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OPERATION OF MULTIPATH ULTRASONIC GAS FLOW METERS IN NOISY ENVIRONMENTS

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SUMMARY

A 12" KOS FMU 700 multipath ultrasonic transit time gas flow meter (USM) has been used in testing at Statoil's K-Lab, in order to investigate the ultrasonic noise radiated by a 6" control valve with silencer trim in the operational frequency band of USMs, and the characteristic influence of the valve noise on the performance of USMs, when installed in the vicinity of such valves. The paper discusses the frequency contents of the valve noise, the signal-to-noise ratio (SNR), and the dependence of these parameters to gas/flow/valve parameters such as the gas pressure, the pressure drop of the valve, the flow rate, upstream/downstream operation of the USM relative to the valve, the distance from the valve, the lateral position of the acoustic paths in the USM, and the piezoelectric transducer orientation and directivity. Possible methods for noise suppression in USMs are discussed.

ABBREVIATION AND SYMBOL LIST

USM:	Multipath ultrasonic transit time gas flow meter.
SNR:	Signal-to-noise ratio (Eq. (6)).
P:	Hydrostatic pressure upstream of the control valve [bar].
ΔP:	Hydrostatic differential pressure (pressure drop) over the valve [bar].
v:	Average axial gas flow velocity, at line conditions [m/s].
v_{min}, v_{max}:	Minimum and maximum average axial gas flow velocity specified for the meter, respectively [m/s].
v_i:	Average axial gas flow velocity along path no. i, at line conditions, i = 1, ..., N [m/s].
D:	Pipe diameter (here, D refers to a 12" pipe) [m].

1. INTRODUCTION

The use of multipath ultrasonic transit time gas flow meters (USM) is by the gas industry today seen as a realistic, competitive and cost-saving alternative to the use of more conventional technologies for fiscal metering of natural gas [1], [2], [3], [4], [5], [6]. The USM technology offers significant advantages such as high accuracy, compactness, bi-directionality, short upstream

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and downstream requirements with respect to bends, no pressure loss, short response time, and large turn-down ratio (1:50).

Through testing and operation of first generation USMs it has been demonstrated that ultrasonic noise generated by flow control valves deteriorates the performance of such meters [7]. For certain applications, valves may be installed close to the USM, and ultrasonic noise radiated by the valve may interfere with the flow meter signals. In testing with high pressure drops over the control valves, it has been experienced that USMs may fail to operate. Current industrial requirements as specified by European gas companies (i.e., GERG, the European Group for Gas Research) [1] state that USMs installed upstream of a control valve should tolerate relative pressure drops of $\Delta P/P \approx 25$ % and 15 %, at v_{min} and v_{max}, respectively.

In a commercial USM, problems with valve noise are being reduced by implementing a noise suppression algorithm, based on a signal averaging method ("stacking"). Significant improvements have been reported using this technique [7]. However, current noise suppression methods have potentials for further improvemed with respect to robustness and response time, to enable the following of rapid changes in the gas flow rate to the same high extent as has been demonstrated for USMs in test lines without valve noise present [8], [9]. Development work within this field is ongoing, by several manufacturers.

In order to further improve the robustness and response time of USMs operating in valve noise, the knowledge about such noise and its influence on USM should be improved, in the range of ultrasonic signal frequencies where such meters are operated [1]. That means, typically, in the 100 - 200 kHz range. A number of parameters or conditions may be expected to influence on the sensitivity of USMs to control valves, such as

(a) The frequency content of the valve generated noise (i.e., the type of valve) in the operational frequency band of the USM.
(b) The frequency filtering used in the USM.
(c) The relative differential pressure of the valve, $\Delta P/P$.
(d) The hydrostatic pressure in the pipeline, P.
(e) The average axial gas flow velocity, v.
(f) USM installed upstream / downstream relative to the valve.
(g) The distance of the USM from the valve.
(h) Receiving transducer facing the valve / facing away from the valve.
(i) The lateral position in the pipe of path no. i.
(j) The inclination angles of the acoustic paths, relative to the pipe axis.
(k) The directivity of the piezoelectric transducers (beam width and side lobe level), at the dominating noise frequencies, in gas at operational pressure and temperature conditions.
(l) The conversion efficiency and signal level of the piezoelectric transducers.
(m) The transit time detection method implemented in the acual meter, including possible noise suppression methods.
(n) The degree of flow profile disturbance caused by the valve (primarily for USMs installed downstream of the valve).
(o) Whether the noise is primarily gas borne or pipe borne, or both. For significant pipe borne noise, the degree of acoustic isolation between the piezoelectric transducers and the spoolpiece (i.e., the transducer mounting) is an essential factor.

From practical operation and testing of USMs close to valves, some qualitative information on the influence of such parameters has been gained. It has been observed that [7]

- Valves equipped with silencer moves the noise towards ultrasonic frequencies,
- The more efficient the silencer is, the more energy is radiated at higher frequencies,
- The noise level at a given frequency increases with differential pressure and flow rate,
- More noise is radiated in the downstream direction than in the upstream direction,
- High frequency ultrasonic noise from the valves can interfere with the acoustic signals in the flow meter, resulting in degraded or even ruined measurement signals.

In general, the high-frequency distribution of the radiated acoustic noise from valves, and the characteristic influence of valve noise on the performance and accuracy of USMs installed close to a valve, is currently not well known. As part of a work to improve the robustness and accuracy of USMs installed close to valves, better information about the noise and its influences on USM signals is of interest.

In the present paper, the influence of some of the above mentioned factors are investigated experimentally. Noise characteristics of a 6" control valve with silencer trim are investigated in a frequency band of relevance for USMs, and its influence on a commercial 6-path USM (the KOS FMU 700 meter) is examined, in the case where noise suppression algorithms are not activated. The recorded information serves as a base to improve noise suppression methods. The paper discusses the frequency contents of the valve noise, the signal-to-noise ratio (SNR), and the dependence of these parameters to gas/flow/valve/installation parameters such as (c)-(i) listed above. Possible methods for noise suppression in USMs are discussed.

2. FLOW TESTING AT K-LAB

The 12" KOS FMU 700 six path USM [9] was installed in a gas test loop at Statoil's K-Lab, in series with a 6" control valve with silencer trim. In the tests, the USM was installed 10D and 5D upstream of the valve[2] (2.6 m and 1.3 m, respectively), and 10D downstream of the valve, cf. Fig. 1. (Here D here refers to the USM diameter, 12".) No flow conditioner was used. Sonic nozzles were used as the reference flow meter, with a 8" Instromet turbine meter as a backup reference (installed downstream of the valve and the USM). The gas temperature and pressure were measured upstream of the valve and downstream of the valve. For the USM installed upstream of the valve, the gas temperature at the USM was in the range 37-39 °C. For the USM installed downstream of the valve, the temperature at the USM varied more, in the range 29-37 °C.

Table 1 shows the run matrix, i.e. the combinations of parameter settings (USM position / pressure / differential pressure / velocity) used in the test. In the table, "nominal" refers to the approximate, desired parameter setting, and "actual" refers to the actual (measured) parameter setting achieved in the test.

For each parameter setting (run) of Table 1, the analog output voltage signal delivered by each of the 12 piezoelectric transducers in the USM was sampled (digitized, at 10 MHz sampling rate and 8 bits resolution) and stored for later signal processing. The transducers were mounted in their transducer ports, as for ordinary flow metering operation of the USM. For each piezoelectric transducer, up to 32 succeeding signal traces were logged per run, for the purpose of SNR estimation, and the study of noise suppression techniques. Each recorded signal trace contains the received ultrasonic signal transmitted from the corresponding (opposite) transducer in the path, and the ultrasonic noise signals received by the transducer (cf. Figs. 2 and 3). It should be noted that the signal traces are of course influenced (filtered) by the frequency response of the piezoelectric transducers, and the frequency filter settings used in the meter electronics.

[2] More precisely: upstream of the 12"-to-6" conical diffuser installed at the valve spool, cf. Fig. 2.

Consequently, from a viewpoint of characterizing the valve noise only, an alternative measurement setup would be preferred, using a broadband high-pressure microphone (with a preferably flat and calibrated response to at least 200 kHz). However, the present setup, with recordings of signal and noise using the FMU 700 piezoelectric transducers, enables a more flexible and extended application of the recorded data. In addition to be used for "characterizing" the valve noise (at least to some extent), information about the SNR ratio in the meter is obtained, as a function of several flow parameters listed in the Introduction, cf. Section 3. In addition, the recordings are used directly in the study of noise suppression methods in the meter, cf. Section 4. Microphone recordings would not be so useful for the two latter purposes. The present setup is therefore used as a reasonable compromise.

The recorded signal traces are used to estimate the signal and noise levels, V^{rms}_{signal} and V^{rms}_{noise}, respectively (both expressed as root-mean-square (rms) voltages), and the signal-to-noise ratio, SNR. Each recorded voltage trace, $V_m(t)$, m = 1, 2, ..., M, consists of a time window containing essentially noise ("noise window"), and a time window containing the ultrasonic signal superposed with noise ("signal window"), cf. Fig. 3. To estimate the rms noise level, V^{rms}_{noise}, the rms noise level of trace no. m is first calculated over a time window of T_1 = 350 μs within the noise window of the trace, i.e. as

$$V^{rms}_{noise,m} = \sqrt{\frac{1}{T_1}\int_{t_1}^{t_1+T_1} V_m^2(t)dt} \ , \tag{1}$$

where t is the time, and t_1 is a time in the beginning of the noise window. The rms noise level is then found by averaging over a number of N traces, i.e. as

$$V^{rms}_{noise} = \frac{1}{N}\sum_{m=1}^{N} V^{rms}_{noise,m} \ . \tag{2}$$

To estimate the signal level, V^{rms}_{signal}, up to M = 32 signal traces are first averaged ("stacked") in order to suppress the superposed noise, giving an averaged voltage trace,

$$V_{average}(t) = \frac{1}{M}\sum_{m=1}^{M} V_m(t). \tag{3}$$

The rms signal level is then calculated over a time window of T_2 = 100 μs within the signal window, on the resulting averaged signal trace, i.e. as

$$V^{rms}_{signal} = \sqrt{\frac{1}{T_2}\int_{t_2}^{t_2+T_2} V^2_{average}(t)dt} \tag{4}$$

where t_2 is a time in the stationary part of the signal. The signal-to-noise ratio is then calculated as

$$SNR = \frac{V^{rms}_{signal}}{V^{rms}_{noise}} \tag{5}$$

This is done for most of the parameter settings (runs) shown in Table 1, for several selected piezoelectric transducers of each run.

3. RESULTS

Selected results from the flow tests of the USM in valve noise at K-Lab are presented in the following. The results should be considered as preliminary, since data are presented for selected transducers only, in the two paths marked A and B shown in Fig. 2a.[3]

Fig. 2b show an example of a voltage signal trace for a low noise metering situation (recorded with the USM 10D upstream of the valve, P ≈ 23 bar, v ≈ 0.5 m/s, and ΔP/P ≈ 1 %). Traces of this type form the basis for measurement of transit times in USMs. The trace shown here, with a high signal-to-noise ratio, SNR, may be representative for the combination of low flow velocity and low pressure drop of the valve (as shown here), or for USM flow metering without valves installed in the line. For the latter case, a measurement accuracy of 0.5 % or better has been reported using the present meter [9].

With valves installed in the line, the signal is more influenced by valve noise as the flow velocity or the pressure drop increases, as discussed in the following.

3.1 Frequency content of valve noise

Fig. 3 shows single voltage signal traces recorded at one of the piezoelectric transducers, for the USM mounted 10D upstream of the valve, P ≈ 100 bar and ΔP/P ≈ 19 %. Traces are shown for three different gas flow velocities: v ≈ 0.24, 2.26 and 6.76 m/s. The transducer is facing towards the valve, at an oblique angle relative to the pipe. The same time and amplitude scales are used for all three traces. The noise window extends to about 1.05 ms, at which time the ultrasonic signal arrives. The figure clearly demonstrates that the noise level increases with increasing flow velocity, v, while the signal level is kept essentially constant. For the three velocities shown in Fig. 3, the SNR is calculated to about 22, 9 and 2 dB, respectively (cf. Fig. 5a). Additional results (not shown here) reveal that the noise level increases also with ΔP/P, with a corresponding reduction in SNR (cf. also Fig. 5).

Fig. 4 shows the magnitude FFT (Fast Fourier Transform) spectrum of the noise signals given in Fig. 3, taken within the noise window of the respective traces, in the frequency band 100-200 kHz. The average of 10 magnitude FFT spectra are shown here. When using these results for noise characterization, one should be aware that the noise spectrum is influenced both by the filter setting used in the USM, and the frequency response of the receiving transducer (cf. the discussion of Section 2), so that the present results do not give the correct frequency spectrum of the noise. In spite of that, the results reveal important noise components in the frequency band 110-150 kHz, for the present valve. The results also show that the frequency contents of the noise is essentially the same at the three flow velocities.

Other results of the study (not shown here) indicate that the frequency contents of the noise is essentially invariant to the parameter ΔP/P as well; that it is essentially the same at 10D upstream and 10D downstream of the valve; and that it is independent of the transducer facing the valve or facing away from the valve.

3.2 Pressure, differential pressure and flow velocity effects

Fig. 5a shows the SNR (plotted on a dB scale, i.e., $20\log_{10}(SNR)$) as a function of the flow velocity, v, at different values of ΔP/P, for the transducer facing towards the valve. (Note that the

[3] Note that the two paths A and B shown in Fig. 2a are located at different lateral positions in the pipe. This is shown in the left part of the figure, but not in the right part, which has been simplified in this respect.

curve for $\Delta P/P \approx 19$ % corresponds to time traces as shown in Fig. 3.) The SNR is observed to decrease systematically with increasing v, and with increasing $\Delta P/P$, due to an increasing level of the valve noise. The corresponding results at 23 bar (not shown here) are to a large extent equal, within less than 3 dB for most of the runs. This result (which has been observed for transducers facing towards and away from the valve, and for different paths) indicate that the pressure dependence of the SNR appears essentially through the parameter $\Delta P/P$.

The observed increase of the valve noise level by increasing ΔP and v (and the corresponding decrease of the SNR) is probably explained by the increase of the gas flow velocity in the narrow opening slit of the control valve which follows from increasing the pressure drop, ΔP; increasing gas the flow velocity in the pipe, v; or both.

3.3 Transducer orientation effects

Fig. 5a and 5b show SNR results for path A, for the two transducers which are facing towards the valve and facing away from the valve (nos. 4 and 7), respectively. A systematically higher SNR is observed for the transducer facing away from the valve. For the present path example, the difference is approximately in the range 9-13 dB.

This result may probably be explained by the directivity properties of the transducer, cf. Fig. 6. Assumed that the noise propagates essentially in the direction of the pipe, the noise will probably be received primarily through the 1st side lobe for the transducer facing towards the valve, since the main lobe will not be very sensitive to the direction of the noise, and since the level of the higher-order side lobes is expected to be lower than for the 1st side lobe.

On the other hand; for the transducer facing away from the valve, the noise will probably be received primarily through the higher-order side lobes, since both the main lobe and the 1st side lobe will not be sensitive to the direction of the noise (unless a considerable amont of the noise is reflected at the pipe wall or the opposite transducer).

Thus, since the level of the higher-order side lobes is expected to be significantly lower than the level of the 1st side lobe, the noise level will be higher for the transducer facing towards the valve.

One should be aware that there are factors which complicate the above qualitative analysis, and which are not controlled at present. These are the directivity properties of the transducers at the gas/pressure/temperature conditions used, and the influence on the directivity of the geometry of the transducer mounting ports. The effective directivity of the transducers in the pipe, under the actual test conditions, is thus not sufficiently known. In spite of that, the above analysis is expected to hold, qualitatively.

It follows from such an analysis that the noise level will also vary with the inclination angle of the path, ϕ. The variation will depend on the actual transducer directivity under the operational gas/pressure/temperature/mounting conditions.

3.4 Influence of lateral position of path

Figs. 7a and 7b show SNR results for transducers facing towards the valve, for the acoustic paths A and B, respectively. A higher SNR is observed for path B, by about 6-7 dB. About half of this increase is probably explained by the shorter propagation length of path B, giving a higher signal level. It is also expected that for the outer path (path B), the effective transducer directivity will be more influenced by the tranducer mounting port than for path A, giving a larger "shadowing effect" of the noise for path B than for A, due to the geometry of the port. This may contribute to the observed higher SNR ratio for path B. A third factor is of course the possibility of lateral variation of the noise level in the pipe. This factor is not known at present, however.

3.5 Installation effects

In Fig. 8, SNR results are compared for the USM installed 10D and 5D upstream of the valve (i.e. 1.3 m and 2.6 m upstream, respectively). For the lower velocities, an increase of the SNR of up to about 4-5 dB has been observed for the path shown here, by moving the USM from 1.3 m to 2.6 m from the valve. No significant increase of the SNR has been found for the upper part of the velocity range (v ≈ 6-8 m/s), however. This observed difference in the increase of SNR over the flow velocity range has not been explained so far, and is to be investigated also for the other paths of the meter.

Fig. 9 illustrates the influence of installing the USM 10D (2.6 m) upstream or 10D downstream of the valve. Signal traces are shown for each of the two cases, for the case of P ≈ 100 bar, v ≈ 2.5 m/s, and a relatively large pressure drop, $\Delta P/P \approx 19$ %. A significant reduction of the SNR is observed for the USM installed downstream of the valve, relative to the upstream installation, due to a higher noise level downstream. Similar results have been observed also for other transducers and paths, and are qualitatively in agreement with results reported in ref. [7]. The results may indicate that the present valve type radiates more strongly downstream than upstream. The results also suggest that if possible, USMs should be installed upstream of the valve, in order to reduce the noise level and increase the SNR.

4. DISCUSSION

Various strategies for improving the SNR of USMs operating in valve noise may be considered, as discussed in the following. Combined techniques for raising the received signal amplitude, and for noise suppression, are of interest.

4.1 Received signal amplitude

For piezoelectric transducers working in the linear range, the SNR can of course be increased by ***increasing the input voltage signal amplitude***. The maximum input voltage that can be used is, however, limited by at least three factors: safety requirements, nonlinearity in the piezoelectric transducers, and nonlinearity in the gas under the operating pressure and temperature conditions.

With respect to possible nonlinearity in the transducers and the gas, both increase by increasing input voltage. In high-precision applications of USM, such as fiscal gas metering, the transducers are recommended not to be driven in the nonlinear range, which might introduce problems with reciprocity and signal distortion. It appears that the input voltage limit will in general depend on the design and properties of the transducer, and is thus meter dependent. It will also depend on the gas properties (pressure, temperature, gas composition). For a given transducer design, the limiting input voltage (with respect to nonlinearity) should be determined experimentally. For the FMU 700 transducers, such measurements have been made in air at 1 atm. conditions. At present, documentation with respect to possible nonlinearity effects in the operational pressure, temperature and gas compositional ranges of the commercial USMs does not seem to be available.

For certification in the safety class EEx ia IIB T4, the maximum allowed electrical power delivered to the zone 0 area is about 4.8 W. This maximum power puts restrictions on the input voltage which can be delivered to the piezoelectric transducer. The allowed voltage depends on the electrical input impedance of the transducer, and will depend on the specific transducer design used in the meter. However, for a given maximum power delivered to the transducer, the SNR can be increased by ***improving the conversion efficiency of the transducer***, assumed that nonlinearities in the transducer and the gas do not occur (as discussed above).

The signal level (and thus the SNR) can also be increased by ***increasing the transducer directivity***, i.e., by narrowing the main lobe. This will give a higher signal level for the same input voltage to the transducer, i.e., for the same power consumption.

4.2 Noise suppression

With respect to noise suppression, the use of ***more optimal frequency filtering*** of the time signals may be advanteageous. That means, to remove as much as possible of the valve noise by filtering, without severely influencing the amplitude and time delay of the ultrasonic signal. Even for USMs using signal frequencies in the vicinity of a dominant frequency band of the valve noise (such as 110-150 kHz, for the present valve, cf. section 3), the SNR may possibly be somewhat improved by such filtering.

For directive transducers, as used here, the results indicate that a significant part of the noise may be received through the transducer's side lobes (the first side lobe and the higher side lobes, for transducers facing towards and away from the valve, respectively). Since the signal is received through the main lobe, the SNR ratio may thus probably be increased by ***lowering the side lobe level of the transducers*** (at the dominating noise frequencies) relative to the main lobe (at the signal frequency), especially for the first side lobe. To evaluate the degree of noise suppression which can be obtained by such ***spatial filtering***, information is necessary about the transduser directivity (beam width and side lobe level), at the signal frequency and the dominating noise frequencies, and at the operational pressure, temperature and gas compositional conditions. This directivity may be significantly different from the directivity in air at 1 atm. and room temperature conditions. For the FMU 700 meter, the transducer properties have been measured for the most part in air at 1 atm. conditions, supplied with measurements at various pressure and temperature conditions. At present, documentation of the transducer directivity of commercial USMs, in the operational pressure, temperature and gas compositional ranges of these meters, and over the relevant frequency band, does not seem to be available.

A complicating factor here is of course the ***influence of the transducer mounting port on the transducer directivity***. Due to such influence, the "effective directivity" (beamwidth and side lobe level) of the transducer mounted in the spoolpiece is not the same as the transducer's directivity in freefield (measured without mounting in the port), and this influences on the meter's sensitivity to valve noise. Since the geometry of the various ports are different, the "effective directivity" of the various transducers mounted in a USM may also be different. However, transducers with a low side lobe level will be less influenced by the port than transducers with a higher side lobe level. To evaluate possibilities for noise suppression by lowering the side lobe level, the influence of the transducer ports on the transducer directivity should be investigated experimentally.

Significant noise suppression can also be obtained using ***digital signal processing*** methods. ***Signal averaging ("stacking")*** methods have been used successfully in a commercial USM. The tolerated differential pressure, ΔP, may be increased by a factor 2-5 using such methods [7]. Fig. 10 shows an example of how a signal largely influenced by valve noise (SNR $\approx$ 9 dB, cf. Figs. 3 and 5a) can be recovered to a large extent using a signal averaging technique. The averagings shown in Fig. 10 are made according to Eq. (3), with averaging number M = 1, 5 and 27, respectively. In the present example, the SNR is increased by about 16 dB by averaging 27 signals. Using such averaging, the robustness of the time detection may be improved considerably, and the meter operated in more noisy environment.

However, sampling and averaging of signal traces is very time consuming, and with up to about 30 traces averaged, as considered in the present study, the response time of the meter may be significant (several tens of seconds). That means, the meter may not be able to follow rapid changes in the flow rate, or may even fail to operate over a certain time period, after which the meter is again operating [7].

Consequently, there is today an interest in developing a signal processing method for noise suppression which is at least as powerful as the signal averaging method with respect to the suppression of noise, but which has considerably shorter response time. Work in this direction is ongoing, in a cooperation between KOS and CMR. Fig. 11 shows a comparison of (1) a time detection method based on averaged ("stacked") signals (as illustrated in Fig. 10), and (2) an ***alternative signal processing method*** for time detection which is under development and testing. The figure shows the relative difference in the transit time difference, Δt_i, for the two methods (1) and (2), for a single path (no. i) in the meter (here chosen as approximately a "worst case" path with respect to the SNR, cf. Fig. 5a)[4]. The figure indicates that with respect to the measurement of Δt_i for path no. i, the alternative method (2) has an accuracy similar to the "stacking" method (1). For the present example, the difference is less than 0.08 %. Due to the relation between Δt_i and v_i (cf. Fig. 11) it follows that the alternative method (2) may have an accuracy similar to the "stacking" method (1) also for measurement of v_i, the average axial flow velocity along path no.i. The main advantage of the alternative method (2) is the significantly reduced processing time relative to method (1). The promising potentials of the present method with respect to retaining similar measurement accuracy in valve noise as the "stacking" method, while significantly improving the response time of the meter relative to the "stacking" method, are being further explored.

5. CONCLUSIONS

In testing over several years, USMs have demonstrated to be accurate instruments for measurement of gas flow, with a number of advantages for the gas industry. However, when installed close to control valves, the ultrasonic noise radiated by the valve represents a problem for the first generation of USMs, and work is ongoing to overcome such problems.

In the present work, a 12" USM (the KOS FMU 700) is used for measurement of valve noise, and to study characteristic performances of USMs in valve noise, over the parameter range P $\approx$ 23 and 100 bar, v $\approx$ 0.5-8 m/s, and $\Delta P/P \approx$ 1-19 %. Some conclusions of the work are:

- Important noise components are found in the frequency band 110-150 kHz, for the present 6" control valve with silencer trim.

- In the frequency range of the meter, the frequency content of the valve noise is found to be independent of P, $\Delta P/P$, v, transducer orientation, distance from the valve, and upstream/downstream installation of the USM.

[4] The transit time difference of path no. i, Δt_i, is defined in the figure as the difference between the upstream and downstream transit times of the path, $t_{up,i}$ and $t_{down,i}$, respectively. Note that in the axis text of Fig. 11, $(\Delta t_i)_1$ and $(\Delta t_i)_2$ are replaced by $(\Delta t)_1$ and $(\Delta t)_2$, for simplicity in notation.

- The pressure dependence of SNR appears essentially through the parameter ΔP/P.
- The SNR is significantly reduced by increasing v, and by and increasing ΔP/P.
- The SNR is significantly lower upstream of the valve than downstream, which suggests that USM should preferably be installed upstream of a valve, if possible. However, with improved noise suppression methods, installation downstream of the valve may be feasible, possibly at a reduced accuracy.
- The SNR varies with distance from the valve, but more work is needed to clearify the effects.
- The SNR is higher for a receiving transducer facing away from the valve than for the corresponding receiver facing towards the valve. The result may be explained by the transducer directivity. The noise is probably received primarily through the side lobes of the transducer.
- The SNR depends on lateral position of the path. Parts of this effect may be explained by the difference in path length, and possibly by the geometry of the transducer mounting port.
- Results from the study (not shown here) show that the SNR depends on the inclination angle of the path.

These results are based on the use of a commercial USM, but are expected to be reasonably representative for other USM as well, at least qualitatively, in the range of ultrasonic signal frequencies where such meters are operated (typically in the 100-200 kHz range), and for the present valve type. Similar investigations should be carried out also for other valve types.

For robust metering in strong valve noise, a combination of several of the possible remedial actions discussed in Section 4 may be advantageous, for sufficient improvement of the SNR. For certain of these actions, the SNR may possibly be raised by several dB, while others might give only a few dB increase of the SNR. In sum, the total increase of the SNR may be significant by combining several remedial actions. In case of marginal operating conditions, a SNR increase of the SNR by even 10 dB (say), may be a significant improvement, which can extend the range of applications for the USM.

Results of the work indicate that robustness against valve noise can be significantly improved by a noise supression algorithm, so that the USM can operate with an accuracy similar to a signal averaging ("stacking") method, but with a significantly reduced response time relative to a conventional "stacking" method. The noise suppression algorithm is currently being refined and tested, in order to be implemented in the KOS FMU 700 multipath gas flow meter. The accuracy of improved USMs installed near valves will be continuously addressed as the methods for noise suppression improves.

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carried out in a cooperation between CMR, KOS, Statoil, The Research Council of Norway (NFR) and Fluenta AS. From May 1996, the FMU 700 meter is developed, produced, delivered and marketed by KOS a.s.

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Table 1. **Parameters settings for the USM valve noise testing at K-Lab using FMU 700.**

Nominal				Actual	
Meter position rel. valve	P [bar] (upstrm)	v [m/s]	ΔP [bar]	ΔP/P [%]	v [m/s] [5]
10D up	100 bar	0.5 m/s	≈ 0 bar	**0.12 %**	**0.47 m/s**
			5 bar	**5.5 %**	**0.44 m/s**
			10 bar	**10.1 %**	**0.42 m/s**
			20 bar	**19.6 %**	**0.24 m/s**
		3 m/s	1 bar	**0.9 %**	**2.92 m/s**
			5 bar	**4.9 %**	**2.80 m/s**
			10 bar	**9.9 %**	**2.65 m/s**
			20 bar	**19.2 %**	**2.26 m/s**
		6-8 m/s	6 bar	**5.9 %**	**8.21 m/s**
			10 bar	**10.3 %**	**7.82 m/s**
			20 bar	**19.4 %**	**6.76 m/s**
	23 bar	0.5 m/s	≈ 0 bar	**0.74 %**	**0.49 m/s**
			1 bar	**4.5 %**	**0.47 m/s**
			2 bar	**8.6 %**	**0.45 m/s**
			4 bar	**16.8 %**	**0.32 m/s**
		3 m/s	≈ 0 bar	**1.6 %**	**3.09 m/s**
			1 bar	**4.0 %**	**3.01 m/s**
			2 bar	**8.9 %**	**2.85 m/s**
			4 bar	**17.1 %**	**2.60 m/s**
		6-8 m/s	1 bar	**6.5 %**	**8.57 m/s**
			2 bar	**9.1 %**	**8.34 m/s**
			4 bar	**16.7 %**	**7.05 m/s**
5D up	100 bar	0.5 m/s	10 bar	**8.6 %**	**0.84 m/s**
			20 bar	**19.6 %**	**0.74 m/s**
		3 m/s	1 bar	**0.88 %**	**2.94 m/s**
			5 bar	**5.2 %**	**2.81 m/s**
			10 bar	**10.2 %**	**2.66 m/s**
			20 bar	**19.9 %**	**2.37 m/s**
		6-8 m/s	6 bar	**5.9 %**	**8.27 m/s**
			10 bar	**9.6 %**	**7.94 m/s**
			20 bar	**19.2 %**	**5.20 m/s**
10D dwn	100 bar	0.5 m/s	≈ 0 bar	**0.20 %**	**0.47 m/s**
			5 bar	**4.9 %**	**0.47 m/s**
			10 bar	**9.7 %**	**0.46 m/s**
			20 bar	**19.2 %**	**0.27 m/s**
		3 m/s	1 bar	**0.38 %**	**2.96 m/s**
			5 bar	**4.8 %**	**2.95 m/s**
			10 bar	**9.7 %**	**2.93 m/s**
			20 bar	**19.0 %**	**2.59 m/s**
		6-8 m/s	6 bar	**5.5 %**	**8.73 m/s**
			10 bar	**9.6 %**	**8.70 m/s**
			20 bar	**18.7 %**	**6.34 m/s**

[5] For the large majority of runs given in Table 1, the average axial gas flow velocity given in the table, v, was measured using the sonic nozzle bank. In some runs, however, the nozzles were operated subsonic, in which case the turbine meter reading for v is given.

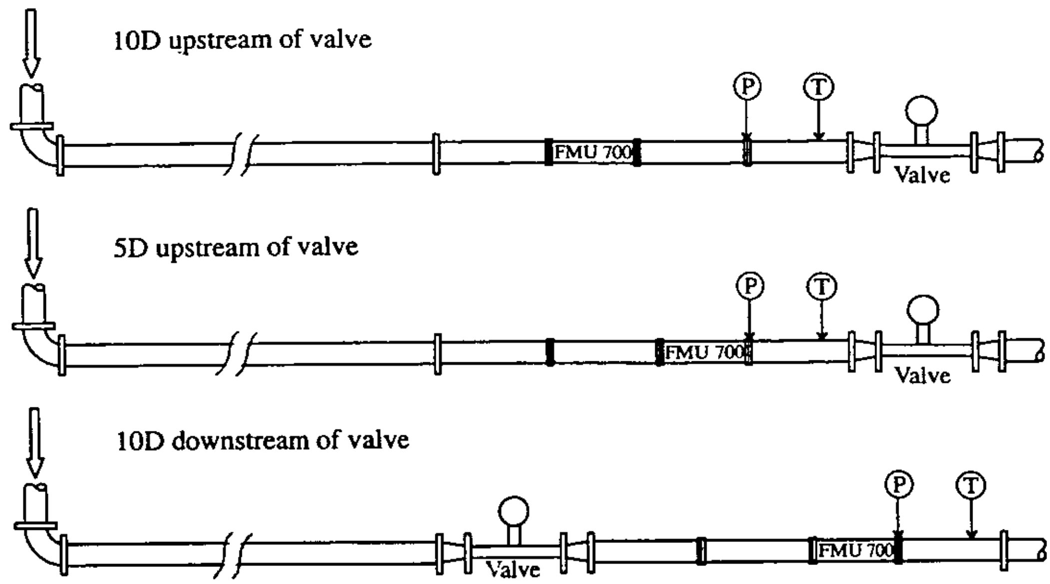


Fig. 1. Sketch of test section used at K-Lab, with the three different installation conditions.

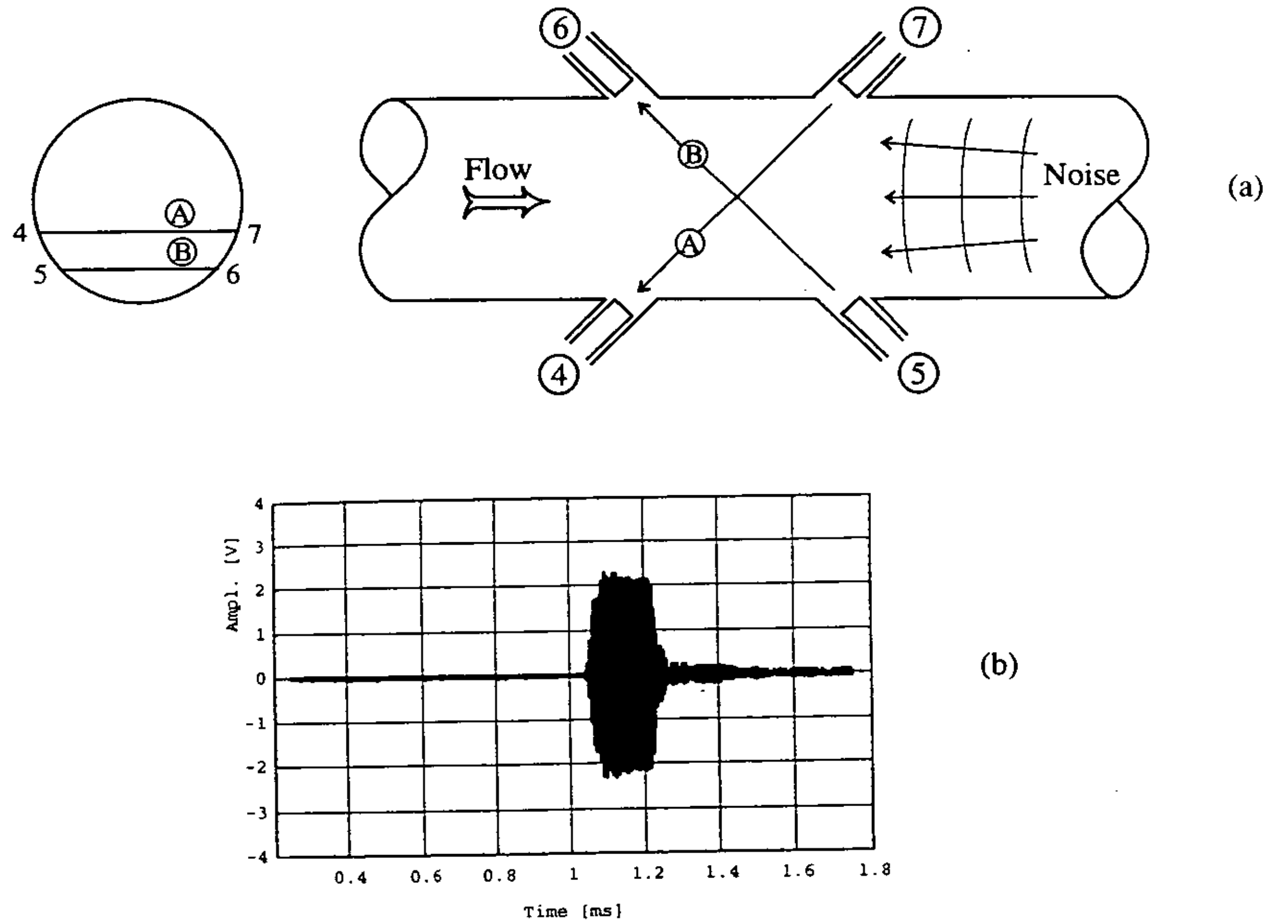


Fig. 2. (a) Sketch of the two acoustic paths A and B of the USM which are used in the results presented here, with the transducer numbering used here (for the case of the USM installed upstream of the valve).
(b) Example of a recorded voltage-vs-time signal trace, for a low-noise metering situation (USM installed 10D upstream of the valve, $P \approx 23$ bar, $v \approx 0.5$ m/s, and a low pressure drop, $\Delta P/P \approx 1$ %).

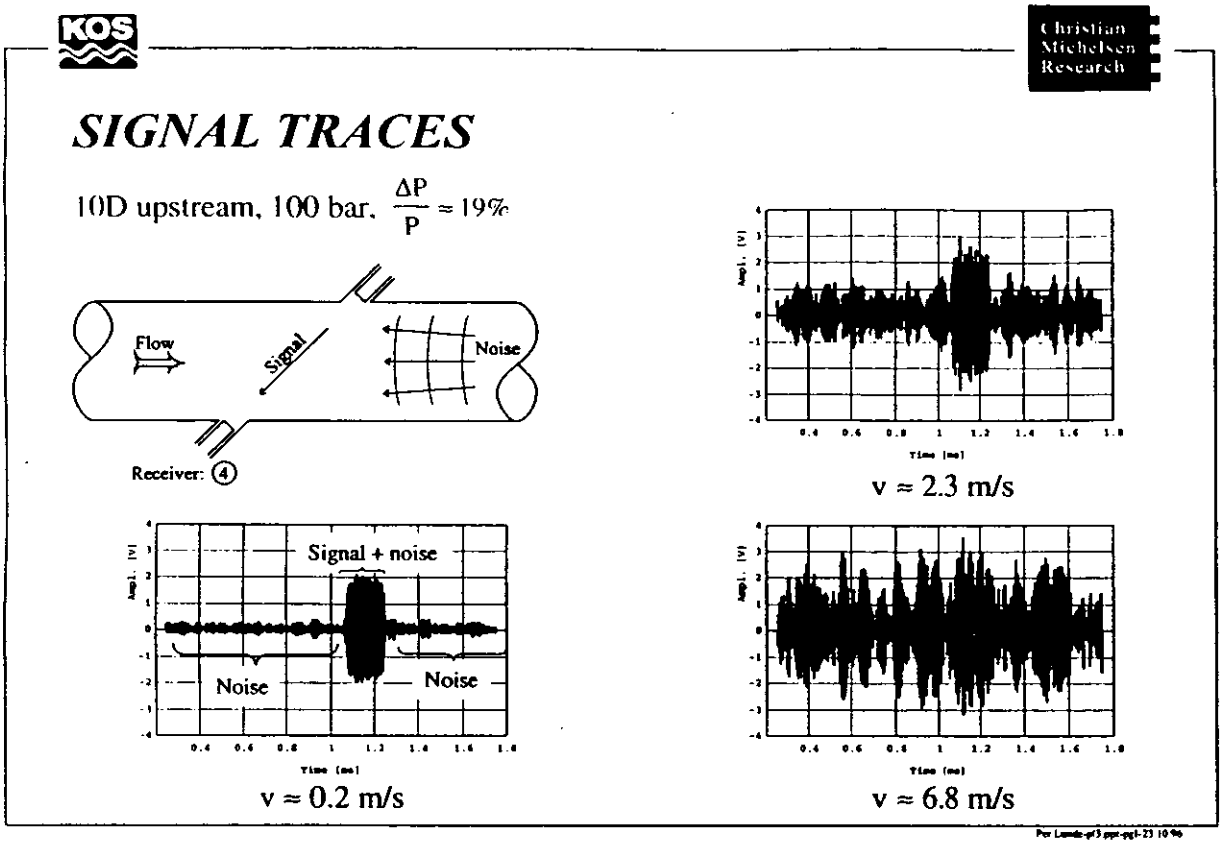


Fig. 3. Voltage signal traces, recorded at one of the piezoelectric transducers of the USM (no. 4), for different flow velocities; v ≈ 0.2, 2.3 and 6.8 m/s. Installation conditions: USM 10D upstream of the valve, P ≈ 100 bar, $\Delta P/P \approx 19$ %, transducer facing the valve, acoustic path A.

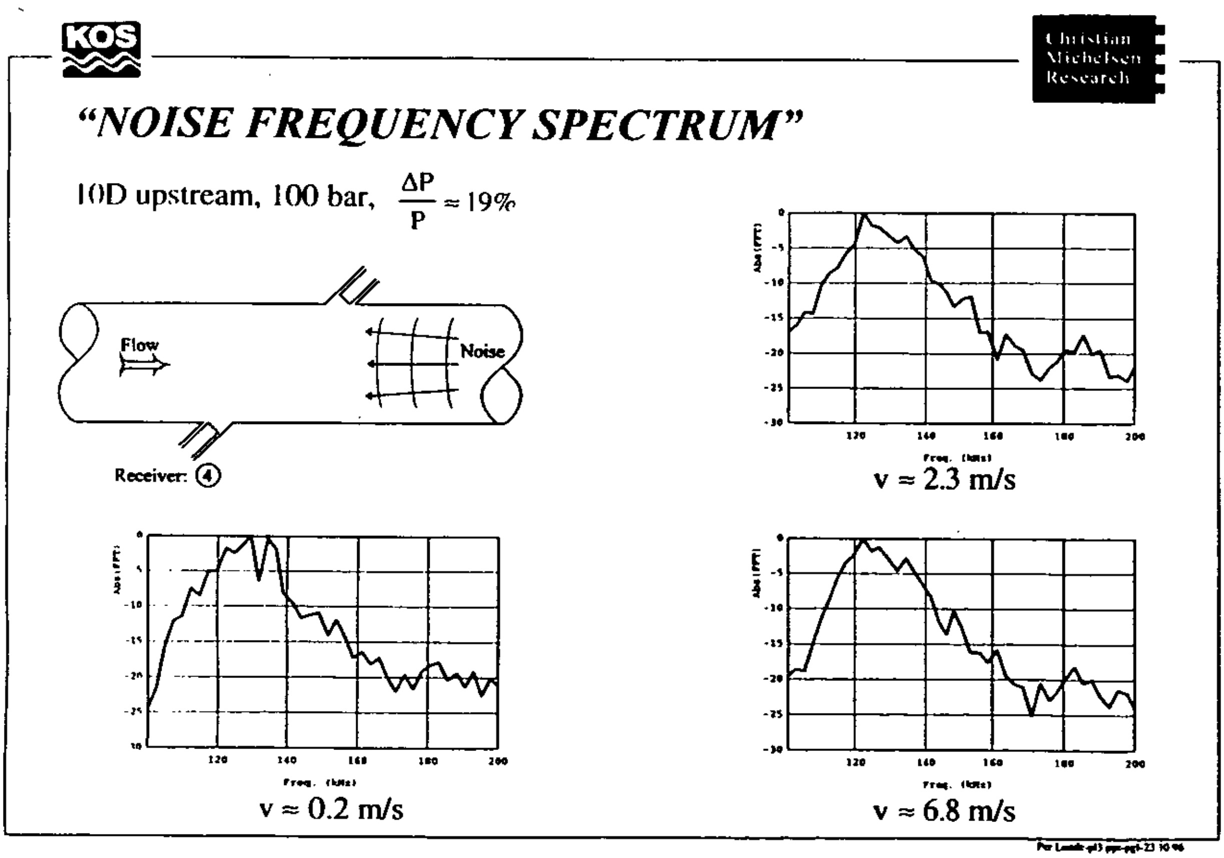


Fig. 4. Magnitude FFT spectrum of the voltage signal traces shown in Fig. 3, taken within the noise window of the traces.

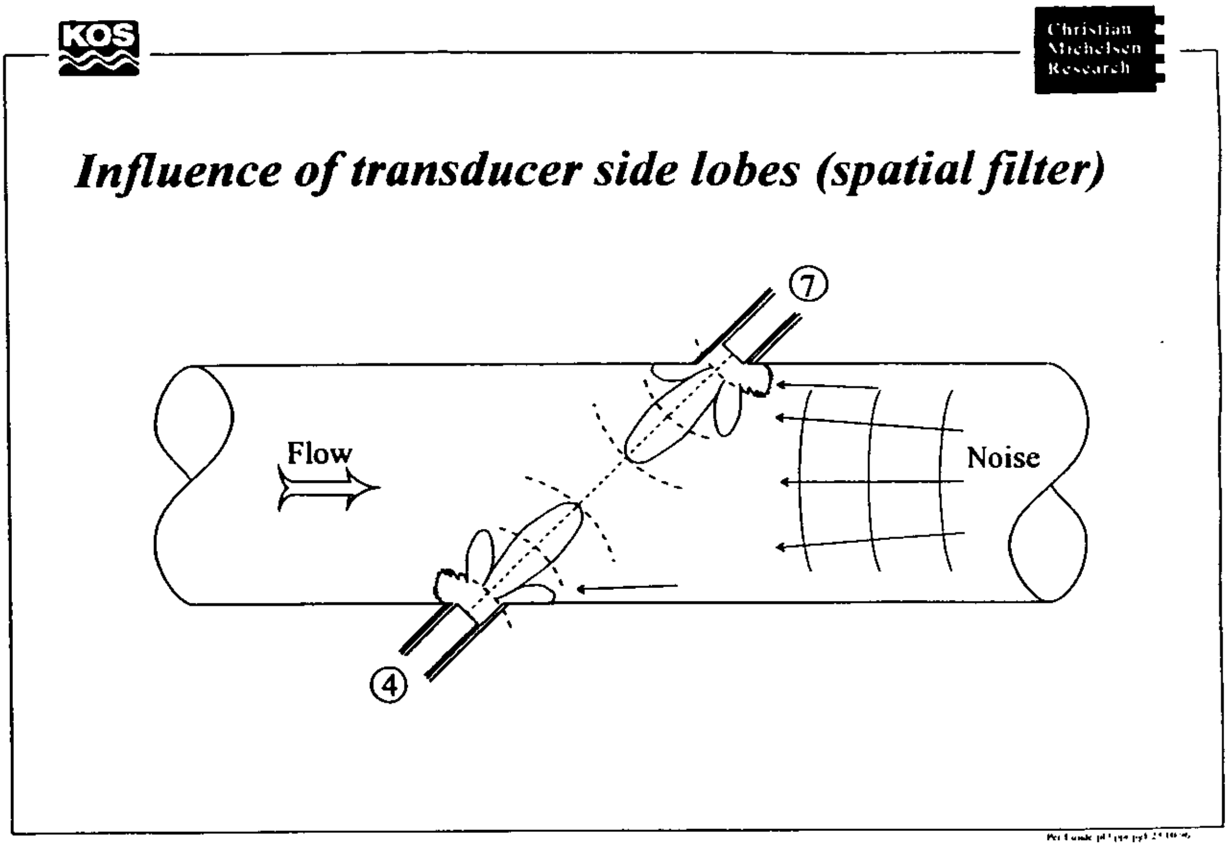


Fig. 6. Qualitative sketch of the transducer directivity (tentative direction and relative levels of main lobe, first side lobe, and higher-order side lobes), for two transducer mounted in the pipe (facing towards and away from the valve, respectively); relative to the expected noise propagation direction.

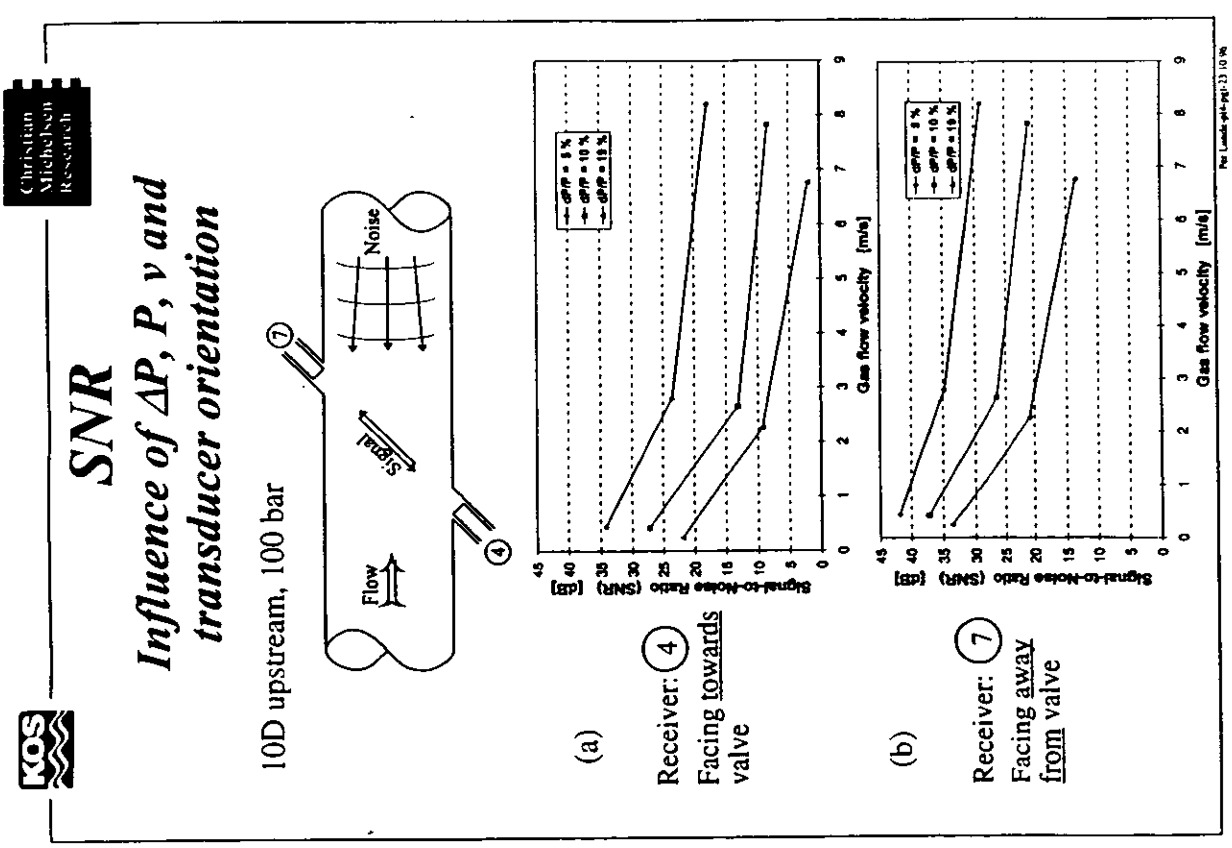
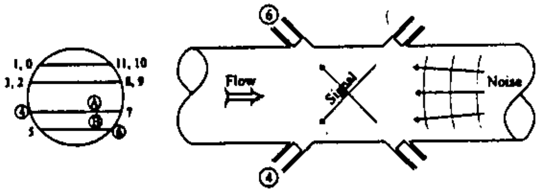


Fig. 5. SNR plotted vs. flow velocity, v, for different ΔP/P.
Conditions: USM installed 10D upstream of valve, P ≈ 100 bar.
(a) Path A, transducer facing towards the valve (no. 4).
(b) Path A, transducer facing away from the valve (no. 7).

SNR

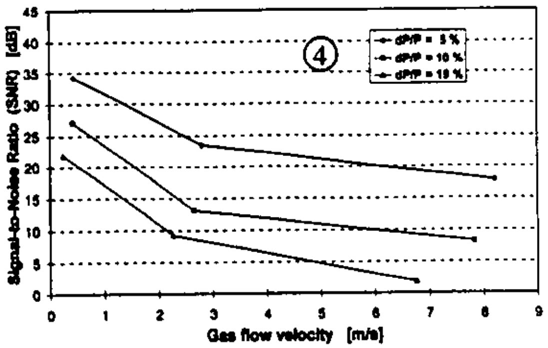
Influence of lateral position of path

10D upstream, 100 bar



(a)

Path (A) :



(b)

Path (B) :

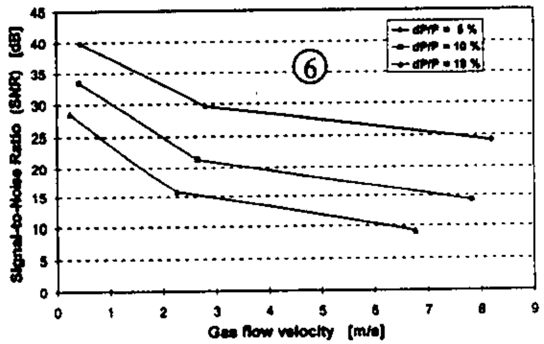


Fig. 7. SNR plotted vs. flow velocity, v, for different $\Delta P/P$.
Conditions: USM installed 10D upstream of valve, $P \approx 100$ bar.
(a) Path A, transducer facing towards the valve (no. 4).
(b) Path B, transducer facing towards the valve (no. 6).

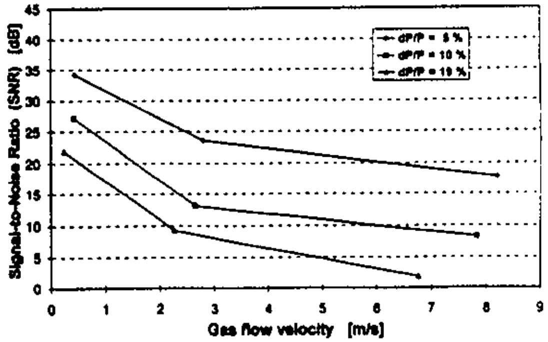
SNR

Influence of distance from valve

100 bar, transducer (4) (facing towards valve)

(a)

10D upstream



(b)

5D upstream

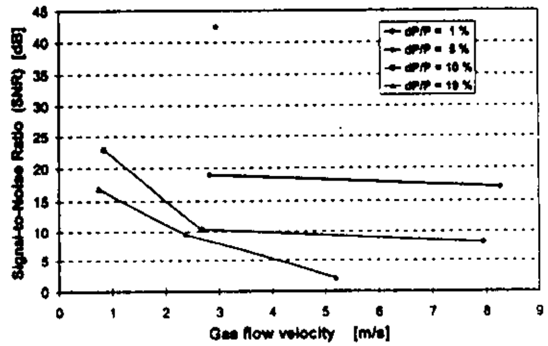


Fig. 8. SNR plotted vs. flow velocity, v, for different $\Delta P/P$.
Conditions: $P \approx 100$ bar, path A, transducer facing towards the valve (no. 4).
(a) USM installed 10D upstream of valve.
(b) USM installed 5D upstream of valve.

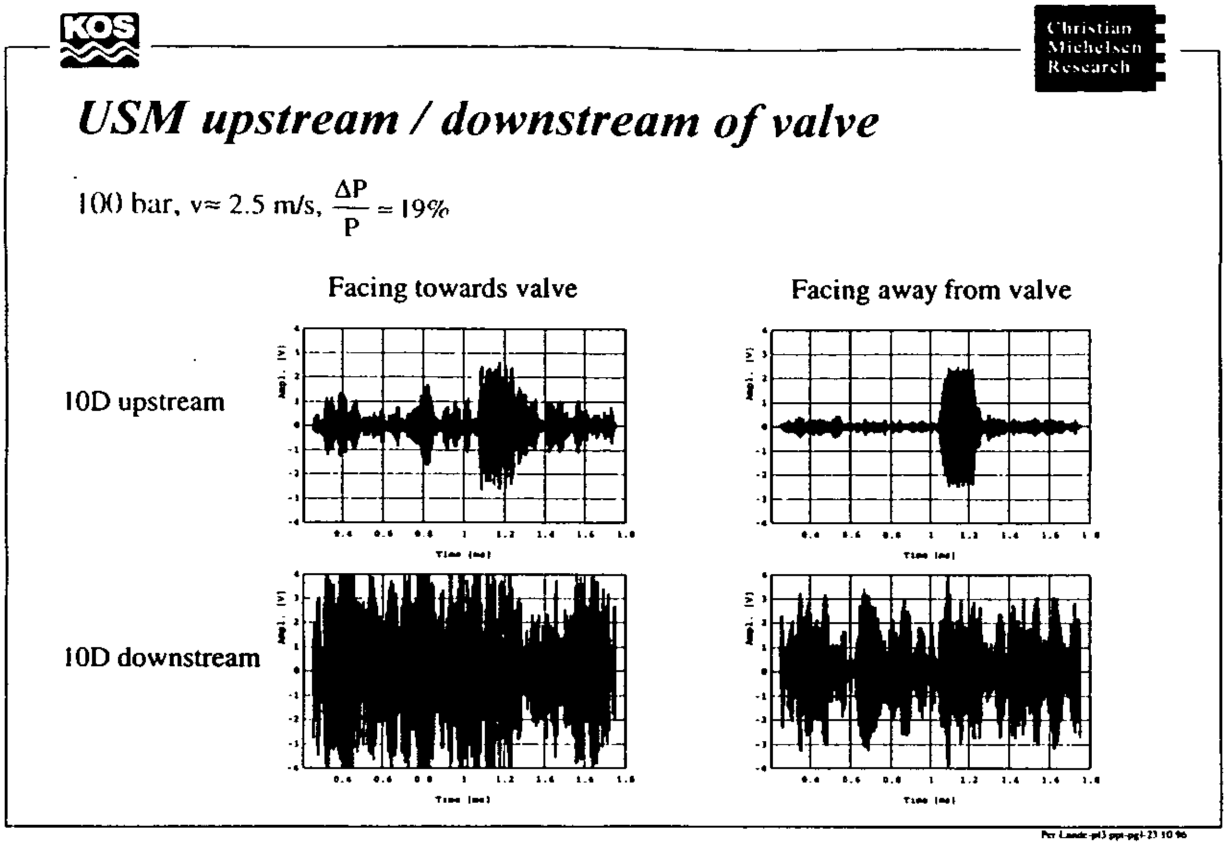


Fig. 9. Voltage signal traces, recorded for different installation conditions, as explained in the figure. For all traces: $P \approx 100$ bar, $v \approx 2.5$ m/s, $\Delta P/P \approx 19$ %.

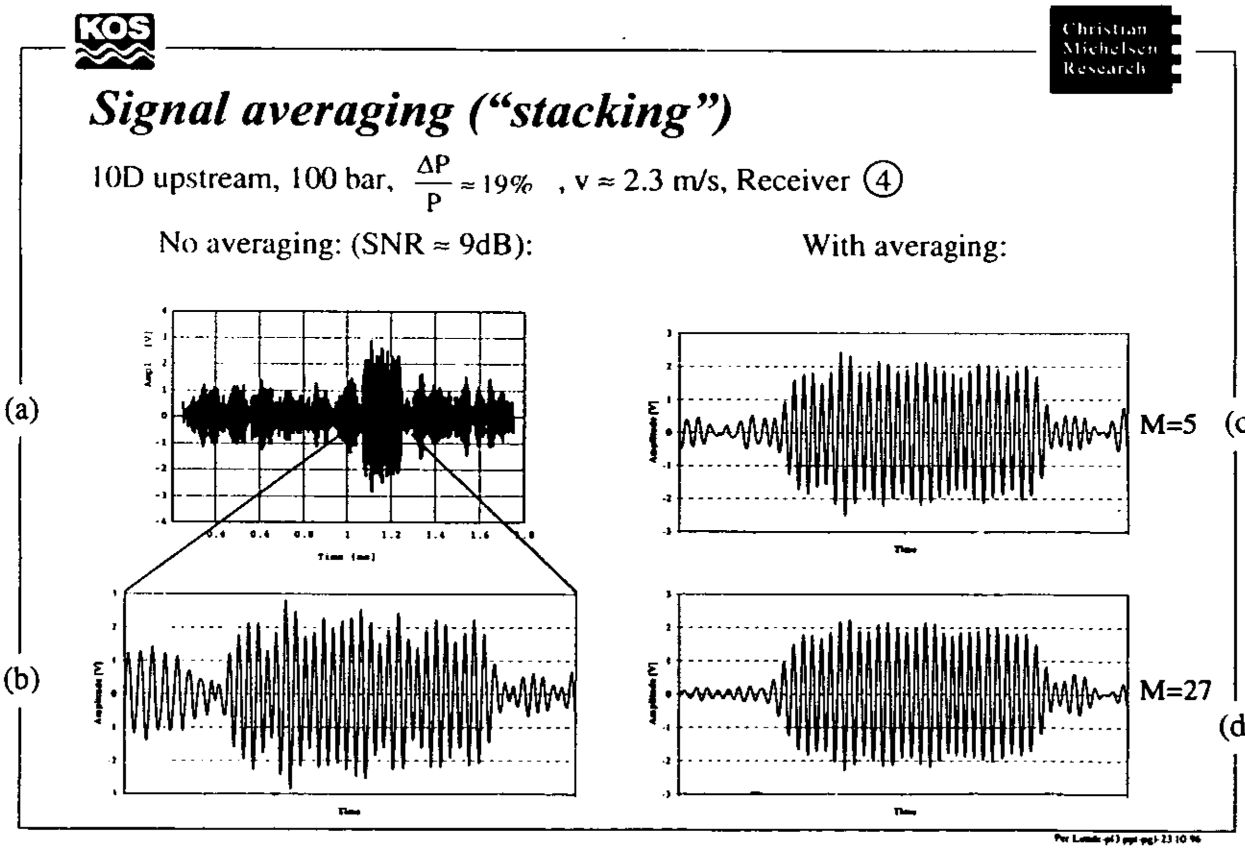


Fig. 10. Effect of averaging signal traces, recorded at one of the piezoelectric transducers of the USM (no. 4), for the following installation conditions: 10D upstream of the valve, $P \approx 100$ bar, $\Delta P/P \approx 19$ %, $v \approx 2.3$ m/s, transducer facing the valve. (a) No averaging; (b) blow-up of the signal part of the trace shown in (a); (c) average of 5 traces; (d) average of 27 traces.

KOS

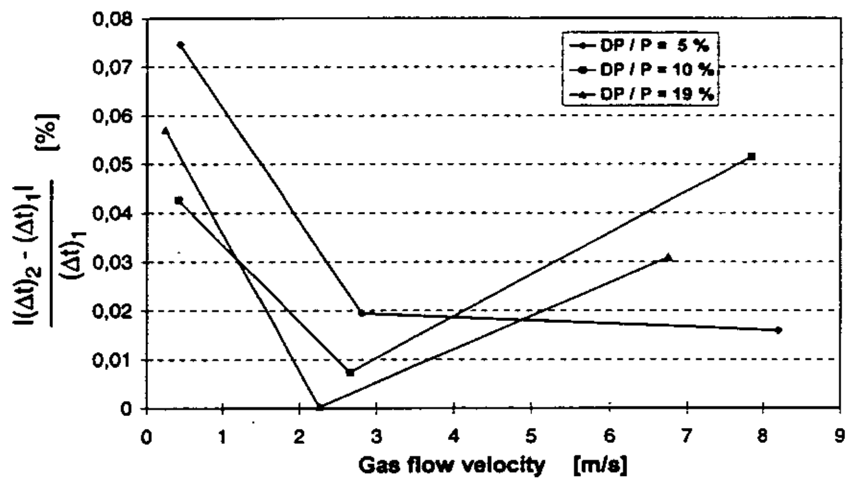
Christian Michelsen Research

COMPARISON OF TIME DETECTION METHODS IN VALVE NOISE

(1) Signal averaging ("stacking")

(2) Alternative signal processing method

≈ "Worst case" path:



$$v_i = \frac{L_i \Delta t_i}{2 t_{1i} t_{2i} \cos \phi_i}, \quad \Delta t_i \equiv t_{up,i} - t_{down,i}$$

$$v = \sum_{i=1}^{N} w_i v_i$$

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Fig. 11. Comparison of (1) signal averaging method ("stacking") and (2) "alternative signal processing method" for transit time detection, for USM installed 10D upstream of the valve, P ≈ 100 bar, and for path A (cf. Fig. 5a). The figure shows the relative difference in Δt_i between the two methods, for a single path. Expressions for the average axial flow velocity along path no. i, v_i ($i = 1, ..., N$), and the average axial (integrated) flow velocity in the pipe, v, are also given.