Low Pressure Gas Measurement Using Ultrasonic Technology
Class # 1195.1

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Introduction

The utilization of ultrasonic metering as a cost effective form of measurement has grown dramatically over the past 10 years. A growing portion of this market is in custody transfer applications. This growth is primarily due to growing acceptance in industry, advances in the technology, extensive self diagnostic capabilities and industry /regulatory standards and recommendations related to their use in custody transfer applications.

With the research and development which has been completed to date, ultrasonic meter use in domestic /residential and high pressure applications has been proven and has widespread acceptance. New research and development is being done to address the segment of the market which poses additional challenges in the use of this technology. This is the use of these meters in atmospheric and low pressure applications such as gas distribution systems, and industrial fuel gas measurement.

Ultrasonics in Atmospheric and Low Pressure Conditions

It is difficult to transmit ultrasonic energy into a gas because of the mismatch of acoustic impedance between solid matter (transducer) and gas. This mismatch decreases as the gas pressure is increased (i.e. gas density increases). Air at ambient pressure is a worst case scenario.

Although all gases will attenuate the signal, the strength of the received signal is also dependent on the meter size (longer path lengths result in increased attenuation) and frequency of the transmitted signal.

Signal to Noise Ratio (SNR)

Consideration of the Signal to Noise ration is imperative to understanding the limitations of ultrasonic meters. The signal quality (and therefore measurement accuracy) deteriorates once the SNR drops below a predetermined value. This value is predicated by the algorithm(s) utilized for the signal analysis.

There are various potential sources for noise in a measurement facility. The most obvious and significant is that emanating from pressure regulators. Additional sources of noise are protrusions into the piping (i.e. thermowells) and even the flowing gas itself. As such, the ultrasonic meter must be able to deal with noise in most applications.

The theory of noise emission and propagation is described comprehensively in [2]. Basically, sound waves in a gaseous medium always propagate in a directional fashion from their source. The sound pressure at a certain point is proportional to the amplitude of the sound-emitting source and decreases exponentially with the distance l from the source of sound. During its propagation, the sound wave is weakened as a result of interactions with the medium (attenuation α). Sound energy is transformed into thermal energy due to the viscosity of, and heat conduction in the medium.

The sound attenuation is very dependent on the properties of the fluid (gas) and the frequency f of the transmitted signal. Since, in the case under investigation, a similar medium is used all the time, this relation can be simplified as follows:

$$\alpha \Leftrightarrow f^2 \qquad (1)$$

If a sound wave hits an interface, its energy will be distributed into a different direction. The distribution will be the result of diffraction and reflection. The ratio of wavelength of the acoustic signal and the dimensions of the disturbing object play a major role here. Also, the ratio of reflector to transmitter surface area defines the resulting reflection signal loss [2]. Fig. 1 illustrates this relationship using a 200 kHz ultrasonic sensor.

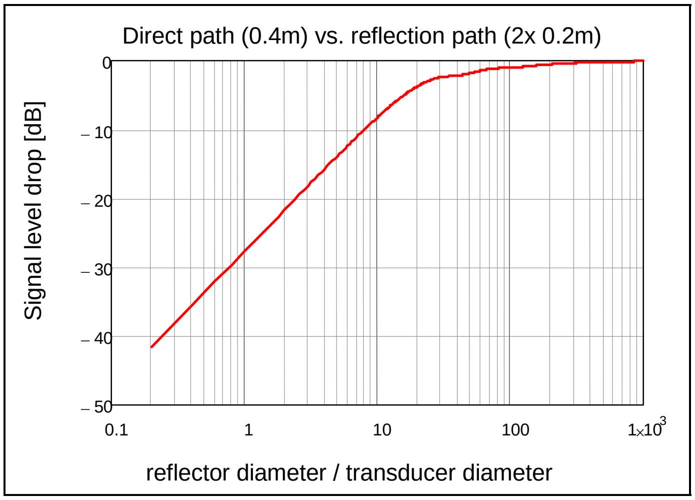


Fig. 1: Signal level loss at a reflective surface compared with direct propagation via the same distance

The ratio of useful signal to interfering signal at the position of the receiver can thus be expressed as follows:

$$SNR = 20 \cdot \log\left(\frac{L_{\text{Ultrasonic Signal at Receiver}}}{L_{Noise}}\right)[dB] \qquad (2)$$

Measures to Improve Meter Suitability to Ambient and Low Pressure Applications

It is not economically practical to remove all noise from a measurement facility. Noise from regulators can be minimized by piping configuration and proximity of the regulator to the meter. Noise reduction measures for regulators are discussed in [1]. The most practical ways to increase the Signal to Noise ratio are:

a) Maximize the sound power to the receiving transducer
b) Optimize signal processing with the target to have a minimum limit value for the SNR, where the meter stops giving reliable results.
c) Selecting a frequency range which is relatively insensitive to other noise (background) generated in the piping.

Optimizing Signal to Noise Ratio at the Receiving Transducer

Path Layout

The sound burst emitted from the transmitting ultrasonic sensor is attenuated in the same way as the interfering noise. The geometric distance between the sensors on each measurement path should therefore be as short as possible to ensure maximum signal strength at the receiving sensor. Each point of reflection in the measuring path normally weakens the useful signal level (see Fig. 1).

The signal level chart in Fig. 2 illustrates the effect of bouncing or reflecting the sound signal. It shows the signal level passing from the transmitter to the receiver of the ultrasonic measuring path for a single-reflection arrangement in contrast to a direct arrangement. The sensor frequency and the angle between measuring path and flow axis shall be the same in both cases. The signal emitted at the position of the transmitter (level A) is attenuated on its way to the receiver. While the direct signal still has about e.g. 70 % (level B) of its original level in this example when it arrives at the receiver, the bounced signal is further attenuated because it travels twice the distance, and because there is an additional loss at the point of reflection.

The noise level in the received signal consists of both electric noise caused by the signal amplifiers and additive noise signals collected by the receiving sensor. Modern, closed-loop amplifier electronics modules (automatic gain control AGC) allow dynamic amplification ranges of 86 dB (1 : 20,000) to be processed without any limitation through electronic noise.

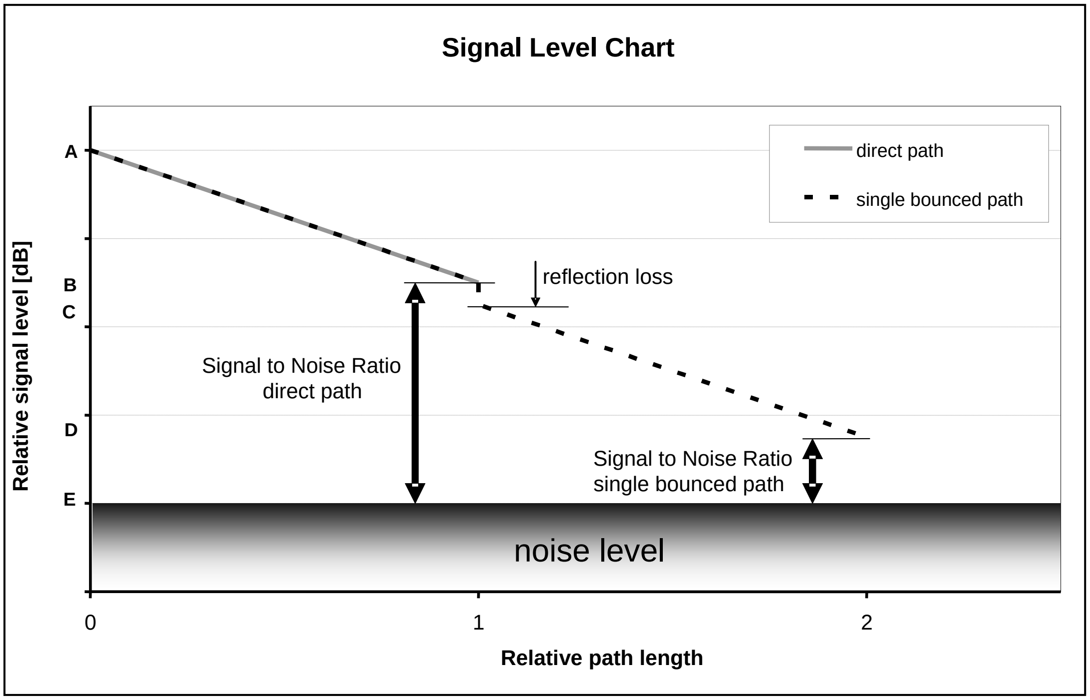


Fig. 2: Signal level chart – basic principle

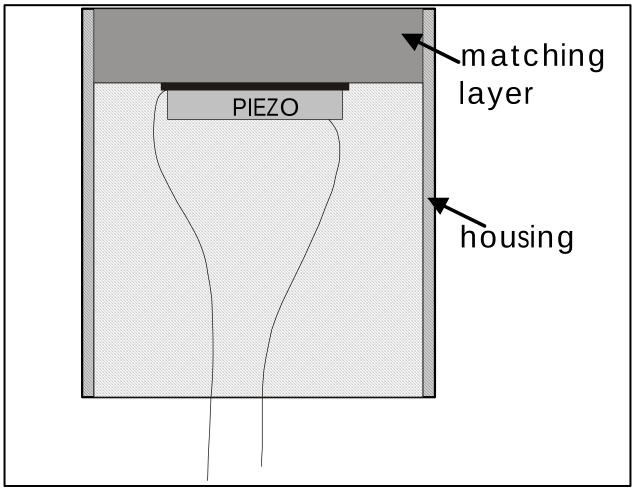
Ultrasonic Sensors

Transducers for ultrasonic gas metering are usually of a piezo-ceramic type. The piezoelectric transducer itself is basically a thin disc. Two different vibration modes can be distinguished:

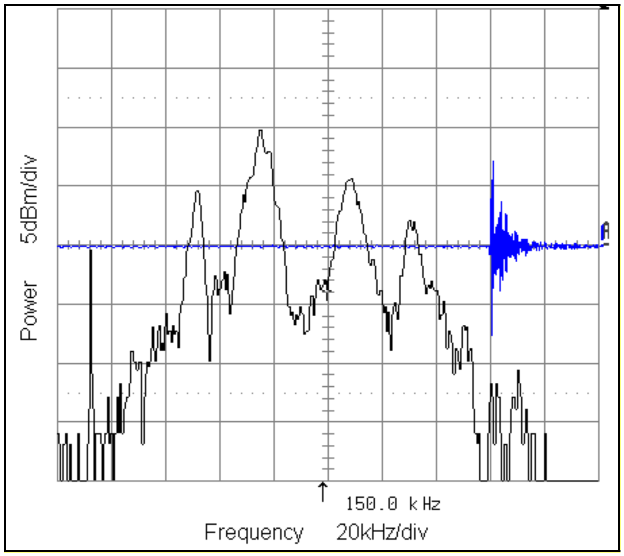
- the radial vibration mode and
- the thickness vibration mode.

If an alternating voltage is applied to the electrodes of the piezo-ceramic elements, their geometry will change. This generates a mechanical oscillation with the frequency of the alternating voltage. The maximum usable electric energy is limited because of the intrinsically safe design of the sensor circuits, which is required in this specific application. Further, because of the acoustic impedance jump between the oscillating surface and the gaseous medium, only a small portion of the energy is transmitted into the medium. In order to achieve the necessary efficiency of the energy transformation and to increase the sound pressure transmitted into the gas, the mechanical oscillation amplitude is amplified by a coupled mechanical oscillator.

Due to their simple design, bimorph transducers (see Fig. 3) are widely used. These transducers have an acoustic matching layer which adheres to the ceramic element and performs this energy transformation. This layer is made of epoxy resins using hollow glass spheres and its thickness is dependent on the working frequency of the ultrasonic sensor. The alternating electrical field excites the piezoelectric disc so that it starts oscillating radially. The radial movement is transformed into an axial movement by the adhering matching layer. Great shear forces must be transmitted by the adhesive layer. In order to protect the epoxy resin of the matching layer from the corrosive effects of gaseous components such as hydrogen sulfide, the layer may be covered by a thin metal foil. However, this leads to a reduction in the amplitude of the transmitted acoustic signal and in the reception sensitivity [5].



a) Schematic diagram

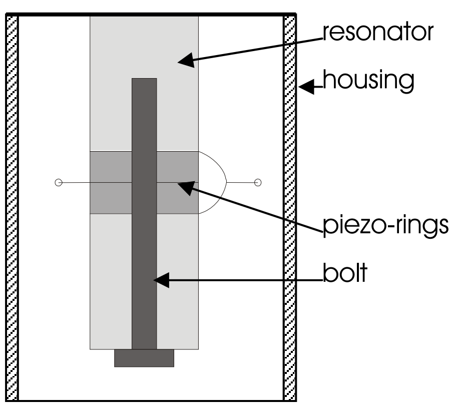


b) Acoustic spectrum of the sound signal

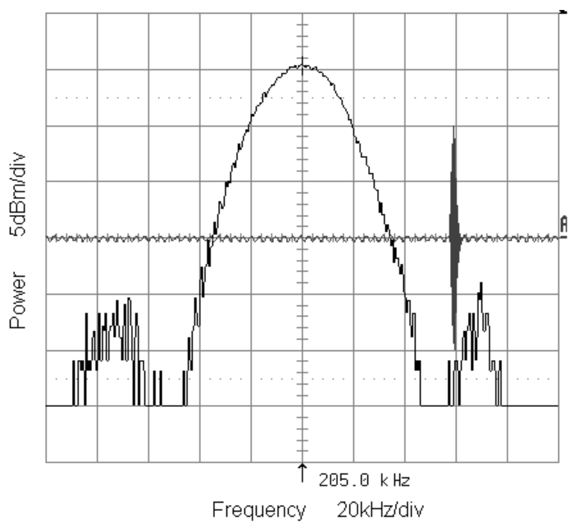
Fig. 3: Bimorph transducer

The acoustic matching layer could be left out if it were possible to achieve sufficient vibration amplitudes at the sound emitting surface. This idea leads to a stacked piezoelectric transducer in the form of a resonance converter. A metallic spring-mass-system is used to increase the amplitude at resonance (see Fig. 4a). Utilizing numerical optimization of mechanical and electrical parameters it is possible to produce sensors which exhibit

- sufficient bandwidth for short signals at great amplitude, and
- a maximum acoustic efficiency.



a) Schematic diagram



b) Acoustic spectrum of the emitted sound signal

Fig. 4: Stacked ultrasonic transducer

This sensor concept is characterized by pure tone resonance mode and a well-defined working range (see Fig. 4b). There are several advantages:

- the energy is efficiently transformed into acoustic energy,
- the transducer is hermetically sealed and has a full metal housing and
- the bandwidth allows relatively short pulse signals.

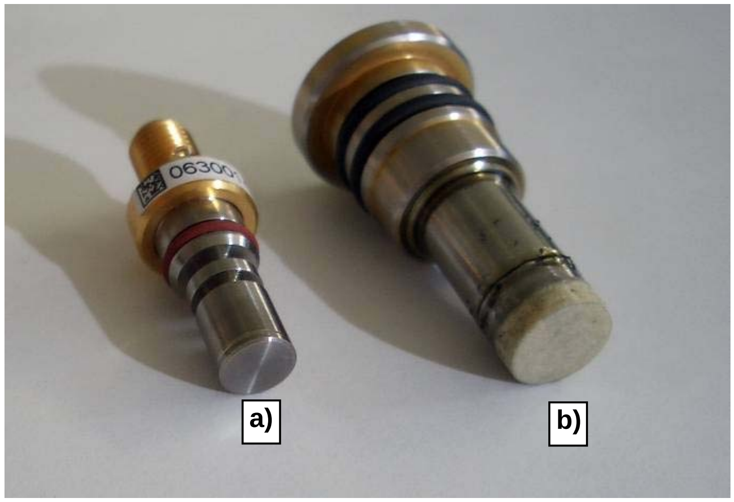


Fig. 5: Examples of two transducer designs
a) without and b) with matching layer

Signal Processing

Generally, the SNR may be improved with the help of signal averaging methods or signal coding. However, specifically in gas flow metering applications the problem is that the signal path is modulated due to turbulence in the flowing gas. This limits the efficiency of the averaging and encoding methods. According to the signal theory, correlation methods provide optimum results in signal transit time measurements, but they cause great computational load during the digital signal processing.

If the SNR falls below a minimum threshold defined by the signal processing algorithm, faulty measurements of the signal transit time may occur. This must be prevented through adequate monitoring and analysis of the received signal quality, otherwise significant measuring errors of the gas velocity would occur.

Frequency selection

Based on the foregoing explanations, optimization criteria for the transducer frequency can be set out.

When a high level of external noise such as that from regulators is anticipated, ultrasonic sensors with a working frequency which is as high as possible are recommended because:

- the noise signals emitted by the pressure regulator are significantly weakened at frequencies greater than 100 kHz;
- the frequency-dependent attenuation of the noise signals at a given distance to the pressure regulator causes lower noise levels compared with lower frequencies.

When certain conditions exist which have a tendency to weaken the signal more than normal, then lower frequencies are recommended (i.e. 130, 80, 40 kHz). These conditions are primarily:

a) High CO_2 content
b) High H_2S content
c) large meters at ambient conditions
d) extremely turbulent conditions

The reason for this selection is the frequency dependent attenuation of the waves in the gas. Lower frequencies are attenuated less by the gas while diffraction and variation of amplitude has a lesser impact than at higher frequencies.

Meter optimized for low pressure applications

Taking into consideration all of the aforementioned requirements, an ultrasonic meter which is relatively insensitive to noise, and can operate in low pressure applications would have the following characteristics:

a) chordal direct path design with four independent paths which are configured in parallel in one plane so as to cover the entire cross-section of the pipe. This layout also has the advantage that it is very insensitive to asymmetrical and swirling flow profiles
b) ultrasonic transducers mounted in the meter are stacked type transducers, which work according to the thickness vibration principle, and are available with working frequencies of 80, 130, 210 kHz and 350 kHz

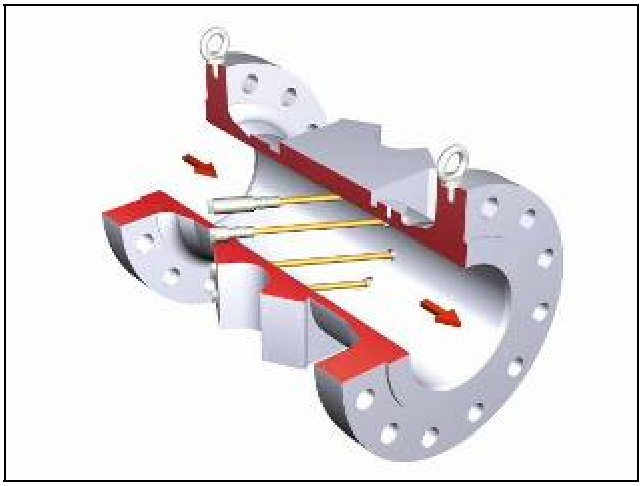


Fig. 6: Chordal 4-path layout of the FLOWSIC600

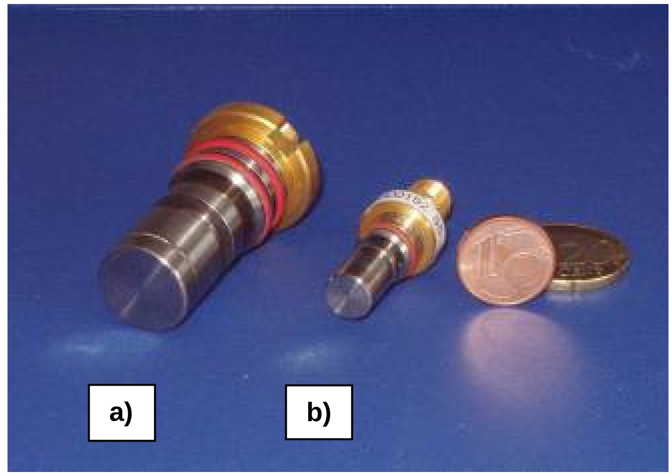
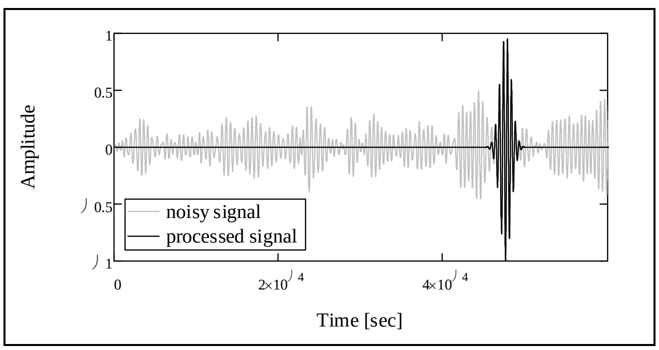
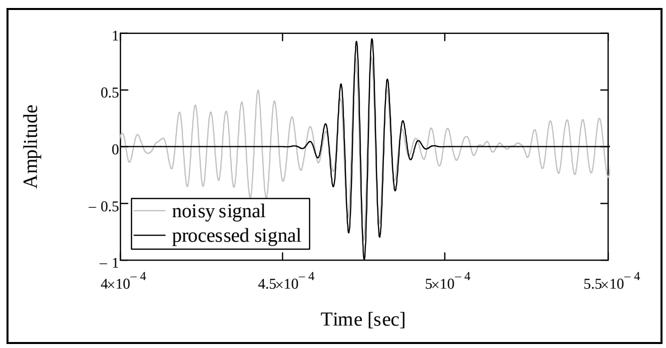


Fig. 7: High performance ultrasonic transducer, a) 210 kHz and b) 350 kHz

c) Signal processing technology which utilizes correlation methods and acceptance criteria which can clearly detect the received signal at extremely low Signal to Noise ratios.



a) noisy signal at SNR = 6 dB



b) zoomed detail showing the ultrasonic burst

Fig. 8: Signal processing in the FLOWSIC 600 - example of a noisy signal reception (SNR = 6 dB)

The signal processing algorithm analyses the received signal to determine the portion which comes closest to the signal model. With extensive plausibility checks, it can be ensured that the measured value is correct even when performance is as low as 5 % (i.e. 95 out of 100 received signals rejected). The signal is evaluated with respect to:

- position in a time frame (not too early or too late)
- amplitude (not too small or overloaded)
- SNR (above the minimum required level) and
- degree of congruence with the model signal

Only if all of these criteria are met, will a threefold transit time calculation be conducted according to different criteria in the signal. At least two of the three calculated transit times must be identical for the result to be validated.

Field Applications – High noise and Low pressure

It is one thing to gather and apply theory to various aspects of a system. It is another to combine all these elements into a functional unit which works in real world conditions. The following shows a few examples where high noise, low pressure or both were present in the measurement system.

Example 1: This is a fuel gas measurement facility with a supply pressure ranging from 400 to 900 psig. The regulator reduces the pressure to 50 psig. As can be seen the piping between the regulator and the meter has been configured to attenuate as much noise from the regulator as possible. The 4-inch ultrasonic meter is a 2-path meter and is not used for custody transfer

a) Regulator and upstream piping b) meter and downstream piping

Fig. 9: Upstream and downstream piping configuration – 50 psig measurement application

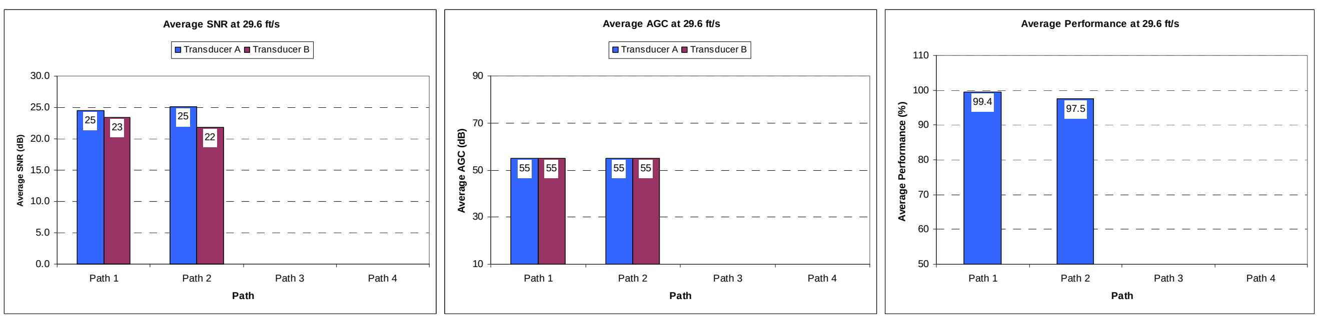


Fig. 10: SNR, AGC, and Performance diagnostic charts

From the above diagnostic charts it can be seen that the meter is not having any problems with noise and low pressure. The SNR is well above the minimum recommended level of 13 dB, although the downstream transducers are seeing slightly more noise due to the fact they are facing in the direction of the regulator. The AGC is also well below the maximum, and the performance indicates excellent signal quality with minimal rejection.

Example 2: This is a low pressure measurement facility supplying fuel to a power boiler at a co-generation facility. The gas is being measured at a pressure of 13 psig (90 kPa). In the Czech Republic, ecological taxes were imposed on all fuels effective January 1, 2008. Only fuel used for co-generation purposes is tax exempt. For this reason fuel used in this type of application must be measured independently from fuel used for other purposes. Monthly volumetric information from the three ultrasonic meters (two 8-inch and one 10-inch) installed at this power station is utilized for invoicing purposes.

Fig. 11: Meter installation for 13 psig fuel gas measurement

Example 3: This meter is measuring air flow at atmospheric conditions. As can be seen from the AGC, SNR Performance and waveforms, the meter is not having any problems under these conditions.

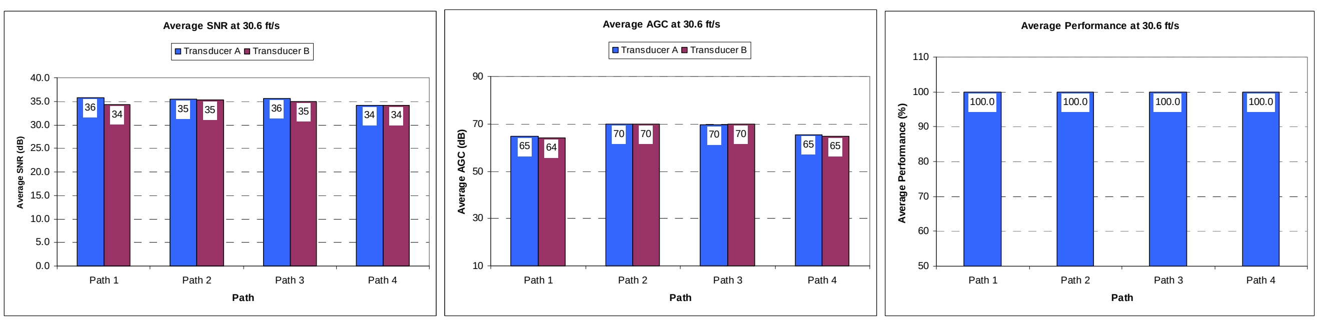
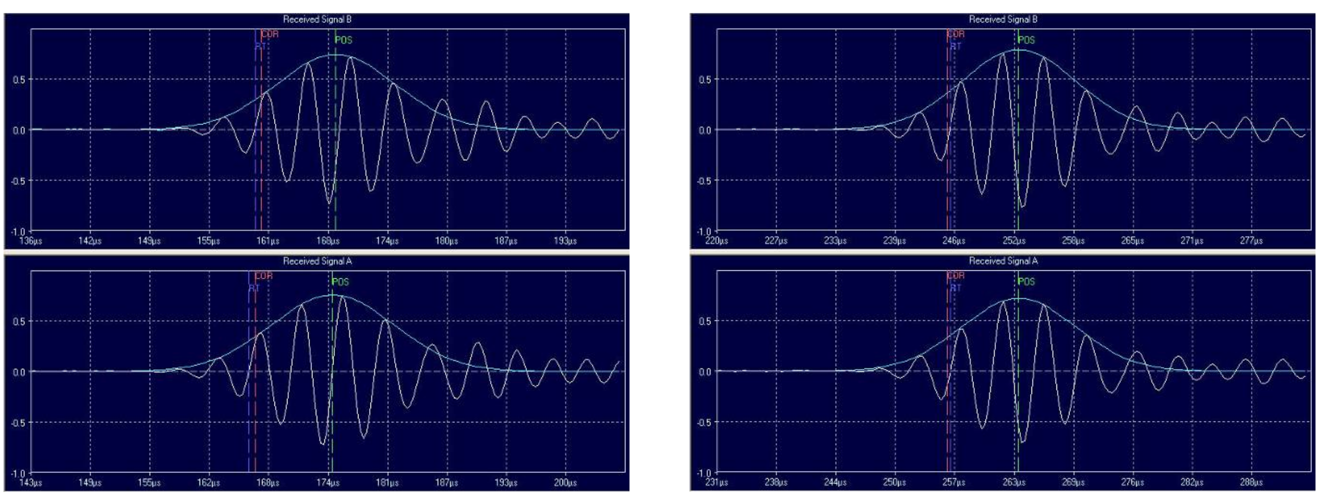


Fig. 12: SNR, AGC, and Performance diagnostic charts



Path 1 Waveform

Path 3 Waveform

Fig. 13: Waveforms – Atmospheric air measurement at 30 ft/s

<u>Ultrasonics in an atmospheric test facility</u> [8]

With the capability to measure gas at atmospheric conditions, the concept of utilizing ultrasonic meters in an atmospheric pressure test facility became a viable option. Some of the benefits of using ultrasonic meters as reference meters include:

- Minimal metering requirements due to high turndown ratio
- Minimal pressure loss resulting in reduced operating costs
- Built in real time meter diagnostics for monitoring meter health

For this purpose, a totally new test rig layout was developed in close co-operation between the PTB [German national metrology institute providing scientific and technical services] and SICK MAIHAK. This was primarily done because the existing testing rules [1b] did not contemplate all aspects of such a test facility, especially since the use of ultrasonic meters as flow standards at atmospheric pressure is a completely new concept.

After considerable study and evaluation of design ideas, it was concluded that the test section would be a single straight section of pipe that was symmetrically balanced within the test room. This was to ensure that the flow approaching the test section was as laminar as possible.

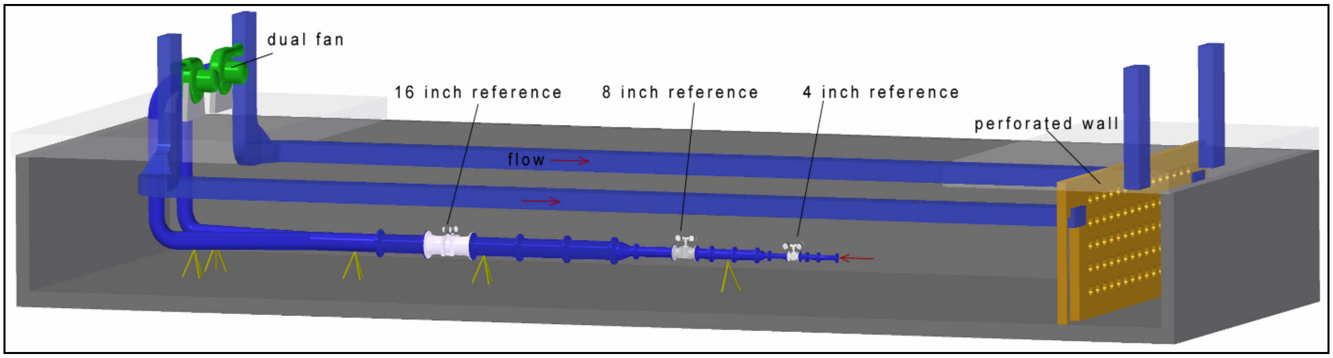


Fig. 14: Overview of the test facility set-up

The test section consists of 3 reference standards, a 16-in, an 8-in and a 4-in ultrasonic flow meter. In order to minimize installation uncertainties, each working standard is a rigidly joined assembly with a 10D inlet section which includes flow conditioners located 2D and 10 D upstream of the meter. Fig. 15 shows the 16-in reference standard package. This set-up also results in an improvement of the flow downstream of diffusers (reducers) that are required if the meter under test has a smaller nominal diameter than the working standard used.

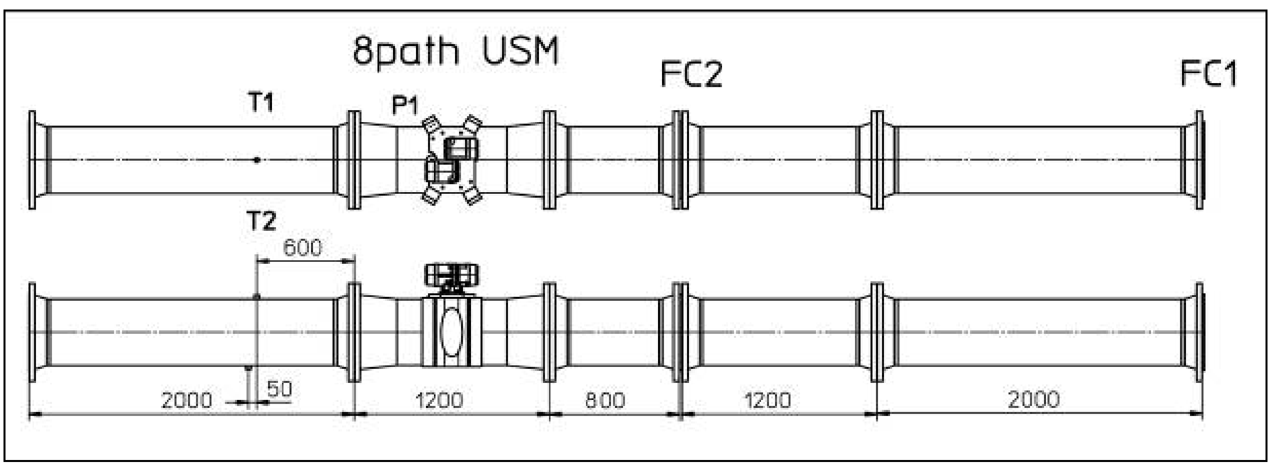


Fig. 15: Set-up of 16-inch reference package

The measurement uncertainty of ultrasonic meters caused by flow perturbations may be reduced by increasing the number of paths in a suitable configuration. To meet this requirement 8-path meters were used as working standards covering a total flow rate range of 350 to 350,000 ACFH (10 to 10,000 m^3/h). The meters basically consist of two 4 path meters in one meter body each with its own independent electronics. See Fig. 16.

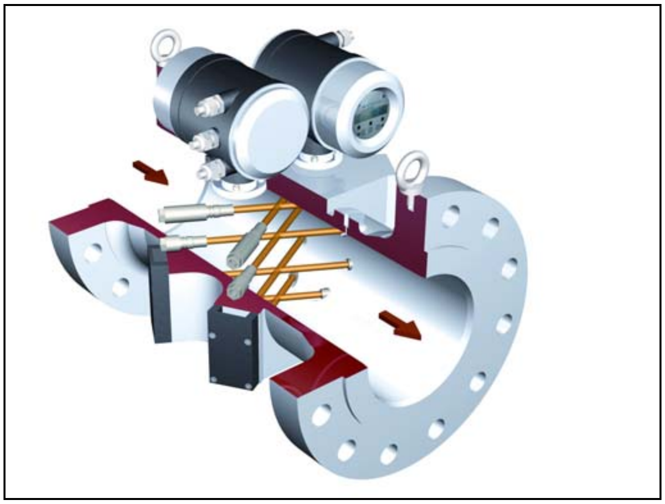


Fig. 16: 8-Path reference meter

Finally, a first comparative measurement of the working standards against each other is presented as a further proof of the accuracy of the new test facility. After calibration at the PTB test facility at Brunswick, Germany, all three reference meters were installed into the test section. A comparison measurement of the 4-inch working standard against the two larger ones was performed. The result is shown in Figure 17. Deviations of 0.1% maximum have been experienced over a measuring range down to 100m³/h for the 16" reference meter and 50m³/h for the 8" reference meter. This is definitely within the limits of the target accuracy, taking into account that an uncertainty of 0.1% must be attributed to each working standard and all deviations caused by disassembly, transportation, and reassembly are contained as well.

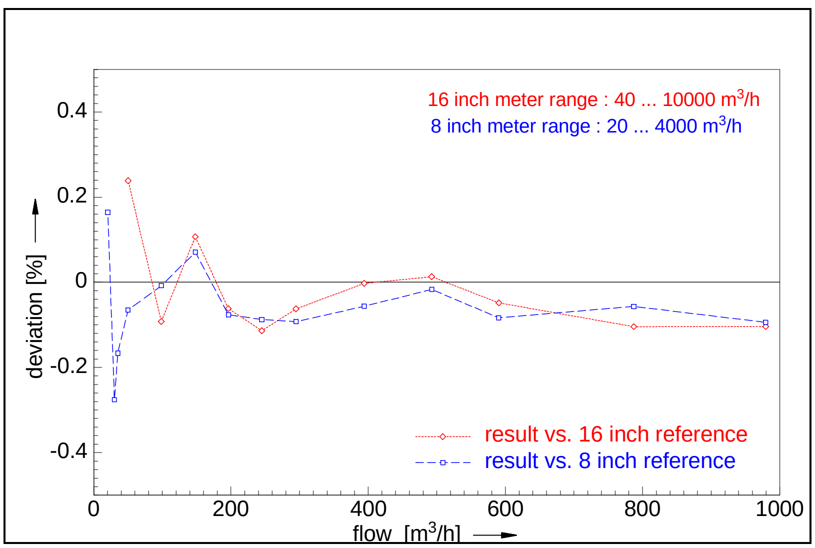


Fig. 17: Comparison between 4-inch, 8-inch and 16-inch reference meters

The atmospheric test facility offers a cost effective possibility for checking the accuracy of the ultrasonic flow meters. Especially for low pressure applications (less than 60 psig) an ambient air calibration is a commonly used method.

This new test Stand is presently used to evaluate, the possible correlation of ambient pressure calibration data to the high pressure calibration data of meters. For this reason ambient air calibration data, derived at the Dresden facility, are compared to high pressure calibration data made with the identical meter. The purpose is to statistically prove the additional uncertainty which would be obtained when using a low pressure calibration instead of a high pressure calibration.

Figure 18 shows a preliminary collection of data from 4 Inch meters. The 4" size has been selected since this small meter size is the most critical one for obtaining high accuracy with minimum uncertainty.

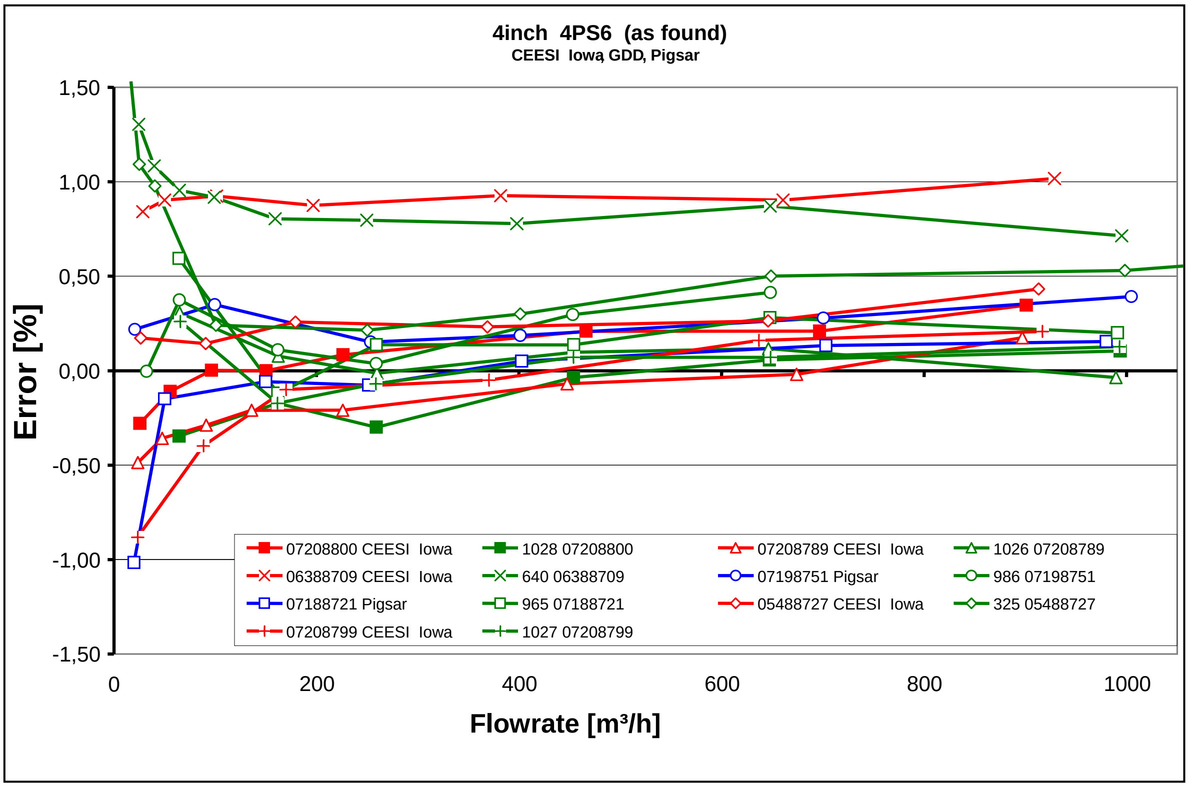


Fig. 18: Comparative results for ambient and high pressure flow tests

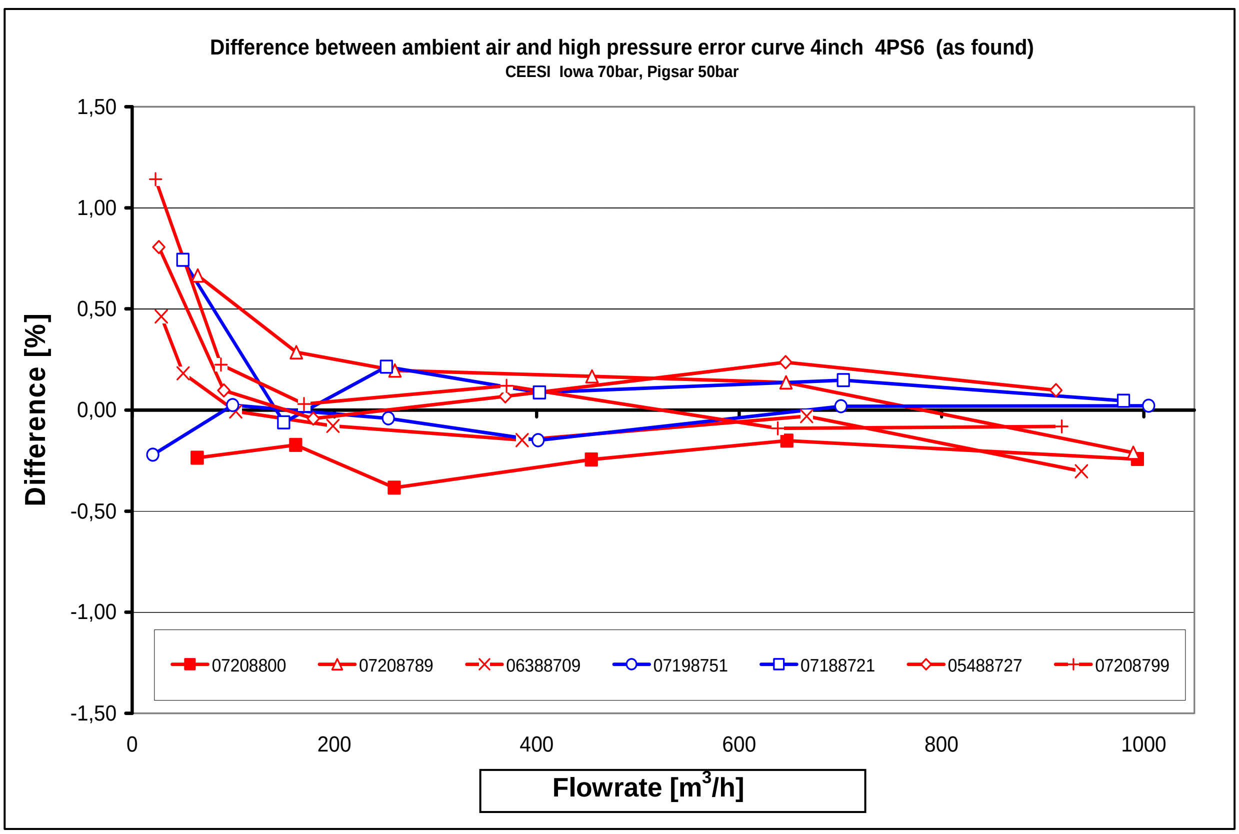


Fig. 19: Differences between high pressure and ambient pressure test results

These data show an agreement of the corresponding baselines in ambient pressure and high pressure which is within the range of uncertainty of the test stands. Meter S/N 06388709 was approximately 1 % off at the ambient calibration. This was confirmed during the high pressure calibration at the CEESI flow test lab at a pressure of 1015 psia (70 bar). The results of the Pigsar® are at 725 psia (50 bar) test pressure.

Figure 19 shows the differences between the ambient and high pressure test results contained in Fig. 18. The graph shows a close agreement between the ambient and the high pressure test labs which is almost all in the combined measurement uncertainty of the labs.

Conclusions

Significant advancements in the use of ultrasonic technology for gas measurement purposes have broadened the field of application. It is now possible to accurately measure gas with an ultrasonic meter at pressures below 100 psig, even down to atmospheric pressure. Many of these applications are in the gas distribution industry, and fuel gas supplies to boilers and power equipment. A significant number of these facilities also include pressure regulators, often in the near vicinity of the meters. Utilizing appropriate transducers in these applications along with noise attenuating piping eliminates the effects of the noise generated from the regulators resulting in no degradation of measurement quality.

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