

THE IMPACT OF LOW-FREQUENCY PULSATIONS ON A DUAL-BEAM ULTRASONIC FLOWMETER

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ABSTRACT

The impact of flow and pressure pulsations on flowmeters of various measuring principles, like turbine, vortex or DP-based flowmeters is well known and published at several occasions. To the author's knowledge, there have been no publications on investigations regarding the impact of low frequency pulsations on commercially available ultrasonic flowmeters. The influence of high frequency acoustic noise, as caused by control valves, is part of several investigations and reported in recent publications [1,5].

This paper describes the impact of low frequency, almost sinusoidal pulsations in the range from 25 to 100 Hz, which are imposed on a 4-inch, dual-beam, commercially available ultrasonic flowmeter

The results of our experiments show a strong impact as a result of the aliasing effect for pulsation frequencies coinciding with the sample frequency or multiples thereof. Moreover considerable errors also occur if pulsation frequencies are below the sampling frequency. Errors in reading are over 5 % at a pulsation frequency of 25 Hz with a flow pulsation amplitude of 8 % rms.

It is obvious that ultrasonic flowmeters, as well as turbine, vortex or DP-based flowmeters, will not operate properly close to compressor stations as flow pulsation levels over 50 % rms occur even up to partial flow reversal in case of acoustical resonance. However also flow induced pulsations (FIPS) in metering stations, due to vortex shedding at T-joints, can be considerable in case of acoustical resonance and can result in misreading of the ultrasonic flowmeter. Typical frequencies of FIPS, determined by gas properties, operating conditions and piping geometry, are found in practice to be in the same range as the sample frequencies of the ultrasonic flowmeter.

It is not likely that the phenomenon observed is restricted to the meter under investigation. The TNO Institute of Applied Physics is therefore working on a program in which the impact of pulsations on commercially available ultrasonic flowmeters for gas is investigated systematically.

This paper presents the first results of this investigation. In addition appropriate methods in signal processing will be investigated, so that measures can be taken to minimise the uncertainty in the flowmeter reading.

The aim of the future investigations is to improve the ultrasonic flowmeter by using appropriate signal processing, so that it can operate properly and without misreading caused by flow pulsations.

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

1 INTRODUCTION

Limited information is available on the impact of pulsating flow on ultrasonic flow meters. Hakansson and Delsing [2] have published the results of a series of tests on a small, 1-inch size, single path ultrasonic flowmeter. The AGA report No.9 [3] mentions the possible influence of pulsations if synchronised with the transducer-firing rate, whilst the ISO/TR 12765 [4] on ultrasonic flowmeters does not refer to any pulsation effects.

This paper describes the impact of low frequency, almost sinusoidal pulsations in the range from 25 Hz to 100 Hz, which are imposed on the 4-inch dual-beam ultrasonic flowmeter. The flow pulsations in

the 4-inch air test loop are in the range of approximately 8 % to 60 % rms of the average flow, which ranges from 0-556 m³/h (0 up to 20 m/s). The impact of the pulsations on the flowmeter reading is determined experimentally at various settings of the meter for the flow range described. The effects of flow pulsations on the accuracy of an ultrasonic flowmeters has received little attention so far in open literature and discussion on installation effects on ultrasonic flowmeters. Examples of recent research dedicated to this subject are described in the next chapter.

2 Installation effects on ultrasonic flowmeters

The ultrasonic flowmeter is increasingly being used in gas production and transmission as well as for liquid and 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 has recently reported experiences and research on practical problems with a number of ultrasonic flowmeters [5]. 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 [6] 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 been reported.

Advantages of the ultrasonic flowmeter are no pressure loss and a relatively short inlet and outlet section. For the double-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 [7]. 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.

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 [8,9]. The flow induced pulsations can occur when unsteady flow separation couples with acoustic modes of the gas system.

Standing waves in closed side branches occur at frequencies similar to the vortex shedding or Strouhal-frequency, which depends on average flow in the main line and diameter of the side branch:

$$f_{\text{str}} = \text{Str} * U_0 / D \text{ in which:}$$

- f_{str} : Strouhal frequency, Hz
- Str : Strouhal number dependent on geometry 0.2 – 0.5
- U_0 : average flow velocity, m/s
- D : Diameter of side branch, m

The PULSIM program, originally developed by the TNO Institute of Applied Physics for the calculations of pulsation levels and forces due to positive displacement machinery, is nowadays also capable to predict pressure and flow pulsations due to vortex shedding. Source models for flow induced pulsations have now been implemented in this package inclusive the effect of flow direction and edge rounding on the source strength. The package has been applied to evaluate flow-induced pulsation problems in gas flow metering and control stations in industry [10, 11]

3 The theoretical aliasing error due to pulsations

We assume a steady flow with an average velocity U_0 in a pipe system. If we add a sinusoidal pulsating flow component to the flow, the instantaneous flow can be written:

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

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:

$$U_n(t_n) = (1/t_i) \int_{t_n}^{t_n+t_i} U_t dt \quad (2)$$

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

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

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:

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

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:

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

We used the expression for E_r from equation (5) to compare with the measured pulsation error.

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 fig 4.1, consists of a large buffer vessel of 2m³ to dampen pressure and flow fluctuations from the compressor. The maximum capacity of the compressor is 800 Nm³/h at 100 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 controlled by measuring pulsations at the turbine flowmeters

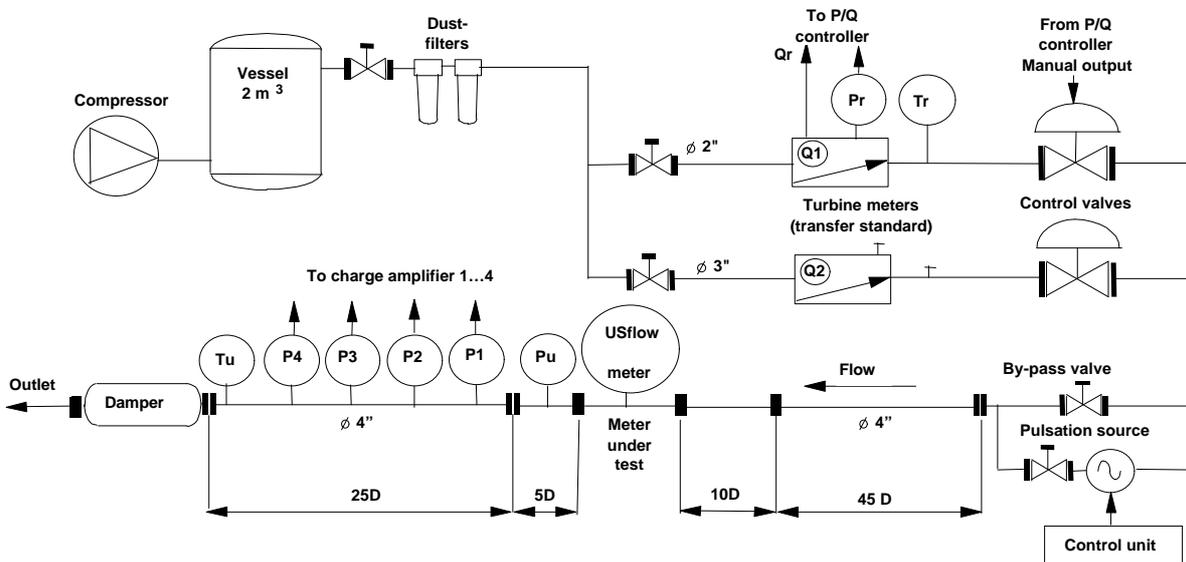


fig.4.1. Pressurised Air Flow Test-Facility set up to determine the impact of pulsations



fig. 4.2 Overview of test facilities



fig.4.3 Ultrasonic flowmeters in test rig

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.

The pulsation source generates pulsations, which can be varied in frequency from 5-300 Hz, with a flow pulsation amplitude u_{rms}/U_0 between approximately 8 and 65 % 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 Q_r is determined from the high frequency pulsed output. The

actual flow at the ultrasonic meter tested is determined by measuring P_u and T_u and correcting the reference flow Q_r .

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 the pulsator 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.

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 m³/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.

5 Impact of flow pulsations as a function of pulsation frequency and amplitude on the ultrasonic flowmeter

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 25 to 100 Hz. An overview of the measurements and the corresponding (maximum) aliasing error according to formula (5) is shown in table 5.1 below.

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

PULSATION FREQUENCY f, Hz	MEASUREMENT SERIES I		MEASUREMENT SERIES II	
	u_p/U_0 (% rms)	Max. error E_r (%)	u_p/U_0 (% rms)	Max. error E_r (%)
25	8	7.2	16	14.2
31	-	-	17	12.3
50	38	17.1	62	27.8
100	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 m³/h to -0.7 % for the maximum flow of 550 m³/h (see fig. 5.1)

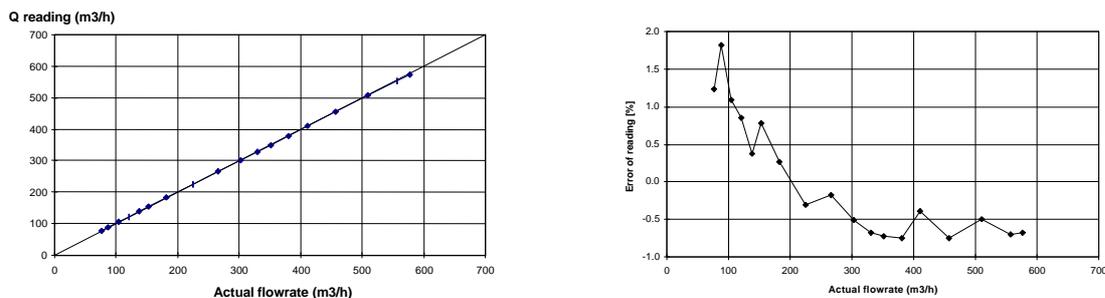


Fig.5.1. Reference curve of 4 inch ultrasonic flow meter

The indicated flow Q_{reading} is determined from the current output of the flow shown in fig. 5.2, which shows an example of the strongly fluctuating output signal at an average flow of 250 m³/h at a pulsation frequency of 25 Hz and a pulsation amplitude of approximately 16 %.

The flow in the experiments is varied from 75 to 550 m³/hr or from 2.7 to 20.7 m/s in the 4-inch line. The investigation is performed at atmospheric pressure (1 bara) and ambient temperature, which is approx. 20 degrees C; this means that all measurements are done in the turbulent flow region with Reynolds numbers varying from approximately $1.9 \cdot 10^4$ to $1.5 \cdot 10^5$.

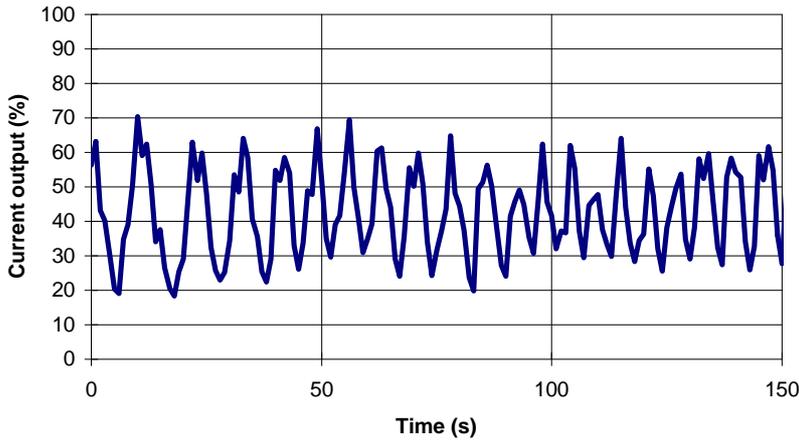


Fig.5.2. Current output at an average flow of 250 m³/h; $f_p = 25$ Hz- flow pulsation amplitude 16% rms

The current output varies considerably and shows a fluctuating or beating output, of which the periodic variation depends on the average flow and pulsation amplitude. The figures fig 5.2 and 5.3 show the fluctuating output at an average flow of respectively 350 m³/h and 550 m³/h.

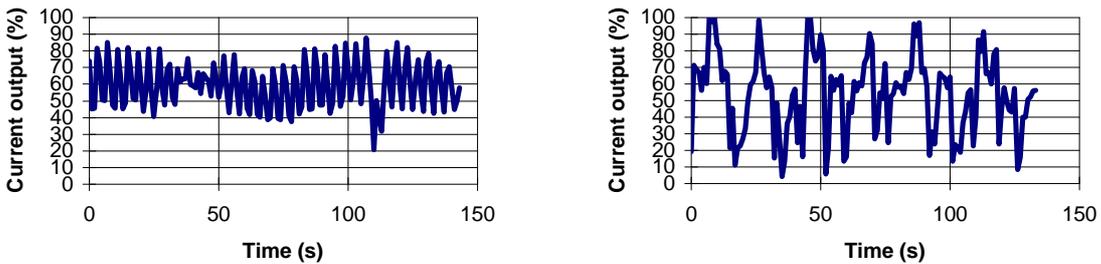


fig.5.3 Current output at 350 m³/h and 550 m³/h at ; $f_p = 25$ Hz- flow pulsation amplitude 16% rms

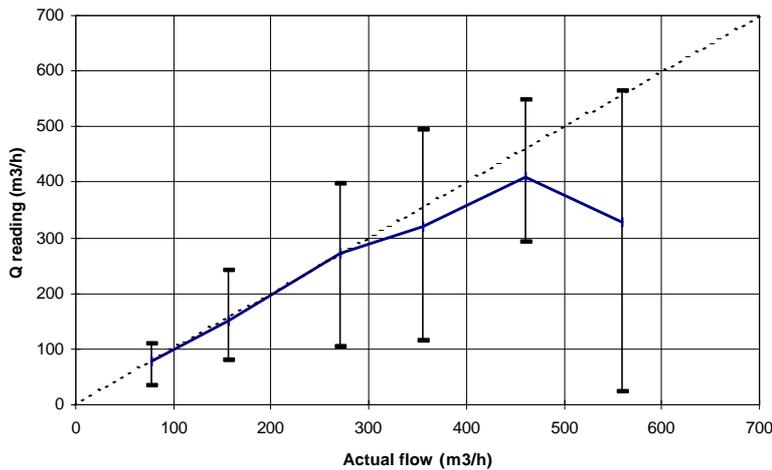


Fig.5.4. Indicated flow versus actual flow with flow pulsation at 25 Hz; pulsation amplitude 16% rms

The fluctuation of the current output varies with the actual average flow and is visualised by the error bar at each flow measuring point. There is however also a slight variation in pulsation amplitude it varies from 15-19 % rms. The error in reading is plotted in the next graph in fig. 5.5. showing 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 m³/h.

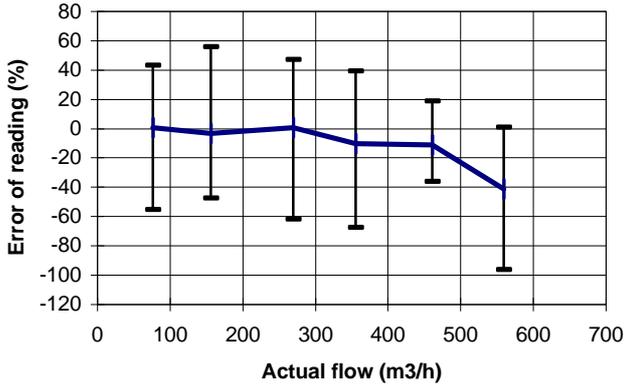


Fig.5.5 The error in reading (in %) with a flow pulsation at 25 Hz; pulsation amplitude 16% rms

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 m3/hr as shown in fig. 5.6.

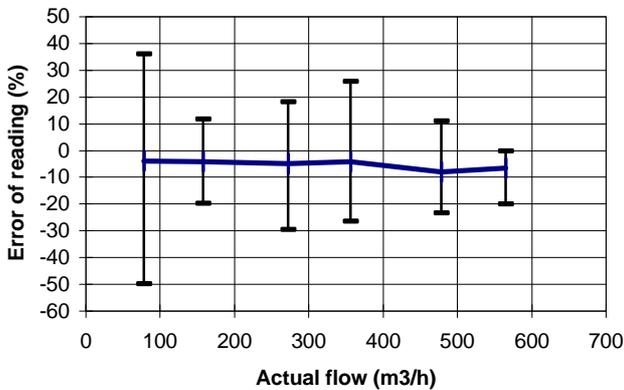


Fig.5.6. The error in reading (in %) with a flow pulsation at 25 Hz; pulsation amplitude 8% rms

6 Impact of flow pulsations at various frequencies and amplitudes on the flowmeter reading

In addition to the measurements at 25 Hz, described in chapter 5, the impact of pulsations has been determined at 31 Hz, 50 Hz and 100 Hz. The results are shown in the figures below, which show the deviation of the meter reading of the ultrasonic flowmeter (Q_{reading}) against the actual flow. In addition the error of reading is shown as a function of the flow. The error tends to increase with flow, for a constant pulsation frequency in all cases. If the pulsation amplitude is increased the error also increases. For 100 Hz (twice the sampling frequency) the ultrasonic meter does not even show a reading for actual flows above 250 m3/h.

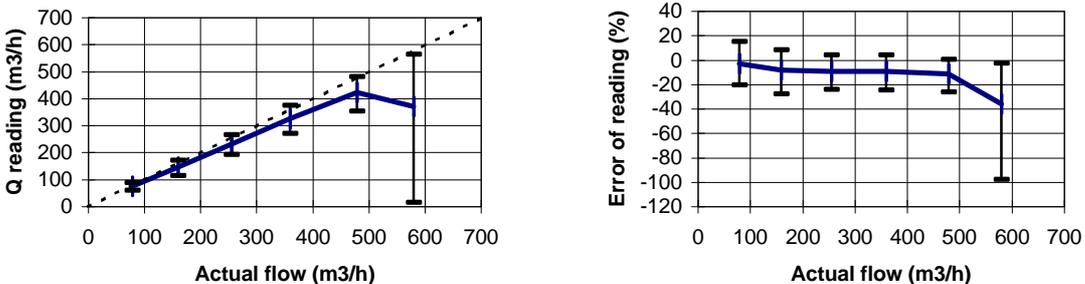


Fig.6.1 The error in reading (in %) with a flow pulsation at 50 Hz; average pulsation amplitude 62% rms

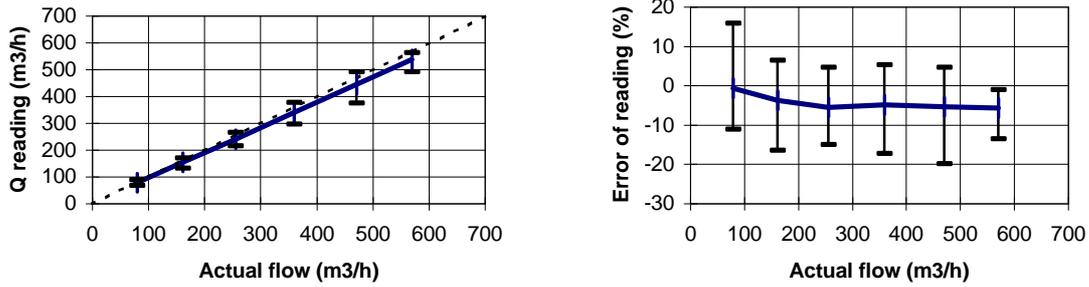


Fig.6.2 The error in reading (in %) with a flow pulsation at 50 Hz; average pulsation amplitude 38% rms

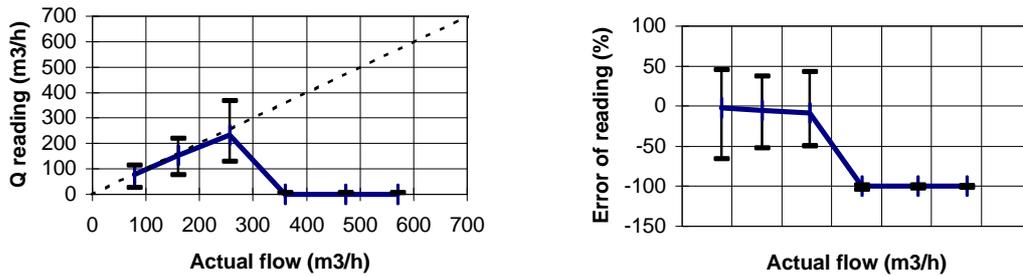


Fig.6.3 The error in reading (in %) with a flow pulsation at 100 Hz; average amplitude 58% rms

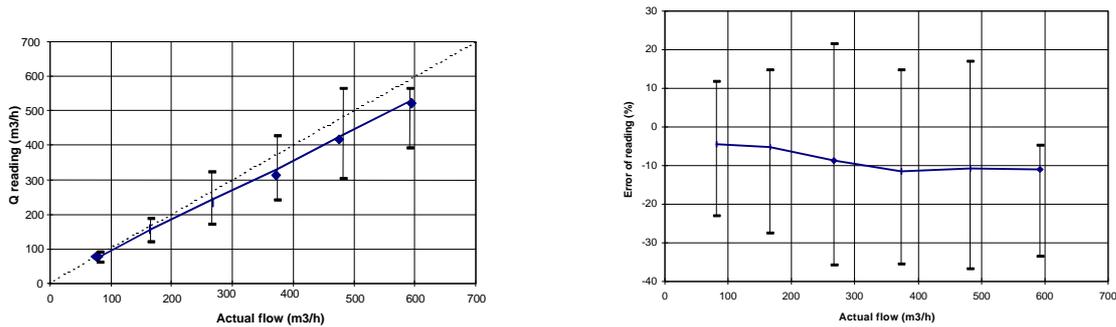


Fig.6.4 The error in reading (in %) with a flow pulsation at 100 Hz; average amplitude 30% rms

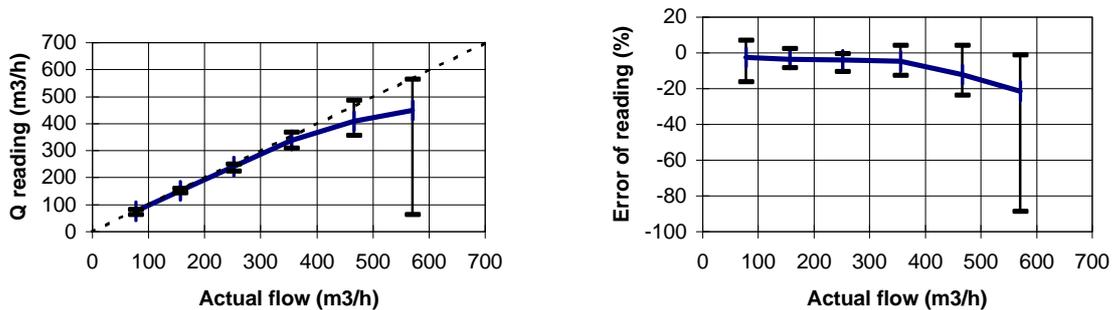


Fig.6.5 The error in reading (in %) with a flow pulsation at 31 Hz; average amplitude 16% rms

7 Conclusions and recommendations

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

For the frequencies of 31 and 50 Hz the error bars in chapter 6 show 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 fig.5.4 - 5.5) and 100 Hz (see fig.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 m³/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 fig. 5.5). The investigation shows a tendency of increasing errors at increased pulsation amplitudes, though the number of tests is too limited for further conclusions.

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 [2], 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 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 [2] also report heavy distortion of the ultrasound pulse for high Reynolds numbers ($Re > 11000$) resulting in large negative errors, which corresponds to our findings.

8 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 therefore 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 frequencies below 25 Hz (5-25 Hz) and 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 [8,9,11].

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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