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IMPACT OF PULSATION SOURCES IN PIPE SYSTEMS ON MULTI-PATH ULTRASONIC FLOWMETERS

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1 INTRODUCTION

In this paper we describe the impact of low frequency pulsations in the frequency range from 10 to 100 Hz, which are imposed on a commercially available 4-inch dual-beam ultrasonic flowmeter.

It is well known that various flow metering techniques, widely used in oil and gas industry like turbine, vortex or pressure differential flowmeters are influenced by flow pulsations. Guidelines on the effects of pulsations on these flow measurement instruments, based on research in the last decades, are presented in the latest review of ISO/TR 3313 [1]. Ultrasonic flowmeters are however not included in this ISO Technical Report and publications on the impact of pulsations on this type of flow meters are scarce. The AGA (American Gas Association) Report No 9 on multipath ultrasonic flow meters [2] mentions the possible influence of pulsations if synchronised with the transducer-firing rate, though does not specify any limits regarding allowable pulsations. The recently published ISO Technical Report ISO/TR 12765 [3] on ultrasonic flowmeters does not refer to any pulsation effects.

The impact of high frequency acoustic noise as caused by control valves is well known and published at several occasions [4]. Hakansson and Delsing [5] reported the results of a series of tests on a 1-inch size, single path ultrasonic flowmeter regarding aliasing errors due to low frequency pulsations. To the author's knowledge, there have been no publications, in open literature, regarding the impact of *low frequency pulsations* on commercially available ultrasonic flowmeters.

The first results of the tests we performed on an ultrasonic flowmeter have been presented at an earlier occasion [6]. The test have been extended by measurements in a wider frequency range, between 10 and 100 Hz, and lower amplitudes to cover a range of existing pulsation sources in pipe systems. Fluid machinery of the positive displacement type, like reciprocating compressors and pumps are strong sources of pulsating flow. So close to compressor stations high flow pulsation levels can occur up to partial flow reversal in case of acoustical resonances in the piping, even if pressure pulsations are low and acceptable according to for example API618 or API674 standards. Obviously flow meters should not be located close to compressor stations without considering pulsation effects. However also in metering stations flow induced pulsations, due to vortex shedding at T-joints, can also be considerable and may result in misreading of the ultrasonic flowmeter.

In the tests described in this paper flow pulsations in the air rig can be varied between 5% and 100% rms of the average flow, which ranges from 0-1200 m^3/hr. The impact of the pulsations at frequencies of 10, 15, 25, 50 and 100 Hz on the flowmeter reading is determined at an average flow from 2-20 m/s. The results of these tests show a considerable influence on the meter reading, partly due to the aliasing effect, for pulsation frequencies coinciding with the sample frequency or multiples thereof. Errors in reading are over 5% at a flow pulsation amplitude of 10% rms. It is not likely that the phenomenon observed is restricted to the flowmeters investigated.

The Flow Centre of TNO TPD is working on a continuing program in which the impact of pulsations on commercially available ultrasonic flowmeters for gas is investigated systematically. In addition appropriate methods in signal processing are investigated, so that measures can be taken to minimise the uncertainty in the flowmeter reading.

Keywords: Pulsations, installation effects, aliasing error, and ultrasonic flowmeters

2 PULSATION SOURCES IN PIPE SYSTEMS

The ultrasonic flowmeter is increasingly being used in gas production and transmission as well as for liquid and high-pressure steam applications. There is still hesitation in applying the technique for custody transfer and sales gas flow metering, as experience in this application field is limited.

The European Gas Research Group (GERG) has recently reported experiences and research on practical problems with a number of ultrasonic flowmeters [7]. Regarding installation effects this research has been concentrated on the impact of non-ideal flow and the influence of (valve) noise. Further work on possible improvement by the use of flow conditioners is recently reported by SWRI [8] and applies to three 12-inch, different make ultrasonic flowmeters and various flow conditioners.

These investigations do not include the impact of low frequency flow pulsations on the accuracy of ultrasonic flowmeters. It is recognised that pulsations at the sampling frequency may influence flowmeter function and accuracy, though investigations on commercially available ultrasonic flowmeters have not yet been reported.

Advantages of the ultrasonic flowmeter are no pressure loss and a relatively short inlet and outlet section. For the dual-beam ultrasonic flowmeter these distances, as specified by the manufacturer, are respectively 15D and 5D. It is obvious that this distance is not related to pulsation sources, like compressors and pumps, as low-frequency pulsations can propagate over a long distance with minor damping. Measurements in practice have shown that pulsations can result in flowmeter and vibration problems at large distances over 1000 meter from the pulsation source, if adequate damping is not provided at the source [9]. Pressure and flow pulsations caused by positive displacement fluid machinery like reciprocating compressors and pumps are periodic signals, related to the running speed. The type of compressor or pump, the operating conditions and the kind of capacity control determines the pulsation, which are excited at the compressor speed and harmonics thereof.

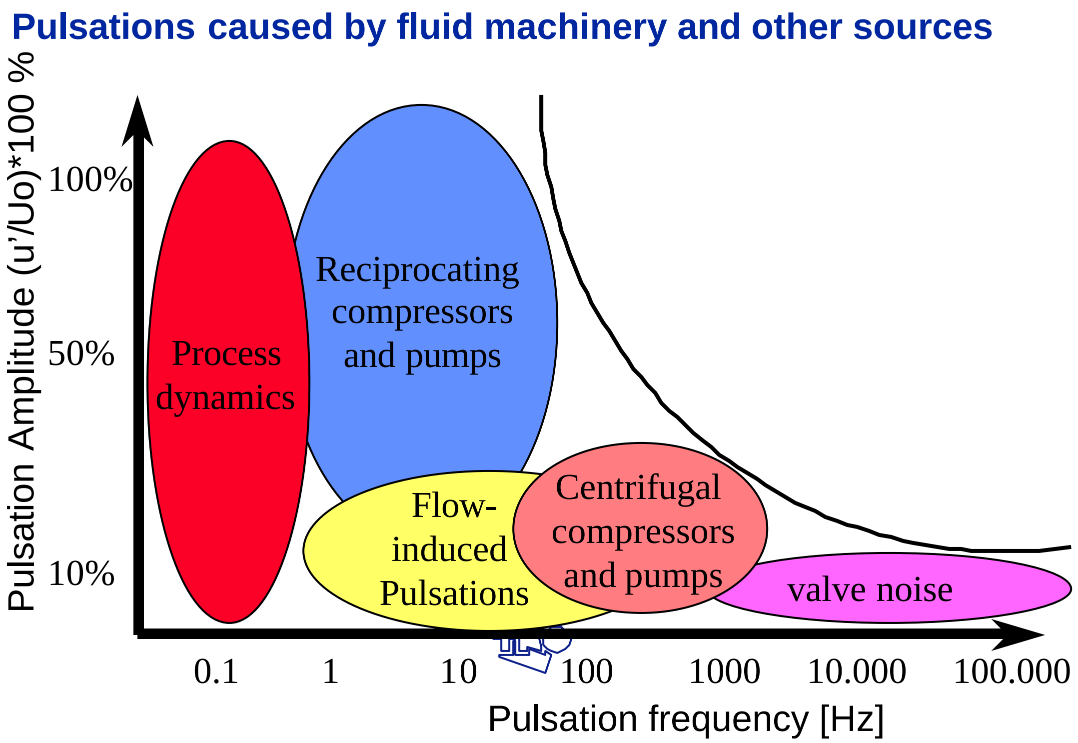

Figure 2.1 *Sources of pulsating flow in process installations*

Next to pulsations caused by positive displacement fluid machinery flow-induced pulsations are observed in flowmetering and control stations of gas transport systems. This pulsation mechanism is due to vortex shedding at T-joints when flow is passing along closed side-branches [11]. The flow induced pulsations can occur when unsteady flow separation couples with acoustic modes of the gas system . In Figure 2.1 an overview of pulsation frequencies and amplitudes as caused by various pulsation sources is presented. It shows that flow fluctuations or pulsations can occur in a wide frequency range on a scale from 0.1 Hz up to 100 kHz with decreasing flow pulsation amplitudes at higher frequencies.

The PULSIM program, originally developed by TNO TPD for the calculation of pulsation levels and forces due to positive displacement machinery, is also capable to predict pressure and flow pulsations due to a variety of sources including flow-induced pulsations. PULSIM predicts the flow pulsation frequencies and levels at the location of flow measurement devices and can be used to optimise the installation to minimise measuring errors due to pulsating flow. The package has been applied successfully to evaluate pulsation problems in flow metering and control stations in industry [9,10].

3 THE ALIASING ERROR DUE TO PULSATING FLOW

According to Hakansson and Delsing [5] an error caused by the aliasing effect is one of the main effects leading to a misreading. In theory, when the sampling frequency is equal to the pulsation frequency, the error in reading can be equal to the flow pulsation amplitude relative to the mean flow. When the sampling frequency is different, the error can be determined as follows. If we assume a steady flow with an average velocity U_0 in a pipe system and add a sinusoidal pulsating flow component u_p to the flow, the instantaneous flow can be written:

$$U(t) = U_0 + u_p \sin 2\pi f_p t \qquad (1)$$

In which:

- U_0: average flow velocity, m/s
- u_p: pulsation amplitude, m/s
- f_p: pulsation frequency

To prevent aliasing the sampling frequency should be at least twice the highest pulsation frequency according to the Nyquist sampling theorem. The ultrasonic flowmeter, as the one tested, is provided with a signal converter with a fixed sampling rate, which is often in the order of 25-50 Hz. Intermediate time between samples can sometimes be controlled to obtain less sensitivity for aliasing effects. Hakansson and Delsing [2] have derived an expression for the theoretical aliasing error. Assuming a time constant t_i, the sampled value of the flow U_n at t_n can be written as:

$$U_n\ (t_n) = (1/\ t_i) \int_{tn}^{tn+ti} U_t\, dt \qquad (2)$$

The relative error on the meter reading or indicated flow E_r is defined as:

$$E_r = 100(U_n - U_0)/U_0 \text{ in } \% \qquad (3)$$

A combination of the Equations (1), (2) and (3) results in an expression for the metering error E_r related to the pulsation amplitude and frequency and the integration time:

$$E_r = 100\ (u_{rms}/Uo\sqrt{2}\pi f_p t_i)[\cos 2\pi f_p t_i - \cos 2\pi f_p (t_n + t_i)] \text{ in } \% \qquad (4)$$

The maximum error occurs if cosine terms are maximised, thus an expression for the maximum meter reading due to the aliasing error is related to pulsation amplitude, frequency and integration time in the following way:

$$E_r \leq 100\sqrt{2}(u_{rms}/Uo/\pi f_p t_i) \quad \text{in } \% \qquad (5)$$

The expression for E_r from Equation (5) will be used in Section 5 to compare with the measured error due to a pulsating flow.

4 TEST SET UP FOR FLOW AND PULSATION MEASUREMENT

The impact of flow pulsations on the ultrasonic, two-path 4-inch flowmeter has been determined experimentally on the low-pressure air flow test-facility of the TNO Institute of Applied Physics.

The test rig, shown schematically in Figure 4.1, consists of a large buffer vessel of 2 m^3 to dampen pressure and flow fluctuations from the compressor. The maximum capacity of the test rig is 1200 Nm^3/h at 100 kPa, or a lower capacity at a higher pressure, up to a maximum of 700 kPa. Turbine flowmeters, diameters 2" and 3", with an accuracy better than 0.5% are used as transfer standards. These flowmeters are installed in the high-pressure section (700 kPa) upstream of the control valves, whereby both pressure and flow can be controlled. The 4-inch ultrasonic flowmeter under test is located at a distance of 55D (5.5 m) downstream of any flow disturbing elements, like elbows, T-joints or reducers. This distance prohibits flow disturbances to affect flow meter readings.

The steady flow to the flowmeter can pass the pulsator, which consists of a cylinder with a number of holes. The flow is periodically blocked, thereby generating strong pulsations. The amplitude of the flow pulsation is controlled via the bypass valve parallel to the pulsator. The tests are carried out at atmospheric pressure and ambient temperature in the downstream section of the control valves.

Above a critical pressure drop, pulsations generated downstream of the control valve cannot travel upstream of the valve. Thus the reference turbine meters are located in a steady flow, which is checked by measuring the dynamic pressure at the turbine flowmeters.

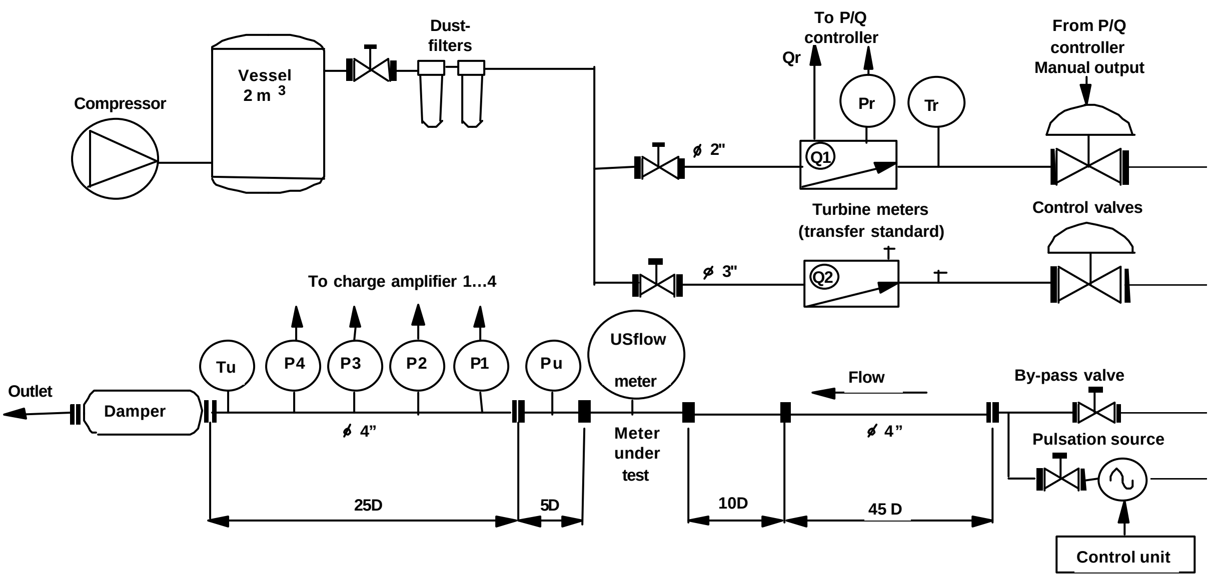

Figure 4.1 *Pressurised AirFlow Test-Facility set up to determine the impact of a pulsating flow*

In the section downstream of the ultrasonic flowmeter, reference pressure (P_u) and temperature (T_u) are measured. This section also contains a number of dynamic pressure transducers (P1-P4) used to determine actual pressure and velocity at the meter under test by means of the two-microphone method. To check this method, the pulsating flow is also occasionally measured by means of a hot-wire anemometer.

The pulsation source generates a pulsating flow, which can be varied in frequency from 5-300 Hz, with a flow pulsation amplitude u_{rms}/U_0 between approximately 5 and 100 % rms, dependent on frequency and average flow U_0. The pressure and flow in the test rig are regulated via the 2" or 3" control valve and the reference flow from the turbine meter Qr is determined from the high frequency pulsed output. T he actual flow at the ultrasonic meter under test is determined by measuring P_u and T_u and correcting the reference flow Qr, taking into account the compressibility of the gas.

The investigation is performed at atmospheric pressure (1 bara) and ambient temperature, which is approximately 20ºC; this means that all measurements are done in the turbulent flow region with Reynolds numbers varying from approximately $1.9*10^4$ to $1.5*10^5$.

The 4-inch ultrasonic flowmeter has a current output and a pulse output from 0-1000 Hz for a flow range of 0 – 565.5 m^3/h (0-20 m/s). The sampling rate of the flowmeter is fixed at 20 ms. The inaccuracy, as specified by the manufacturer, is less than 2 % of the measured value.

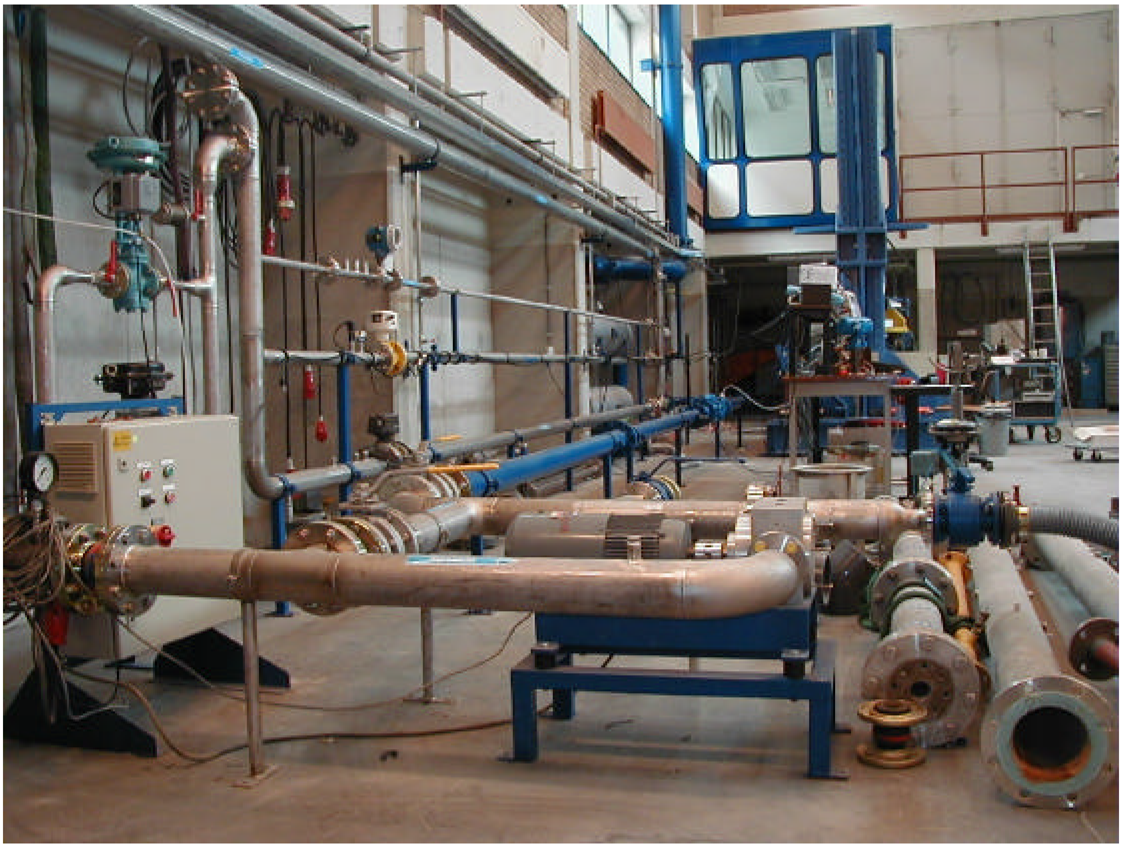

Figure 4.2 *Overview of test facilities at TNO TPD*

The flow pulsation amplitude varies per frequency as the acoustic response of the piping determines the pulsation amplitude at the flow meter location. Moreover the flow pulsation cannot be kept constant over the complete flow range. To achieve various pulsation amplitudes and pulsation frequencies the pulsation source can be adapted by replacing the rotating cylinder. In totally 3 versions are available, with respectively one, two or three holes equally divided over the cylindrical circumference, thus generating pulsations at 2, 4 and 6 times the rotating speed of the cylinder.

5 IMPACT OF FLOW PULSATIONS ON THE CURRENT OUTPUT

The flow pulsation generated is an almost sinusoidal fluctuation on the average flow U_0, the frequencies for which the impact on the reading of the 4-inch dual-beam ultrasonic flowmeter has been applied are ranging from 10 to 100 Hz. The flow in the experiments is varied from 75 to 575 m3/hr or from 2.8 to 21.6 m/s in the 4-inch line.

An overview of the measurements and the corresponding maximum theoretical aliasing error $E_{r\ according}$ to formula (5) is shown in Table 5.1 below.

Table 5.1 - *Overview of pulsation frequencies and amplitudes and theoretical maximum aliasing error E_r*

Pulsation Frequency	Measurement series I		Measurement series II		Measurement series III	
f, Hz	$U_p/U_{0,}$ % rms	Maximum aliasing error E_r, %	$u_p/U_{0,}$ % rms	Maximum aliasing error E_r, %	$u_p/U_{0,}$ % rms	Maximum aliasing error E_r,%
10	'5%'	11.2	'10%'	22.4	'25%'	56.1
15	'5%'	7.5	'10%'	14.9	'25%'	37.4
25	'8%'	7.2	'16%'	14.2	'25%'	22.4
50	'10%'	4.5	'38%'	17.1	'62%'	27.8
100	'10%"	2.2	'30%'	6.7	'58%'	13.0

We determined the reference curve of the ultrasonic flowmeter, the meter showed an 'error in reading' deviating from the turbine reference with +1.5% for the minimum flow of 50 m^3/h to – 0.7% for the maximum flow of 565 m^3/h (see Figuure 5.1). The indicated flow $Q_{reading}$ is determined from averaging the current output of the flow over a long period of time.

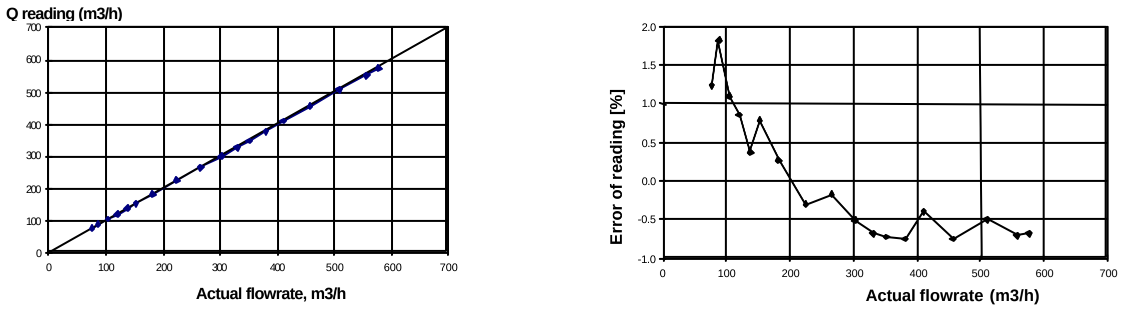

Figure 5.1 Reference curve of 4 inch ultrasonic flow meter

In a pulsating flow, the current output varies considerably and shows a fluctuating or beating output. The periodic variation depends on the average flow and pulsation amplitude. For example, Figure 5.2 shows an example of the strongly fluctuating output signal at an average flow of 250 m^3/h at a pulsation frequency of 25 Hz. The variations in the current output are in the order of 50% of the average value.

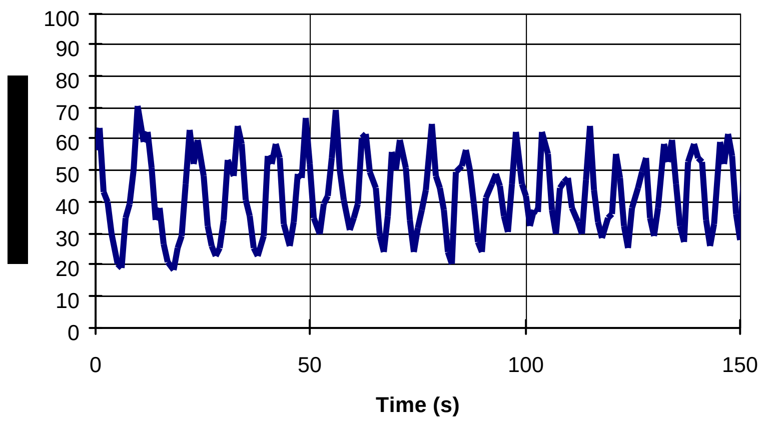

Figure 5.2 Current output at an average flow of 250 m^3/h; fp = 25 Hz- flow pulsation amplitude 16% rms

The Figures 5.2 and 5.3 show the fluctuating output at an average flow of respectively 350 m^3/h and 550 m^3/h.

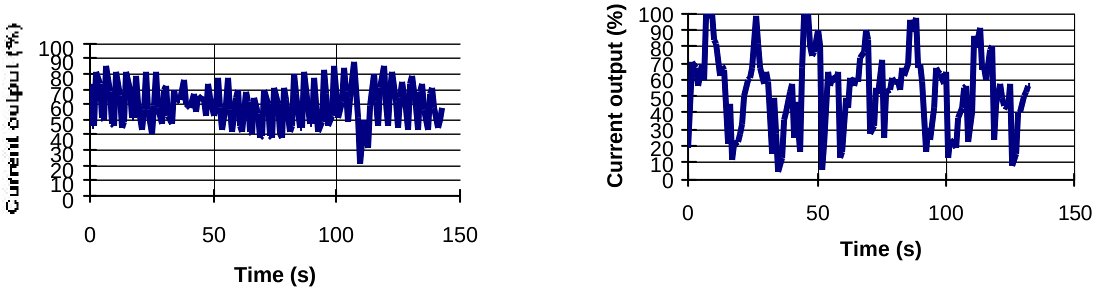

Figure 5.3 Current output at 350 m^3/h and 550 m^3/h at ; fp = 25 Hz- flow pulsation amplitude 16% rms

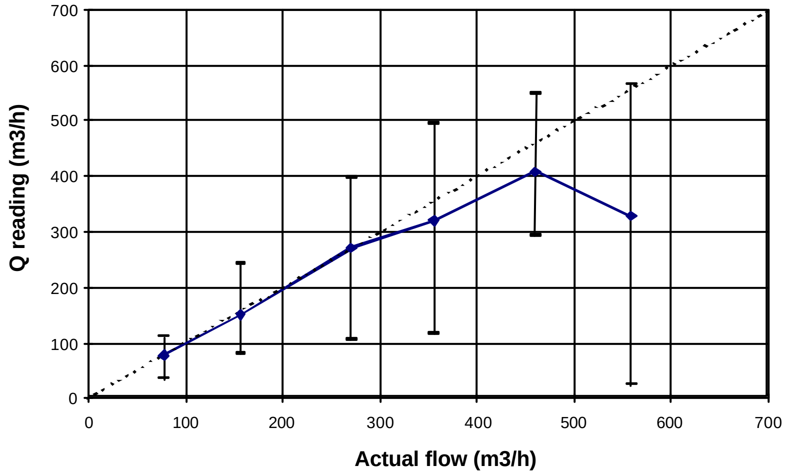

Figure 5.4 Indicated flow versus actual flow with flow pulsation at 25 Hz; pulsation amplitude 16% rms

The fluctuation of the current output varies with the actual average flow and is visualised by the error bar at each flow measuring point. During the measurements, there is a slight variation in pulsation amplitude from 15-19% rms. The error in reading, plotted in Figure 5.5. shows the varying current output and the average flow indicated by the ultrasonic flowmeter, which shows a negative error up to –40% at the maximum flow of 550 m^3/h. Except for the last measurement point, this corresponds to the theoretical maximum error of 14%.

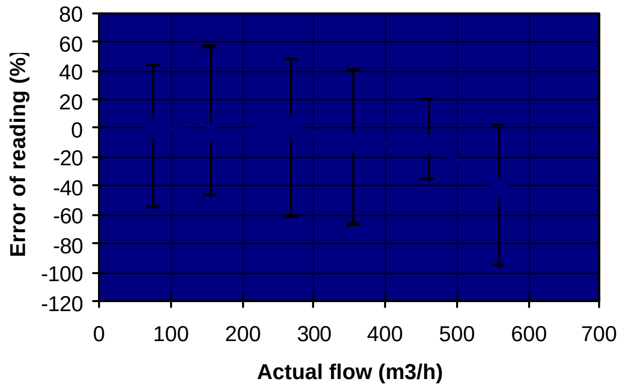

Figure 5.5 The error in reading (in %) with a flow pulsation at 25 Hz; pulsation amplitude 16% rms

If we decrease the pulsation amplitude to approximately 8% rms the resulting error is less, but still considerable with a maximum of –8% at the maximum flow of 550 m^3/hr as shown in Figure 5.6. Also this value corresponds to the theoretical error due to aliasing.

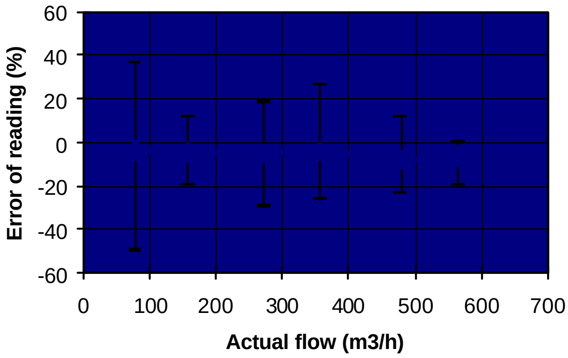

Figure 5.6 The error in reading (in %) with a flow pulsation at 25 Hz; pulsation amplitude 8% rms

6 IMPACT OF FLOW PULSATIONS AT DIFFERENT FREQUENCIES AND AMPLITUDES ON THE FLOWMETER READING

In addition to the measurements at 25 Hz, described in Section 5, the impact of pulsations has been determined at lower (i.e. 10 and 15 Hz) and higher (i.e. 31, 50 and 100 Hz) frequencies. The results of the higher frequencies are shown in the figures below. The deviation of the meter reading of the ultrasonic flowmeter ($Q_{reading}$) are presented against the actual flow. In addition the error of reading is shown as a function of the actual flow. The error tends to increase with flow, for a constant pulsation frequency in all cases. In theory, the error in reading should be independent of the flow rate, but since the pulsation amplitude cannot be kept constant, small variation may occur. In general, when the pulsation amplitude is increased also the error in reading increases. For 100 Hz (twice the sampling frequency) the ultrasonic meter does not even show a reading for actual flows above 250 m^3/h for the highest pulsation level. At a lower level, the error in reading is close to the theoretical value.

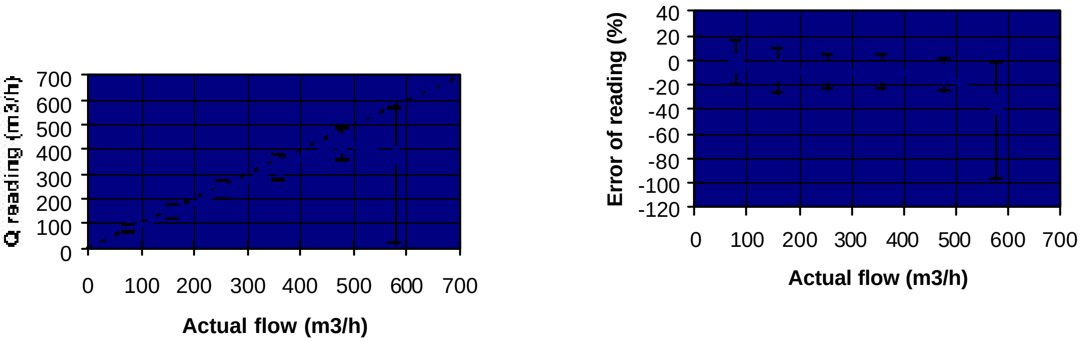

Figure 6.1 The error in reading (in %) with a flow pulsation at 50 Hz; average pulsation amplitude 62% rms

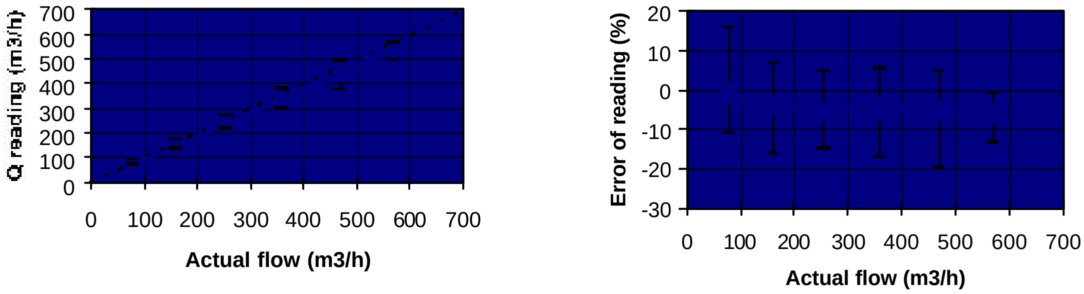

Figure 6.2 The error in reading (in %) with a flow pulsation at 50 Hz; average pulsation amplitude 38% rms

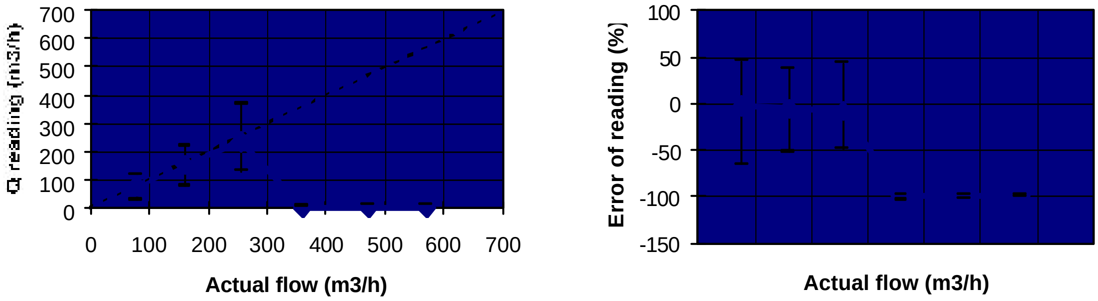

Figure 6.3 The error in reading (in %) with a flow pulsation at 100 Hz; average amplitude 58% rms

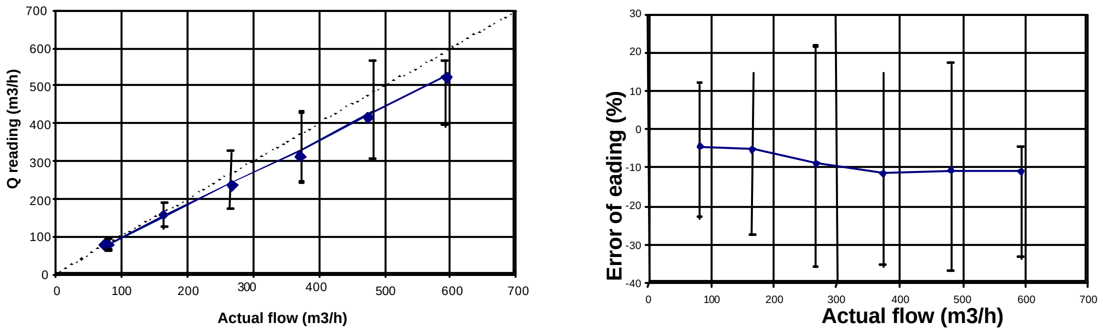

Figure 6.4 The error in reading (in %) with a flow pulsation at 100 Hz; average amplitude 30% rms

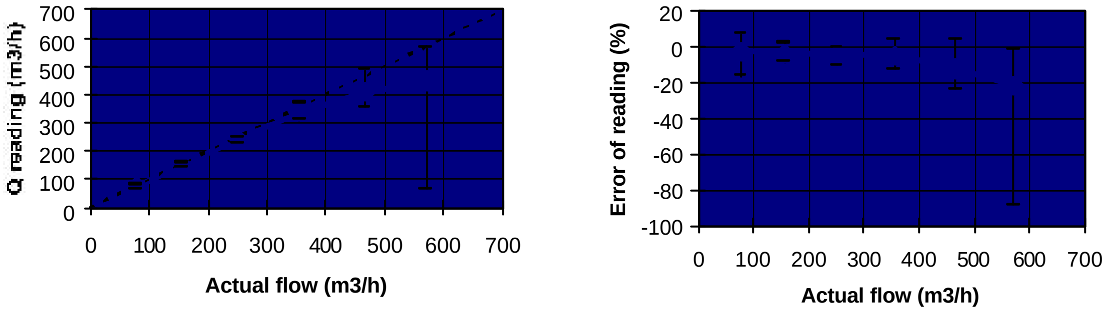

Figure 6.5 The error in reading (in %) with a flow pulsation at 31 Hz; average amplitude 16% rms

7 IMPACT OF FLOW PULSATIONS AT LOW FREQUENCIES AND AMPLITUDES ON THE FLOWMETER READING

The effect of low-frequency pulsations is shown in Figures 7.1 and 7.2 for 3 amplitudes, i.e. 5, 10 and 25%. Again, the error in reading increases with increasing flow rate, but the actual error is much less than the theoretical error due to aliasing. For a pulsation frequency of 10 Hz, the maximum error in reading observed is –12%, while for 15 Hz, the maximum error in reading is –5%. Note that for all the measurements, the error in reading is negative, similar to results obtained for vortex flow meters. This in contrary to orifice and turbine flow meters, which in general have a positive error due to a pulsating flow.

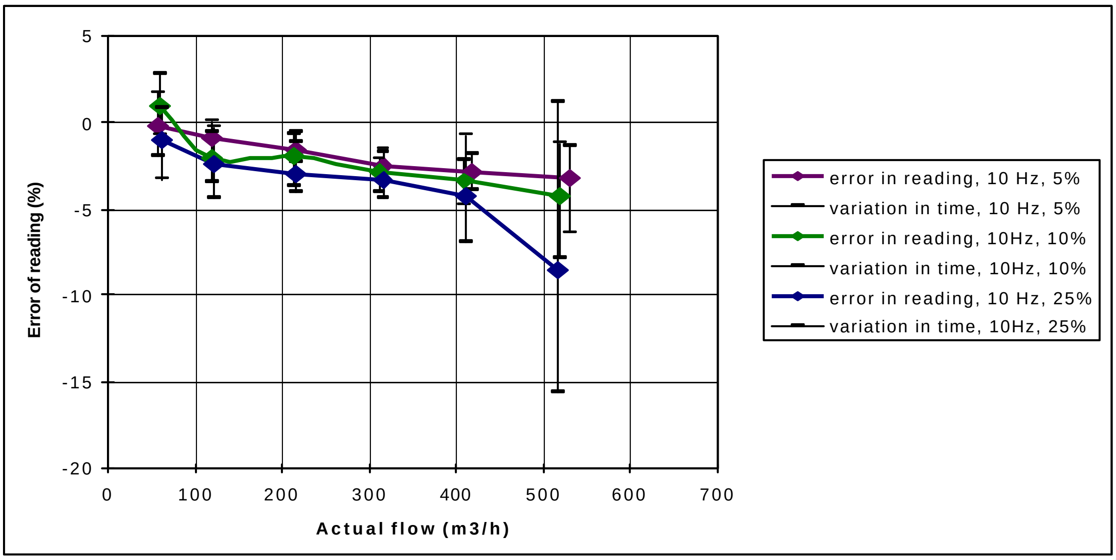

Figure 7.1 The error in reading (in %) with a flow pulsation at 10 Hz; at three pulsation amplitudes 5, 10 and 25% rms

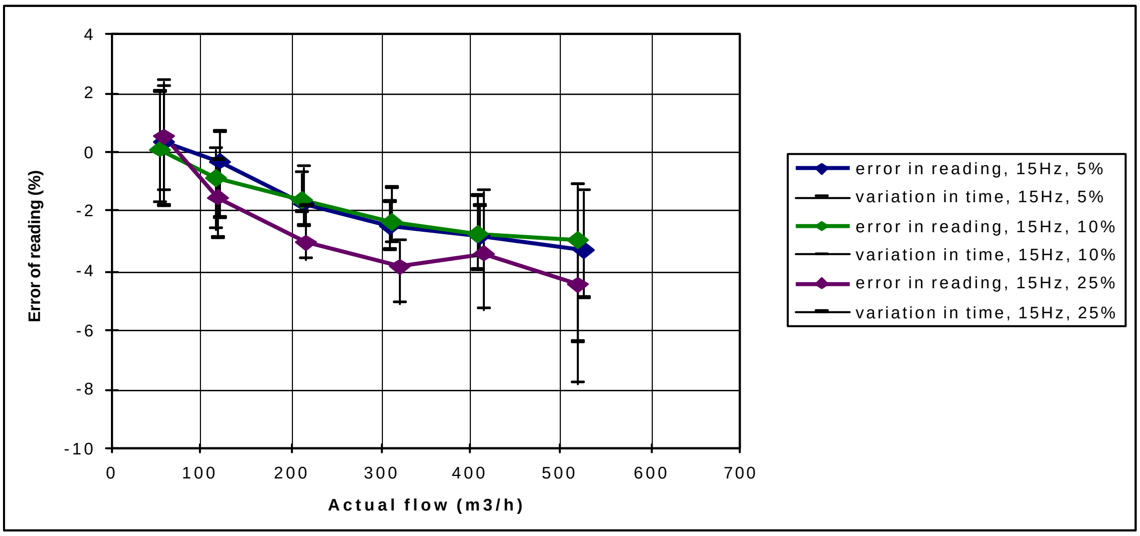

Figure 7.2 The error in reading (in %) with a flow pulsation at 15 Hz; at three pulsation amplitudes 5, 10 and 25% rms

8 CONCLUSIONS AND RECOMMENDATIONS

The measurements show that there is a strong impact of pulsations on the flowmeter reading in the frequency range from 10 to 100 Hz. Not only at the sample frequency of 50 Hz, but also at pulsation frequencies below the sample frequency, at 10, 15, 25 or 31 Hz, the pulsation error is considerable.

For the frequencies of 31 and 50 Hz the error bars in Section 6 shows errors, which are within the aliasing error derived by Hakansson and Delsing [2] as described in Table 5.1.

Though for the pulsation frequencies of 25 Hz (see Figures 5.4 - 5.5) and 100 Hz (see Figures 6.3-6.4) the measured error bar is larger than the theoretical aliasing error. At 100 Hz and a pulsation amplitude of 58% rms the current output signal of the flowmeter is completely distorted and shows a reading of zero average flow for actual flows of 350 m^3/h and higher.

Even for a relatively low pulsation amplitude of 8% rms and a frequency of 25 Hz the error in reading is varying from –3% to –8% (see Figure 5.5).

In all cases the ultrasonic flowmeter tested shows a considerable underestimation of the average flow. This is in line with earlier findings, reported by Hakansson and Delsing [5], though their investigation covers a range of Reynolds numbers from 1700 to 13400 thus including partially laminar flow and the transition range. In the laminar flow region the distortion of the average flow profile, which tends to flatten when pulsations are added, can be an additional cause of a reading error. The pulsation effects on the mean velocity profile in the turbulent range, where we performed our measurements, are less evident and need further investigation.

Hakansson and Delsing [5] also report heavy distortion of the ultrasound pulse for high Reynolds numbers (Re > 11000) resulting in large negative errors, which corresponds to our findings.

The systematic error due to pulsations found for ultrasonic flow meters is negative; similar to vortex flowmeters found in earlier investigations. This is in contrary to pulsation errors reported for orifice and turbine flow meters, which in general have a positive systematic error due to a pulsating flow.

9 PROSPECTS FOR FURTHER EVALUATION AND IMPROVEMENT

The investigation described is applied to a single 4-inch ultrasonic flowmeter of one make for a limited range of pulsation amplitudes and frequencies. It is not likely that the impact of pulsations is restricted to the meter tested. We will therefor continue the investigation for a number of preferably different make ultrasonic flowmeters applied for gases. In the near future pulsation tests will also be conducted in a liquid test rig. The range of frequencies and amplitudes will be extended to lower pulsation amplitudes to be able to determine the threshold value of pulsations, which still have an impact of the ultrasonic flow meter.

The algorithms applied in different make ultrasonic flowmeters are often based on determination of the flow from the moving average value. This may prevent errors due to short duration pulsations, like transients. Pulsations caused by fluid machinery however are periodical and thus often constant in frequency and amplitude over a longer time assuming constant running speed and operating mode. Flow induced pulsations (FIPS), as caused by vortex shedding on T-joints, are due to coupling between vortex frequencies and acoustic resonance frequencies, which may result in fluctuations in amplitude and frequency, strongly dependent on the mean flow velocity and the piping geometry [11, 12].

Further investigation into possibilities for reducing the sensitivity of ultrasonic flowmeters for flow pulsations is recommended. Improvement of algorithms and signal processing techniques is necessary to lower the sensitivity of ultrasonic flowmeters for low frequency flow pulsations.

Furthermore the lay out of flowmetering stations for custody transfer measurements should be such that pulsations are minimised. This is not only restricted to the location of the flow metering station with respect to fluid machinery like pumps and compressors but also to possible FIPS due to the geometric lay out in relation to the average flow velocity. We recommend that standards referring to ultrasonic flow meters and installation effects pay attention to the aspects mentioned above.

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