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Paper 3.3

Coded Multiple Burst (CMB) Signal Processing Applied to Ultrasonic Flow Meters in Applications with High Noise Levels

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1 INTRODUCTION

As ultrasonic meters have replaced traditional measurement technologies during the past ten years, the applications have become more demanding.

One of the most challenging problems for designers to overcome has been the operation of meters near large noise sources such as control valves, regulators and flow conditioners. While following proper installation procedures has helped, many solutions have undesirable trade-offs. Mechanical silencing devices are effective noise blockers but come at a cost in the weight and space budget. Signal averaging techniques (stacking) may help in certain situations but are limited by instabilities in the flow and the associated delays inherent to the process itself.

Instromet has developed a signal processing technique using a frequency domain algorithm combined with a broadband ultrasonic transducer to detect ultrasonic signals in environments previously too hostile. This technique, called Coded Multiple Burst (CMB), has the added advantage that meter update times do not increase, in fact using the Series IV Electronics platform, the system operates with the highest burst rate available on the market today.

This paper will present the results from real-world, field installations comparing the contrasting new technique with traditional techniques. In addition the paper will examine the design criteria which may influence the ability of ultrasonic meters to operate accurately in a noisy environment.

2 ULTRASONIC NOISE MODEL & ISO.

During the mid 90's Instromet became aware of the Ultrasonic noise (US-noise) problem when installing an Ultrasonic Flow Meter (UFM) in the vicinity of a pressure regulating valve. Due to the pressure reduction in the control valve, energy is dissipated in the valve. The energy dissipation will result in high energetic vibrations like audible and ultrasonic noise. The produced levels of ultrasonic noise may exceed the signal strength of the ultrasonic meter and flow measurement becomes impossible.

Instromet felt obliged to it's customers to develop a model which predicts the functionality of the Instromet UFM in the vicinity of a pressure regulating valve. This model takes account of the specific process conditions and installation used by the customer.

The US-noise model has been published before. Initially it was presented, together with Ruhrgas during the 16th North Sea Flow Measurement Workshop 1998 [1]. The presented model has been proven to be successful and as a result it is going to be implemented in the new ISO standard for ultrasonic gas flow meters [4].

2.1 Theory of the ultrasonic noise model.

The ultrasonic noise model is based on three phases:
1. Noise emission by the pressure regulating valve
2. Noise propagation through a pipeline from the valve to the UFM
3. Signal strength of the UFM

2.1.1 Noise emission

The basis of the US-noise model is the theory on valve noise emission described by G. Reedhof and W.C. Ward [3]. An equation is presented, which predicts the amount of acoustic energy, produced by a regulator:

$$E_a \Leftrightarrow Q_m \cdot c^2 \left[\frac{2}{\gamma - 1} \left\{ \left(\frac{P_1}{P_{vc}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \right]^{5/2} \left(\frac{P_1}{P_{vc}} \right)^{\gamma + \frac{1}{\gamma} - 1} \qquad (1)$$

Here E_a is the acoustic energy, Q_m is the mass flow rate, c the speed of sound and γ is the ratio of the heat capacity at constant volume and constant pressure. For natural gas a value for γ of 1.3 is valid for a wide range of process conditions. The pressures mentioned in the equation are the upstream pressure, P_1 and the pressure in the vena contracta, P_{vc}, being the smallest cross-section in the regulating valve with the highest gas velocities (sometimes supersonic). Simplifying equation 1 results in a relation between the acoustic energy E_a and the pressure and flow rate:

$$E_a \Leftrightarrow \left(P_1 / P_{VC} \right)^2 \cdot Q_m \qquad (2)$$

To define the response of an acoustic transducer (piezo crystal), it is not the acoustic energy but the acoustic pressure which is relevant. The relationship between acoustic pressure and acoustic energy is given by:

$$p_a = 2 \cdot \sqrt{\frac{E_a \cdot \rho \cdot c}{A}} \qquad (3)$$

Where, A is the area and ρ is the density. Combining equation 2 and 3, results in:

$$\text{noise}_{\text{valve}} \Leftrightarrow P_1 / P_{VC} \cdot \sqrt{Q}_m \qquad (4)$$

The difficulty of using the above relations based on Reedhof and Ward, is the determination of the P_{vc}. Relations are given by Reedhof and Ward which describe the pressure within the vena contracta with respect to opening of the valve and other process parameters like downstream pressure. Resulting from the practical measurements done by Instromet, a simpler and more useful relationship between the acoustic noise emitted by a valve and the operating pressures could be determined:

$$\text{noise}_{\text{valve}} \Leftrightarrow \Delta P \cdot \sqrt{Q}_n \qquad (5)$$

Here, ΔP is the difference between the upstream pressure and the downstream pressure of the control valve and Q_n is the normalised flow rate. In order to use this equation for a specific type of valve and trim, a valve-weighting factor, N_v is defined:

$$\text{noise}_{\text{valve}} = N_v \cdot \Delta P \cdot \sqrt{Q_n} \qquad (6)$$

The valve-weighting characterizes only one valve-trim combination. Each valve and each trim has another valve-weighting factor, which determines how noisy a particular valve-trim combination is. A high N_v indicates a noisy valve, a low value means a quiet valve.

2.1.2 Noise propagation

In order for noise to propagate through a pipeline, the noise waves are subjected to certain boundary conditions. The high frequencies comply with these boundary conditions and easily propagate through the pipeline. The lower frequencies do not satisfy these conditions and will attenuate easily resulting in a so called cut-off frequency. Acoustic frequencies lower than the cut-off frequency (about 1 kHz) will not propagate through the pipeline. The UFM operates in the high frequency range were the noise propagates easily. To reduce the intensity of these high US-noise frequencies the acoustic wave has to be blocked (interrupting the line of sight). Therefore piping elements like elbows and T's are required to attenuate the US-noise. To define the attenuation of US-noise the attenuation factor N_d is used:

$$N_d = p_{in} / p_{out} \qquad (7)$$

2.1.3 Signal strength of UFM

The perceived signal strength of a transducer is dependent on path length, integration time and the gas pressure (or, more precisely, density),

- Pressure (P): An acoustic pulse is transferred from the solid medium (piezo crystal) to the gaseous medium. During this transition only 1% (or less) of the energy of the acoustic pulses will be transferred into the gas. The transmission efficiency is dependant on the difference in density between both media (solid and gaseous). As so, at high gas pressure, the density difference is smaller and the acoustic signal in the gas is stronger.
- Path length (L): As the path length increases, the signal strength perceived by the receiving transducer will decrease due to the spherical expansion[1].
- Integration time (T): Averaging the ultrasonic signal improves the signal to noise ratio proportional to the square root of the number of pulses being averaged, or equivalent, the integration time[2].

This results in the following equation:

$$\text{Signal} \Leftrightarrow \frac{P \cdot \sqrt{T}}{L} \qquad (8)$$

2.1.4 Signal to Noise ratio (S/N)

Based on paragraph 2.1.1, 2.1.2 and 2.1.3 the "signal to noise" ratio (δ) can be described:

$$\delta = \frac{P \cdot \sqrt{T}}{N_d \cdot N_v \cdot \Delta P \cdot L \cdot \sqrt{Q_n}} \qquad (9)$$

Comparable to the default signal to noise ratio limit of 1, a $\delta_{critical}$ needs to be determined for which:

$$\delta > \delta_{critical} \rightarrow \text{UFM functions}$$
$$\delta < \delta_{critical} \rightarrow \text{UFM fails}$$

2.1.5 Operating envelope

Equation 9 is used to estimate for each type of installation, the tolerance to US-noise. Different parameters in equation 9 like T, N_d, N_v and L are constant for a specific installation. Rewriting equation 9 gives:

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[1] The relation between energy and path length is quadratic (spherical expansion) but the relation between acoustic pressure and path length is linear (eq. 3).

[2] The integration time improves the signal to noise ratio. It does not increase the signal strength. For convenience it is presented as such.

$$\frac{P}{\Delta P \cdot \sqrt{Q_n}} = \frac{\delta \cdot N_d \cdot N_v \cdot L}{\sqrt{T}} \qquad (10)$$

In equation 10 the process conditions are related to installation conditions. Based on the $\delta_{critical}$ a critical parameter related to the process conditions can be defined, $[P/\Delta P\sqrt{Q}]_{critical}$, for which:

$$P/\Delta P\sqrt{Q} > [P/\Delta P\sqrt{Q}]_{critical} \rightarrow \text{UFM functions}$$
$$P/\Delta P\sqrt{Q} < [P/\Delta P\sqrt{Q}]_{critical} \rightarrow \text{UFM fails}$$

The $[P/\Delta P\sqrt{Q}]_{critical}$ is the called the operating envelop for an installed UFM.

2.2 Practical data:

In this paragraph practical results are given related to the in paragraph 2.1 presented theory on US-noise.

2.2.1 Noise emission:

The frequency spectrum of the ultrasonic noise and the valve-weighting factor for different operating frequencies are discussed.

2.2.1.1 Frequency dependency

The noise emission of a control valve as described in paragraph 2.1.1 is frequency dependant. A typical noise frequency spectrum is presented in figure 1. In general it is a broadband spectrum with a maximum between the 30 and 80 kHz. The frequency ranges of importance to Instromet are the 100 kHz (standard transducer) and 200 kHz (noise resistant transducer) ranges. The benefit of having a transducer at a higher operating frequency is the lower level of US-noise, as can be seen in figure 1

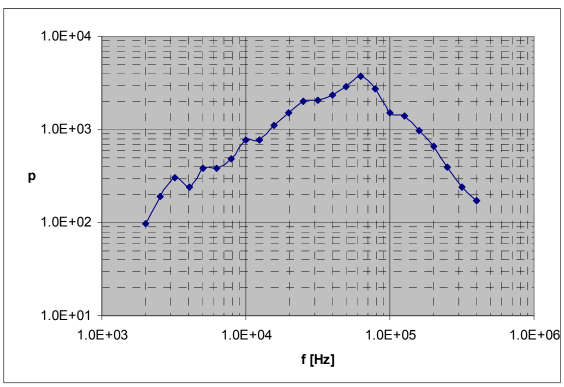

figure 1: Typical ultrasonic noise spectrum of a pressure control valve

2.2.1.2 Valve-weighting factor N_v

The valve valve-weighting factor N_v is defined according to equation 6:

$$\text{noise}_{valve} = N_v \cdot \Delta P \cdot \sqrt{Q_n}$$

A valve-weighting factor needs to be defined for a typical valve-trim combination, in a specific direction (up- or downstream) and for a typical operating frequency (for Instromet the frequency ranges of 100 kHz and 200 kHz are applicable). To determine the valve-weighting factor for different process condition, quantified by $\Delta P\sqrt{Q_n}$, the acoustic pressure needs to be measured. The slope of the linear regression line in the plot “acoustic pressure” versus “$\Delta P\sqrt{Q_n}$” results in the valve-weighting factor.

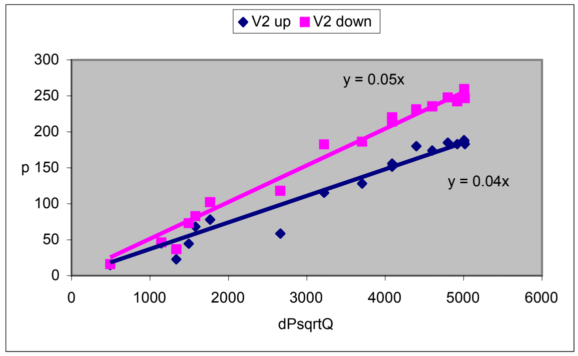

figure 2: Determine of valve-weighting factor: N_{v_up}= 0.04, N_{v_down}= 0.05

2.2.2 Noise reduction by piping elements:

To define the attenuation of piping elements the ratio of, the acoustic noise going into the element and the noise leaving the element, is used. In figure 3 the attenuation is given for a bridge of piping elements consisting of two T's en two capped elbows. The slope of the linear regression line in figure 3 is the attenuation factor N_d.

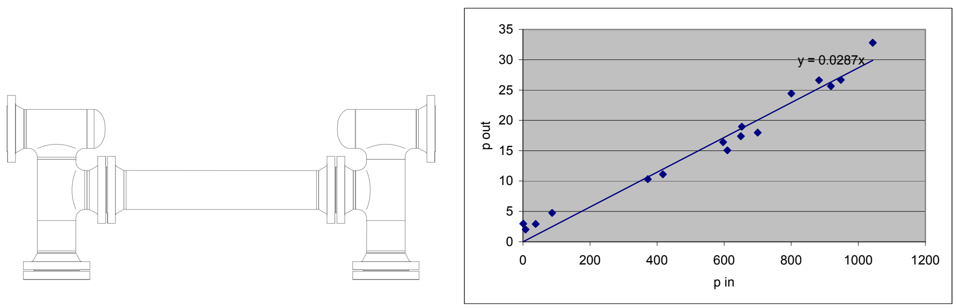

figure 3: Attenuation of piping elements: N_d = 0.0287 or 31 dB

3 CODED MULTIPLE BURST VERSUS STACKING

In equation 9 the dependency of signal to noise in relation to sampling time or averaging is presented. Statistics teaches that if a signal is contaminated with additive uncorrelated noise, averaging of "T" observations will increase the signal to noise ratio by a factor of "√T". Averaging of acoustic pulses (or stacking) however can not be used without restrictions. The drawbacks are:

1. Averaging will slow down the update rate of calculated results.
2. Averaging of an acoustic pulse is only possible if the turbulence within the gas stream does not produce jitter (time shift) in the order of magnitude of the periodicity of the acoustic pulse.

The stacking technique and its drawbacks and a more sophisticated "averaging" technique called Coded Multiple Burst (CMB) are explained in the following paragraphs.

3.1 Stacking

Stacking or averaging is a well known technique and often used. It is based on general statistics and assumes a stochastic nature of the noise. Due to its stochastic nature, the noise components in the measurement will be uncorrelated and will cancel out the averaged result. Averaging the measurements means repeating the measurements several times. This can be very time consuming and will seriously affect the update rate of the meter.

Also averaging will only work in steady state situations. This means that the flow rate has to be stable over the duration of all measurements. But even within these steady state situations, the stability of the arrival time of the acoustic pulses is limited. Turbulence in the gas stream causes small variations in the arrival time of the acoustic pulse. These variations in arrival time are called jitter.

When the jitter is small, relative to the time period of the acoustic pulse, averaging of pulses gives a good result (see figure 4).

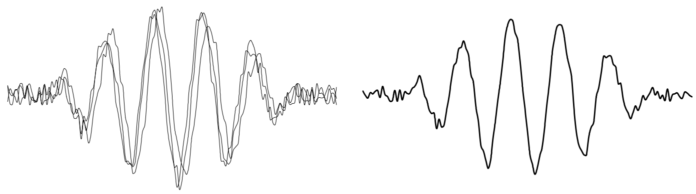

figure 4: Three pulses & noise with low Δt (jitter) and the averaged pulse

However, if the time shift due to the jitter is within the range of the period of the acoustic pulse, averaging will not give an acceptable result (see figure figure 5).

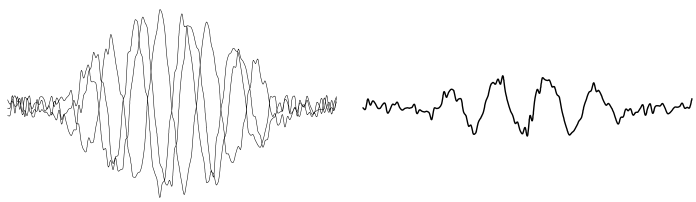

figure 5: Three pulses & noise with large Δt (jitter) and the averaged pulse

Jitter is caused by turbulence. Turbulence consists of eddies in the gas flow. Typically, large eddies have a low frequency but cause a large jitter. Small eddies have a high frequency and cause small jitter. This means that, when measurements are taken a long time apart (as is the case with the traditional stacking technique), the jitter will be high. When measurements are taken at short time intervals, jitter effects will be smal.

3.2 Coded Multiple Burst

To overcome the effect as described in paragraph 3.1 the averaging process has to be speeded up. This high speed averaging is incorporated into the coded multiple burst technique. Also by inserting a unique code into the pulse transmission sequence the tolerance to noise is improved. Finally a more efficiently use of time by the UFM will maintain the measuring update time.

In the following example the inefficient use of time by an UFM is demonstrated:

> *A pulse has a typical length of about 5 periods. The operating frequency is 200 kHz (T = 5 μs), so the duration of an acoustic pulses is 25 μs.*
> *The time of flight of an acoustic pulse for a 16” meter (axial path length is 0.9 m) with velocity of sound is 400 m/s, is 2.25 ms.*
> *This indicates that the UFM is only operating 1% of its time, to produce an acoustic pulse, and is waiting 99% of its time for this acoustic pulse to arrive.*

By using the CMB technique instead of waiting for the first pulse to arrive, almost immediately a second pulse is transmitted, and a third, fourth,…..etc. The same time is now is used to transmit and receive multiple pulses (burst). The multiple pulses transmitted and received improves the signal to noise significantly, without the need to slow down its measuring process.

In figure 6 this process is demonstrated. 17 pulses are transmitted after each other in a preset time sequence. The transmittance of the pulses in a typical sequence (code) results in a burst. The burst travels through the gas and is received by the opposite transducer.

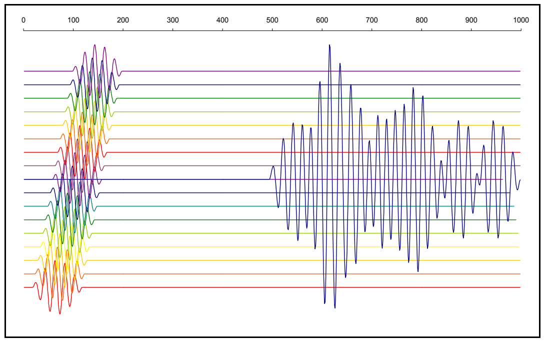

figure 6: Transmitting a burst of multiple pulses.

The time of flight of the acoustic pulse needs to be extracted from the received burst. For this the known time sequence or time code is needed. The received burst is correlated with the transmitted coded burst. As the transmitted pulses are correlated with the coded burst, the transmitted pulse will be reconstructed by the correlation filter and noise will be cancelled out. Correct design of the burst code will prevent cross correlation of the pulses to contaminate the output of the correlation filter

A simple illustration on how the UFM extracts this information, can be demonstrated by the old punched card. A coded punched card as presented in figure 7 is transmitted.

figure 7: Coded punched card

During its travel time noise was added (random punches) and the determination of its starting point seems to be lost.

figure 8: Received punched card and noise added (additional punches)

By using a bar with an identical code as the transmitted punched card the starting point can be found by sliding the identical coded bar over the received card (see figure 9).

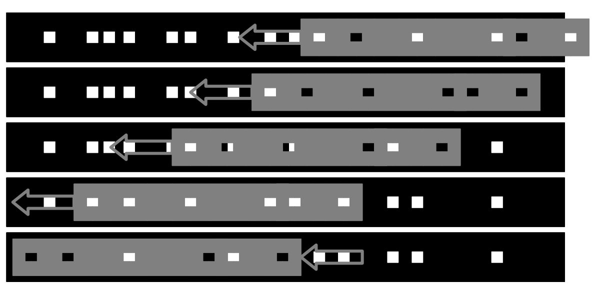

figure 9: Using the identical code to find starting point

3.3 Practical data (100 pulse)

To analyze on a real time basis how a pulse shape is influenced by the gas stream 100 successive pulses were stored by using a high frequency sampling oscilloscope. Two of these “100 pulse” examples will be discussed in the following paragraphs. One example has a distribution in time which allows the use of stacking. Another example shows data whereby due to the turbulence within the gas stream stacking can not be used. The CMB technique in this case operates fine.

3.3.1 Stacking:

3.3.1.1 Example 1: Q.Sonic-5 at 1.6 m/s:

Using a Q.Sonic-5 at 1.6 m/s 100 successive pulses were stored and the result is presented in figure 10. The jitter in this case is relatively small in relation to the period of the acoustic pulse.

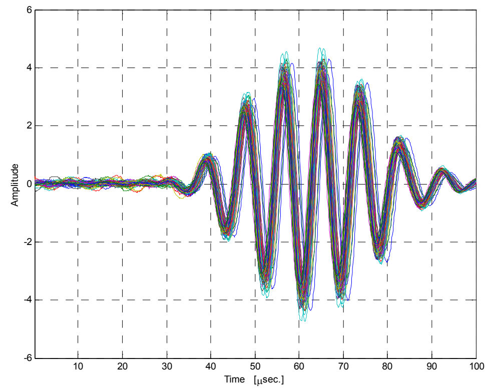

figure 10: 100 pulses, Q-Sonic-5, 20”,1000 m^3/h (1.6 m/s), export station.

Due the small distribution in time, averaging will work. In figure 11 noise is added. The noise levels equal the signal levels (signal to noise ratio is 1). In
figure 12 the average result of the 100 pulses and the maxima and minima of the single pulses are presented. Clearly averaging has been successful. The signal to noise ratio has improved to about 10.

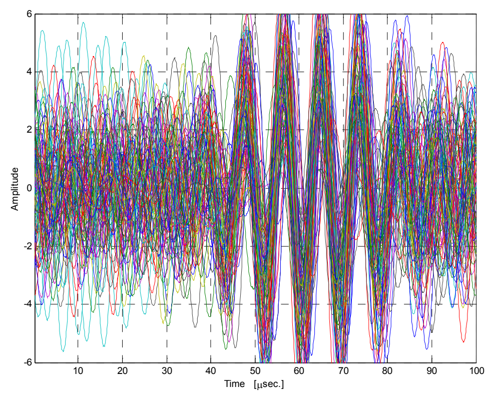

figure 11: 100 pulses + noise, S/N = 1

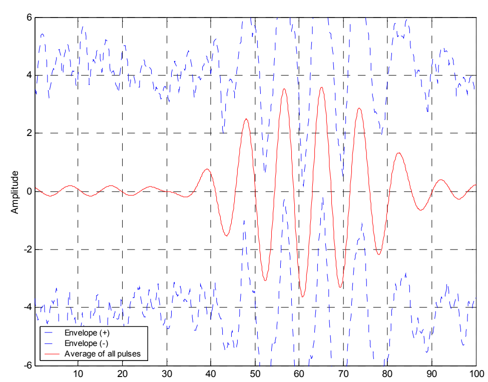

figure 12: 100 pulses + noise, averaged.

3.3.1.2 Example 2: Q.Sonic-4, 8”, at 4.7 m/s:

The second “100 pulse” example is taken from a Q.Sonic-4, 8” at 4.7 m/s. The gas stream behavior is not as steady as in the previous example. More turbulence is present (pulsation). The result of the 100 pulses is presented in
figure 13. The distribution in time is of the same order of the time period of the acoustic pulse and in this case stacking will not work. When noise is added (
figure 14) and stacking is applied the results presented in figure 15 shows an un-acceptable result.

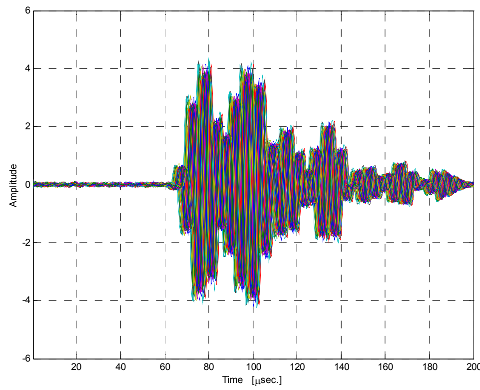

figure 13: 100 pulses, Q.Sonic-4, 8”, 4.7 m/s incl. pulsation.

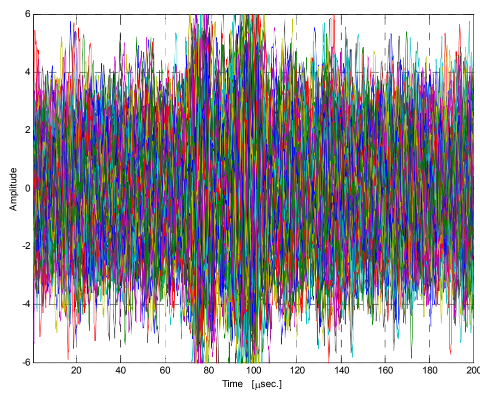

figure 14: 100 pulses + noise, S/N = 1

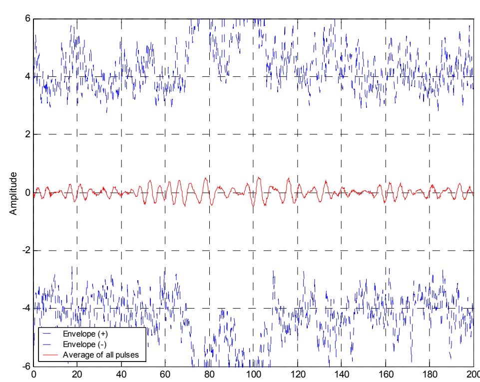

figure 15: 100 pulses incl. pulsation + noise, averaged

3.3.2 Coded Multiple Burst (CMB):

As explained before the large standard deviation of the time distribution is the cause of the problem described in 3.3.1.2. In figure 16 pulse #1 and pulse #2 of
figure 13 are presented. The time shift is about 2 μs. This time shift occurs within $^{1}/_{15}$ of a second (default sampling frequency of UFM) or within 67 ms. CMB technique speeds up the sampling frequency and as a result the variations are much smaller.

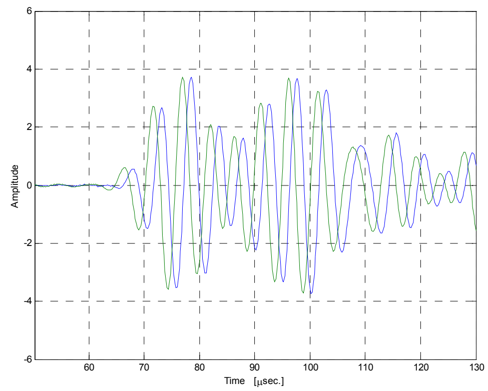

figure 16: #1 & #2 of 100 pulses incl. pulsation

The signal as presented in the above figures has a length of about 100 μs. This pulse is used to construct a burst of 100 pulses according to a pre-set time code. The result is presented in figure 17. The duration of the burst is about 900 μs or 0.9 ms, which is about 75 times less than the time in figure 16 presented successive pulses (duration is $^{1}/_{15}$ s or 67 ms). The time shift due to turbulence between the first pulse in the burst and the last pulse in the burst (#100) is 75 times less than the times shift of 2 μs observed in figure 16. There is a negligible time shift or jitter present.

To prove that CMB works for example 2 (par. 3.3.1.2), again noise is added to the burst signal (see
figure 18, noise level equal the noise level as added in figure 11 and figure 14). The reconstruction of the pulse is presented in
figure 19. And as can be concluded pulse detection and so gas flow measurement is possible (the results of the CMB technique in
figure 19 should be compared to the result of the stacking technique in figure 15).

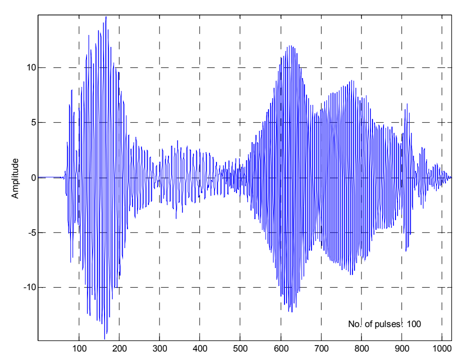

figure 17: burst made from 100 pulses

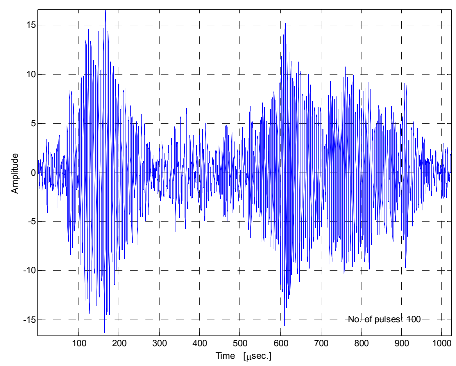

figure 18: burst from 100 pulses + noise

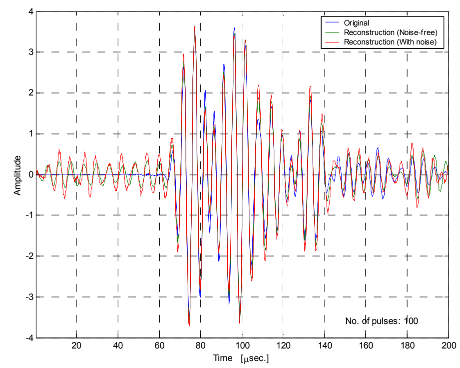

figure 19: reconstruction pulse from burst from 100 pulses + noise

4 EXPERIMENTAL RESULTS.

In the new “Series IV” electronics the new CMB technique is implemented. To test the noise tolerance of the new electronics a test program has been performed at the calibration facility of Advantica at Bishop Auckland.

4.1 Test set up:

The test set up is presented in figure 20 and
figure 21. The ultrasonic noise source is a 12” pressure regulating valve installed upstream of a 16” UFM. The Process conditions were:

- inlet pressure station: 58 - 48 bar
- outlet pressure station: 40 - 33 bar
- pressure drop across the valve: 1 - 23 bar
- Flow rate: 400 – 10.600 m^3/h

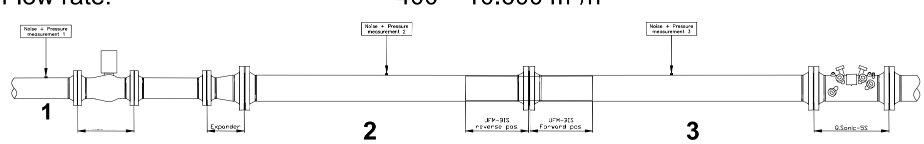

figure 20: Installation drawing

- By regulating the 12” valve the flow rate and the pressure drop over the control valve was set.
- At 3 locations (see figure 20) the static pressure and the US-noise levels were measured using broad banded microphones (see
- figure 21).

- The option was present to install a multi stage silencer between location 2 and 3 to reduce the US-noise levels.

figure 21: installation

4.2 Noise emission N_v.

The frequency dependency of the acoustic pressure levels, measured at different flow rates is presented in figure 22. These spectra are comparable to the previous presented spectrum in figure 1.

For the UFM of Instromet the acoustic pressure at 100 kHz and 200 kHz are relevant. For each frequency the valve-weighting factor needs to be determined.

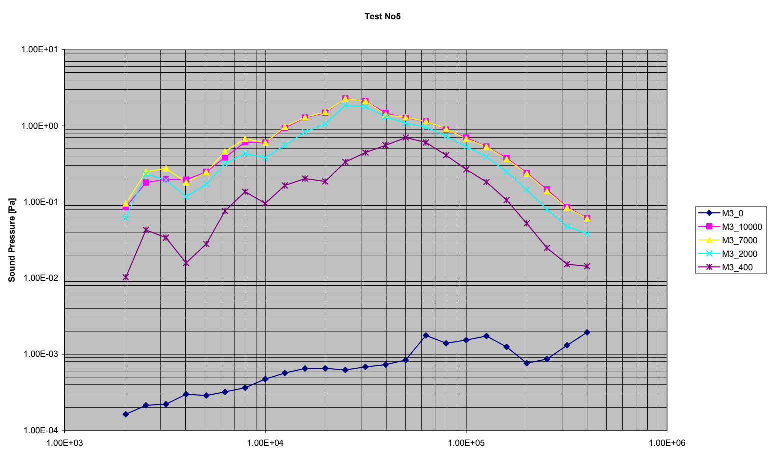

figure 22: Frequency spectrum of the acoustic pressure at different flow rates

By comparing the $\Delta P\sqrt{Q_n}$-value with the measured acoustic pressure at the location of the up- and downstream microphone, the valve-weighting factor of the 12" pressure regulating valve N_v can be determined using equation 6. This has been done n figure 23. The linear relationship as given by equation 6 is clearly present. The slope of the linear regression line is the valve-weighting factor.

It can be concluded that the amount of noise emitted at 100 kHz is about 3 times more than the amount of noise emitted at 200 kHz

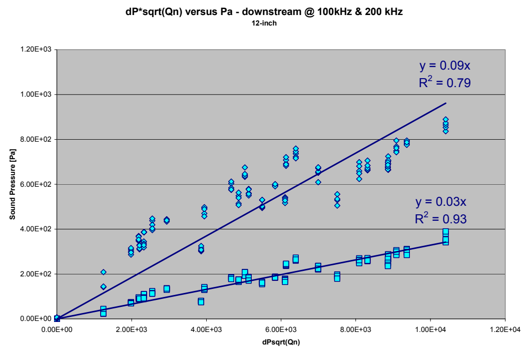

figure 23: Determination N_v of 100 kHz and 200 kHz downstream

The same plot can be made for the upstream emitted noise (see figure 24). The behavior of the upstream noise emission does not comply to the linear relationship as given by equation 6. This is caused due to the close vicinity of the microphone to the regulating valve. For a good measurement the microphone should be installed at a minimum distance of 5D from the valve.

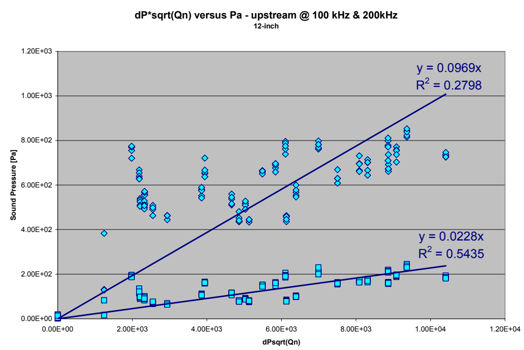

figure 24: Determination of Nv Upstream

4.3 Noise reduction

Besides characterization of the control valve, a multiple stage silencer of Instromet was tested on its pressure loss and its attenuation efficiency (N_d). The silencer consists of successive rings and plates, which block the line of sight but allows gas to pass through it (see figure 25). The silencer can consist of 1, 2 & 3 stages.

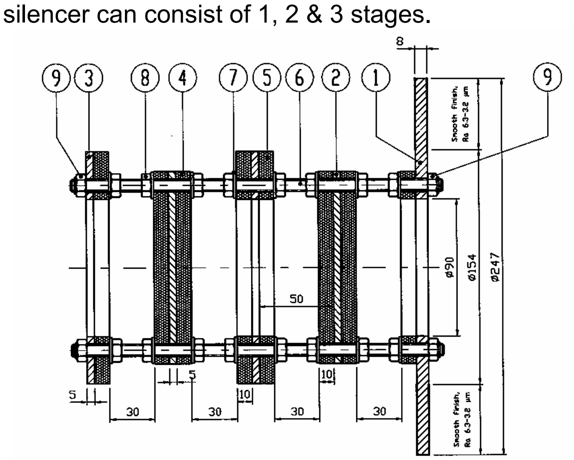

figure 25: multistage silencer (2-stage)

To determine the pressure loss over the silencer the following equation is used:

$$\Delta P = k \cdot \rho \cdot v^2 \qquad (11)$$

If ΔP is plotted in relation to the ρv^2, the slope of the linear regression is the factor k (see figure 26)

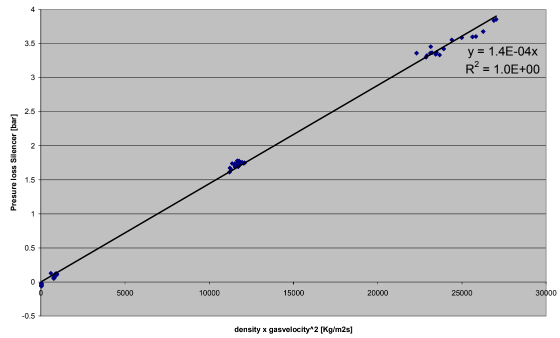

figure 26: Determination of the factor k of a 1 stage silencer k = 0.00014

To determine the attenuation of the noise equation 7 has to be used.

$$N_d = {p_{in}}/{p_{out}}$$

If the measured acoustic pressure before and after the silencer are plotted relative to each other, the slope of the linear regression line N_d is the attenuation efficiency (see figure 27)

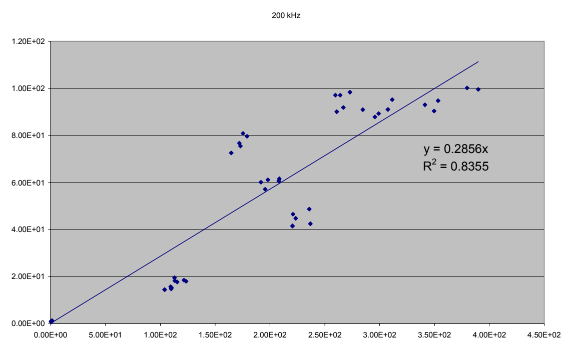

figure 27: Determination of N_d (1-stage) N_d = 0.286 = 11 dB

Results:

Multistage-silencer	$\Delta P = k \cdot \rho \cdot v^2$ k = …..	N_d [dB]
1-stage	0.00014	11
2-stage	0.00033	22
3-stage	-	-

4.4 Noise tolerance using CMB

4.4.1 $\delta_{critical}$ “series-III” electronics (No CMB)

The noise tolerance of an UFM is determined by its $\delta_{critical}$ and δ (equation 9) for which:

$$\delta > \delta_{critical} \rightarrow \text{UFM functions}$$
$$\delta < \delta_{critical} \rightarrow \text{UFM fails}$$

During the North Sea Flow Measurement Workshop in 1998 [1] and during the AGA conference in 2001 [2] the $\delta_{critical}$ was not explicitly given. Only the process to determine the $\delta_{critical}$ was described. For this purpose the Automatic Gain Control (AGC) levels and limits are used.

The AGC level is defined as the amplification factor to amplify the acoustical pulse to a default level.

Example: Default level = 2.5V, received pulse has a strength of 2.5 mV, the AGC level is 1000.

The AGC limit is defined as the amplification factor to amplify the noise to the same default level.

Example: Noise is about 50 times smaller than the signal, noise level is 50 μV, the AGC limit (amplification to 2.5V) is 50,000.

Increasing noise levels decrease the AGC limit and when AGC limit becomes equal to the AGC level the signal to noise ratio level becomes one and the UFM fails.

To determine the $\delta_{critical}$ for each process condition (ΔP, P, Q), for each process installation (N_v, N_d) and for each UFM (L) a δ has to be determined according to equation 9. Secondly, for each calculated δ the ratio of the AGC level and AGC limit (AGC ratio) is determined. Finally the functionality of the paths is given (operating or failure). This data is presented in figure 28.

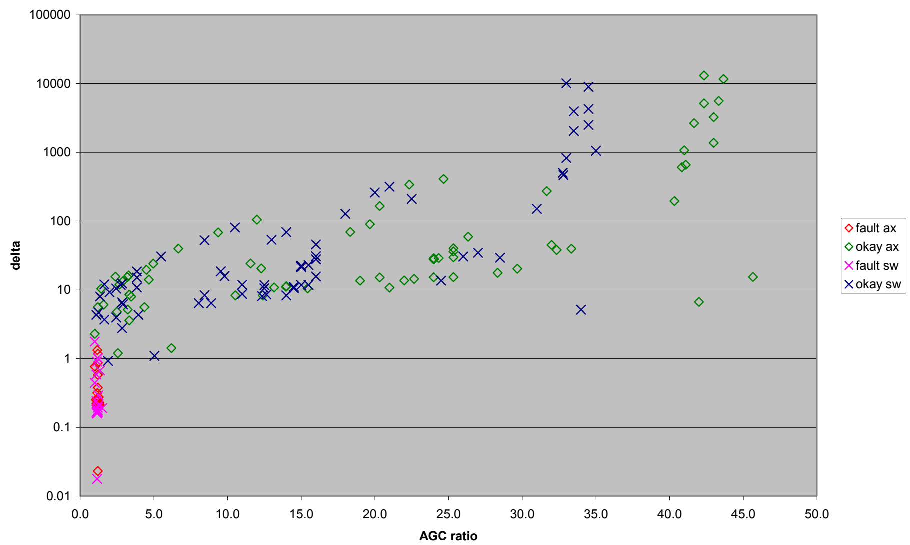

figure 28: determination of $\delta_{critical}$

The figure above shows that if δ decreases (signal to noise ratio get worse) the AGC ratio decreases and the AGC ratio becomes 1, eventually the paths fail. Based on this data the $\delta_{critical}$ can be determined:

$$\delta_{critical} = 1.3$$

This $\delta_{critical}$ is applicable for the “series-III” electronics.

4.4.2 $\delta_{critical}$ “series-IV” electronics (CMB):

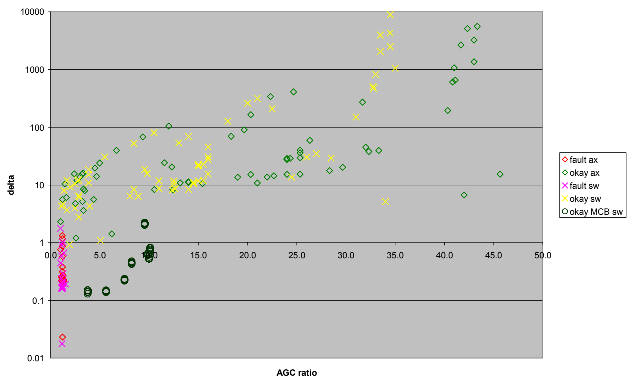

figure 29: $\delta_{critical}$ of “series-III” electronics compared to $\delta_{critical}$ of “series-IV”

During the tests in February a “series-IV” electronic board is tested under high US-noise levels. For each test as described above the δ and AGC ratio were determined. In figure 29 this data is added to figure 28. At each process condition the UFM did not fail and so $\delta_{critical}$ was not reached. The performance of the meter however showed that the UFM was functioning at its limits. The lowest $\delta_{critical}$ observed was 0.13, which is 10 times better than the $\delta_{critical}$ for the “series-III” electronics.

$$\delta_{critical\_S3} = 1.3$$
$$\delta_{critical\_S4\_CMB} = 0.13$$

5 CONCLUSION:

The objective of this paper was to present the design criteria for installation of UFM in high noise environments and secondly present real world data in combination with a new developed signal processing technique called Coded Multiple Burst (CMB).
The design criteria indeed has been presented and this paper showed that the use of the CMB technique within the UFM resulted in a higher noise resistance of about a factor of 10 whereby the increase of noise resistance did not lower the upgrade time of the UFM.

6 REFERENCES

[1] P. STOLL and G. DE BOER et all. Ultrasonic noise characteristics of valves with respect to ultrasonic gas flow meters,, 16th North Sea Flow Measurement Workshop 1998.

[2] M.J.M. VERMEULEN et all. A model for estimation of the ultrasonic acoustic noise level emitted by pressure regulating valves and its influence on ultrasonic flow meters, AGA Conference 2001

[3] G. REEDHOF and W.C. WARD, A theoretically based valve noise prediction method for compressible fluids, Journal of Vibration, Acoustic, Stress and Reliability in Design, July 186, vol. 108/329

[4] ISO17089 (To be released, draft)