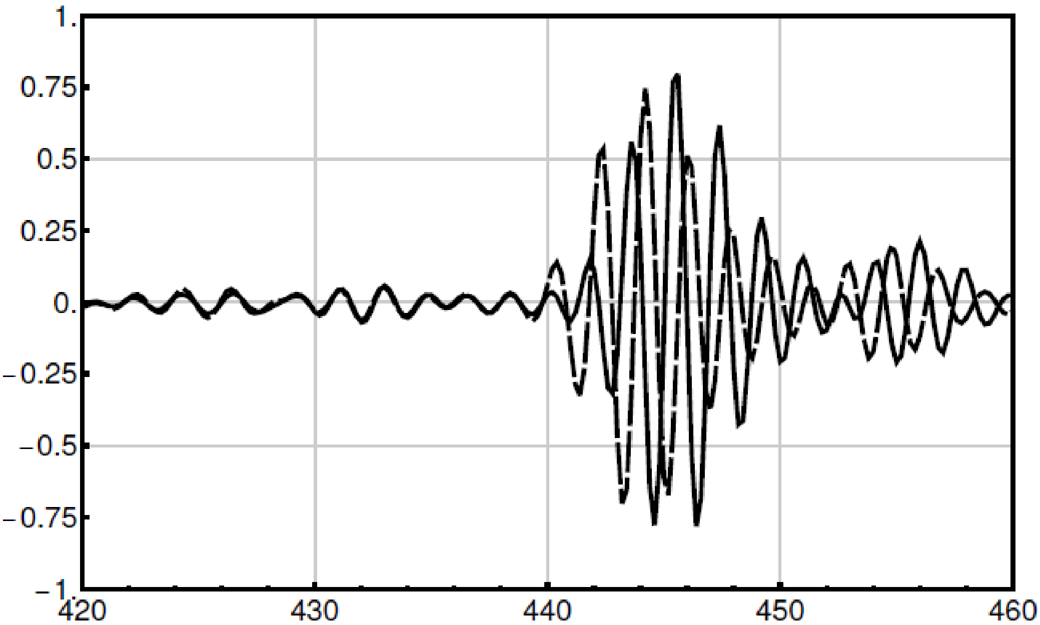

Figure 2 shows an example of a pair of ultrasonic signals that are superimposed on a waveform that is the same for both propagation directions and which does not show any time difference. Therefore, it has not passed through the fluid.

The received signal consists of two parts, the fluid signals that pass through the fluid and show a time difference, and a disturbing noise signal that doesn't pass through the fluid.

As both fluid signals have slightly different transit time, different parts of the noise signal are superimposed on the equivalent parts of the fluid signals. As a result the up and down fluid signals are distorted in slightly different ways which yields a slight change in the time difference of the detected signals in comparison with the undisturbed signals.

The measurement deviation depends on the amplitude of the correlated noise signal and the time delay between noise signal and fluid signal. This yields a random uncertainty of the flow measurement result due to correlated noise signals.

The power of the fluid signal relative to the power of the noise signal is measured and the meter's signal processing repertoire is expanded by an additional diagnostic algorithm. The resulting characteristic value is called ScNR -signal to correlated noise ratio- equivalent to the well know definition of the signal to noise ratio.elated noise signal. Clearly visibly are the upstream and downstream signals.

As the ScNR depends on the actual application the expected maximum measurement error increases with lower ScNR. For a reliable and safe measurement the ScNR should be maximized.
The only possible way is usually to reduce the power of the correlated noise signals.

The main source of correlated noise signals of ultrasonic clamp on meters are ultrasonic pulses that propagates in several different ways other than through the fluid from the emitting transducer to the receiving one. This can be reflections from flanges or welds or signals travelling within thick wall pipes within the pipewall.

These ultrasonic noise signals cannot be reduced by signal processing means and need to be damped. The capability of an ultrasonic meter to calculate the ScNR for each measurement makes it possible to optimize the installation and to observe the measurement quality during the whole operation.

Signals travelling on the pipe walls can be also damped by the application of noise absorbing external “Damping material”.

3.3.2 Uncorrelated Noise

Uncorrelated noise is independent of the measurement process.

All different sources of uncorrelated noise are considered combined as random noise. A characteristic value of random noise is the relation of the fluid signal power to the power of random noise. This relation is known as SNR (signal to noise ratio):

$$SNR\left[dB\right] = 20 \cdot \log \frac{Signal\ Amplitude}{Noise\ Amplitue}$$

(9)

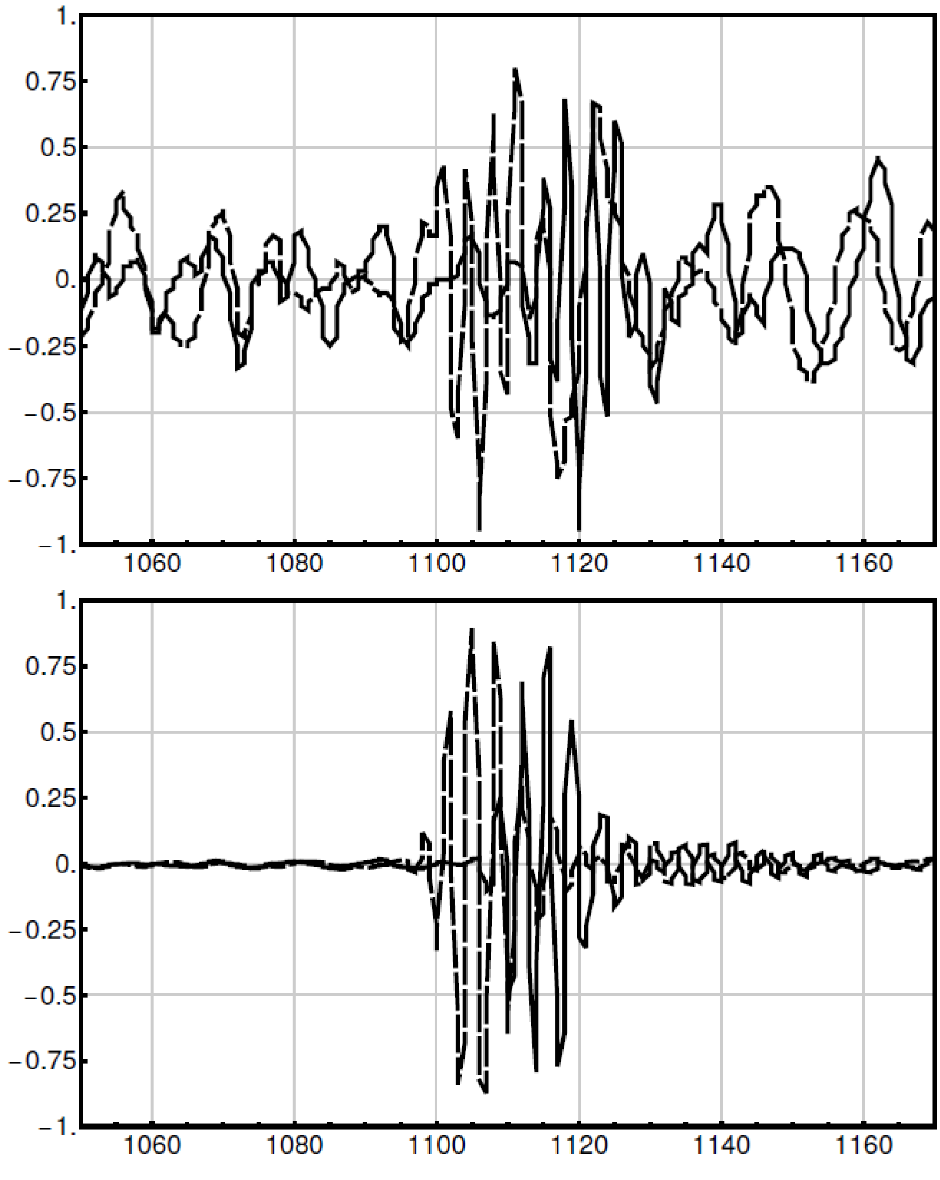

Figure 3 shows uncorrelated noise in a signal snap before and after processing

Due to the stochastic character of random noise, it does not yield a systematic deviation of the measurement result. Usually, the variance of the measurement results is increased with higher noise level or lower SNR. The influence of random noise is widely compensated for by the signal processing of the meter as shown in figure 3. The first diagram shows a single signal pair before processing, the second the result after the signal processing.

The random noise compensation usually works reliably until the noise level becomes higher than the signal (SNR>0).

For higher noise levels an influence on the measurement stability can be seen. In extreme situations the measurement fails. The SNR is processed for each signal and can be used for installation and long term observation to estimate the influence of the environment on the measurement process.

Many source of random noise are known. In principle they originate from electrical sources that influence the meter's electronics directly or from ultrasonic sources. Electromagnetic Interference can be reduced effectively by correct installation related to earthing, avoiding potential differences or electromagnetic influences to signal cables.

Ultrasonic random noise can only affect the meter if it is coupled directly to the pipe system and the ultrasonic transducers.

An example of ultrasonic random noise generators which can be found in gas pipeline systems are control valves. It is known that control vales emit ultrasonic noise in operation typically with a peak in a frequency between 75 and 200 Khz.

The ultrasonic noise wave is generated directly into the gas. This process is completely independent of the ultrasonic flow measurement and yields a decline of the SNR which is compensated for by the signal processing of the flow meter.

3.4 Sound Speed

The sound speed of an ultrasonic signal indicates the velocity at which sound travels through a given medium over the measurement path. Each liquid has a distinct sound speed that varies with process conditions. After installation, confirming the sound speed to the theoretical value of the medium helps ensure the meter is correctly installed according to specifications. And pipe properties are correctly measured.

Sound speed measurement can be also used to calculate back media properties like density, compositions or purity.

Changes in sound speed can be indication for phase contamination, change in fluid composition, temperature or pressure changes or build up.

3.5 Additional Diagnostic Values

Additional parameters like turbulence (VariAmp and VariTime), Quality (simitry of ultrasonic signal) or path differences play a vital role. These parameters help ascertain the flow profile, and transducer positioning and detect turbulence or acoustic noise.

3.5.1 VariAmp and VariTime

VariAmp and VariTime are describing the variation of the measured Amplitude and the measured travel time over the measurement path.

This variation is often observed in processes with rapidly changing flow conditions or where turbulence is naturally by high flow vleocities and disturbed profiles present due to system design or fluid characteristics.

Transducer and setup modifications help mitigate Variations caused by strongly disturbed turbulent flow or second phase.

3.5.2 Quality (symmetry) of Signal

The quality of the ultrasonic signal is analysed through its upstream and downstream profiles symmetry. Poor quality is often attributed to high acoustic noise or inadequate transducer installation.

The quality indication in Flexim ranges from 0 to 100%, which is the range of 90-100% similarity of the signal to gain higher resolution.

To address poor signal quality, solutions include the application of damping materials, adjusting transducer positions, and reducing flow velocity.

3.5.3 Path Differences

Path differences in flow velocity, sound speed, gain, SNR, and SCNR provide a comparative diagnostic measure. Aberrations in path differences are indicative of service issues like cross-flow or asymmetric flow profiles, but also installation or coupling issues on one pair of transducers.

Ensuring uniform transducer distance and addressing pipe inhomogeneities can minimize path difference anomalies.

Diagnostics	Description
Speed of Sound (SOS)	The sound speed of an ultrasonic signal indicates the velocity at which sound travels through a given medium. Each liquid has a distinct sound speed that varies with process conditions. After installation, confirming the sound speed helps ensure the meter is correctly installed according to specifications. Should be within 1 to max 3% to theoretical value.
Signal Amplitude	Signal amplitude is a crucial diagnostic parameter for assessing the quality of ultrasonic measurements. Variations in signal amplitude can indicate changes in process conditions or suggest a potential issue on the acoustic coupling. Signal Amplitude is directly linked to the Gain value in dP.
Signal to Correlated Noise Ratio (SCNR)	SCNR specifically measures the ratio of the desired signal to the correlated noise, which is noise directly linked to the transmitted signal itself. The SCNR range is from 0-50. The meter requires an SCNR of >15-20. Above 25 is acceptable and above 45 is confirming best performance.
Signal to Noise Ratio (SNR)	SNR measures the ratio of the desired signal's strength to the overall background (random) noise within the system. It represents how much stronger the actual measurement signal is compared to all the random, unwanted noise which includes any unpredictable interference or electrical disturbances that may be present in the environment, power supply, or cabling. Should be above 5 above 20 provides best stability.
VariAmp	Signal amplitude variation is often caused by liquid aeration or particulates within the liquid. For a gas meter, it indicates the presence of moisture or particulates in the gas. When conditions are optimal, this value typically remains below 3%.
VariTime	Signal time variation is a measure that indicates the level of turbulence within the medium being monitored.. The scale used for this measurement is the same as that for Variamp, providing a consistent reference for assessing changes in flow dynamics and ensuring that any turbulence is accurately detected and addressed.
Signal Quality **(on display during installation)**	Signal quality describes similarity of up- and downstream signal shape. The signal quality indicator is highly useful for establishing confidence in the measurement, based on the meter's analysis of the transducer signal quality.
Signal Strength **(on display during installation)**	The signal strength of an ultrasonic signal indicates how effectively the signal is transmitted and received through the pipe wall and medium. Flexim displays this signal strength as a percentage ranging from 0 to 100% or 0-10 bars.

Figure 4 Summary of Key diagnostics as used in Flexim Meters

4 Automatic evaluation of diagnostics to evaluate the health status of the installation

Verification after installation verifies that the installation was carried out according to specifications and that the measurement is operated within the specified application limits.
The diagnostic data recorded immediately after installation forms the reference for regular verification. Changes in the diagnostic values compared to this reference enable early fault detection.
Regular verification supports documentation.

Verification during installation is completed with an **installation report** documenting the conditions, set-up and diagnostics of the meter after installation.

Verification measures during maintenance are documented by **a maintenance report**. This report shows the changes in meter condition since installation. It evaluates the **trend of diagnostics to predict potential meter failures**.

If a change in installation is required during maintenance to improve meter performance, a **maintenance change report** can be generated to document the changes and the impact of those changes on the diagnostics.

Flexim clamp-on meters support this reporting with automatic report creation and analysis within the Meter Support software.

5 Summary

Digital signal processing in ultrasonic clamp-on meters enables comprehensive diagnostics. These metrics ensure optimal installation, detect operational deviations, and improve process understanding. Long-term monitoring supports measurement reliability.

Accurate diagnostics are essential for optimizing the performance of clamp-on flow meters. Understanding diagnostic values and limits enables the identification of operational discrepancies and informs necessary adjustments.
This paper encapsulates diagnostic strategies to enhance the reliability and accuracy of clamp-on flow meter systems.

6 REFERENCES

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