

INSTALLATION EFFECTS ON VORTEX FLOWMETERS - THE IMPACT OF PIPING AND FLOW DYNAMICS ON THE SENSOR SIGNAL

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Abstract.

At the Flow Centre of the TNO Institute of Applied Physics installation effects on various types of flowmeters are being studied. Recently, an extensive study on the impact of pulsations and mechanical pipe vibrations on the output of five different make 3-inch industrial vortex flowmeters has been finalised and the comparison has been presented at several occasions [1,2]. To study the impact of bluff body dimensions, the experiments have been repeated for a 1.5" and 4" vortex flowmeter. Also a detailed analysis has been carried out to study the impact of unsteady flow and pipe vibrations on the sensor signal.

The experiments have been conducted in the TNO Flow Centre air rig over a range of pulsation and vibration frequencies and amplitudes at a mean flow from 0-700 m³/hr, covering the full range of the 2 and 3-inch vortex flowmeters.

The pulsation tests have been conducted with sinusoidal flow pulsations in the range from 20-400 Hz and flow pulsation amplitudes from 1 to 30 % rms of the average flow. The sensor signal shows a number of frequencies, which can be related to the frequency and amplitude of the pulsating flow. Errors in reading are not only caused by the lock-in effect, i.e. when the vortex shedding frequency is coupled with the pulsation frequency, but also when due to the distorted sensor signal an irregular pulse signal is generated from the Schmitt trigger. Also for the 1.5" and 4" vortex flowmeter, large systematic errors occur due to the lock-in effect if the vortex frequency of the meter comes close to the frequency of the pulsating flow. Lock-in sometimes occurs already at very low pulsation amplitudes of 3 % rms. Lock-in is shown to occur not only if the vortex flowmeter frequency f_v meets the pulsation frequency f_p , but in several cases also if $f_v = 0.25, 0.5, 1.0, 1.5, 2.0$ times f_p .

The impact of mechanical pipe vibrations imposed on a flowmeter under flow conditions is completely different from the effect of pulsating flow. In the case of pipe vibrations, the vortex shedding process is not influenced by the vibrations, but the sensor cannot distinguish between vortex shedding signal and pipe wall vibration. The effect on the sensor signal can lead to large systematic errors which depend on vibration frequency and amplitude. The location, type of sensor and the type of filter are important parameters, by which further improvement in reducing the sensitivity for pipe wall vibrations can be achieved.

The application of digital signal processing techniques for vortex flowmeters can improve the accuracy of vortex flowmeters in more critical conditions like pulsating flow and pipe vibrations, which are likely to occur in many applications in the process industry.

Keywords: Pulsations, vibrations, installation effects, vortex flowmeters, signal analysis

1 INTRODUCTION

Vortex flowmeters are increasingly being used in industry as a substitution for orifice meters because of among others the large rangeability, linearity, low cost of investment and maintenance and digital output. However, vortex flowmeters are known to be sensitive to installation effects such as vibrations and pulsating flow. During an earlier research project sponsored by the International Instrument Users' Association WIB, the TNO Flow Centre has experimentally investigated the impact of both effects on a series of 3 inch-sized industrial vortex flowmeters. It appeared, that all commercial meters suffer more or less from the effect of pulsating flow and from pipe vibrations, when the frequencies are within the operating range of the meter. Subsequently to this evaluation project, the effect of meter size is determined from testing an 1½" and 4" vortex flowmeter on the effect of pulsating flow. Furthermore, the effect of disturbed flow on the raw sensor signal has been studied extensively. This paper presents the results of these evaluations. In the next section, the experimental set-up and test

conditions will be discussed in which all the experiments have been carried out. In the next section, the effect of pulsations and vibrations separately, and as a combined effect on the sensor signal and meter reading is presented. The optimal use of the information captured in the raw sensor signal to obtain not only the correct flow rate but also information about the flow condition is subject to a separate paper presented by F.M. Braal et al. [3].

2 EXPERIMENTAL SETUP AND TEST CONDITIONS

The vibration and pulsation experiments were carried out in the pressurised air flow facility (PAFLOW) of the TNO Institute of Applied Physics. The test loop (Figure 1) consists of a large buffer vessel to damp high frequency pulsations from the compressor. The maximum capacity of the compressor is 800 m³/h at a maximum absolute pressure of 1 bar(a). Two turbine flowmeters with an accuracy better than 0,2 % (Instromet Q75, 2" and 3") are used as a transfer standard. They are installed in the high-pressure section upstream of a control valve, where both the pressure and the flow can be controlled. Subsequently the flow passes the pulsator, which consists of a rotating cylinder with holes, which periodically block the main flow, thereby generating a strong pulsating flow. The frequency of the pulsations can be varied between 5 Hz and 300 Hz. The amplitude of the pressure pulsations is in the order of 3% of the mean pressure at maximum, which results in flow pulsation levels between 2 and 30%. The pulsator can be partially by-passed by the flow to reduce the amplitude of the flow pulsations. The tests are carried out at atmospheric pressure and ambient temperature in the downstream section of the control valve. Above a critical pressure drop, pulsations generated downstream of the control valve cannot travel upstream of the valve. Thus the turbine meters are located in a steady flow.

The metering section consists of upstream straight tubing sizing 2, 3 or 4 inch of a length larger than 50 D, in order to dampen upstream disturbances of the flow, apart from the flow pulsations. The vortex meter under test is located after this intake section and upstream of a pipe section, in which 4 dynamic pressure transducers are installed in order to determine the pressure and flow pulsations at the flowmeter by applying a so-called two-microphone method. The flowmeter can be imposed to pipe vibrations by exciting the flowmeter in three directions separately: i.e. horizontal axial, horizontal transversal and vertical. Meanwhile, the flow rate can be adjusted between 0 and 700 m³/hr at 1 bar(a). The set-up for the excitation in axial direction is provided by means of two parallel operating exciters. The excitation in the other directions is provided by means of one exciter (see inset). A generator drives the exciters either in a sweep from 20-2000 Hz or at discrete frequencies in between. The acceleration of the excitation can be adjusted from 0.25 g to 2 g peak.

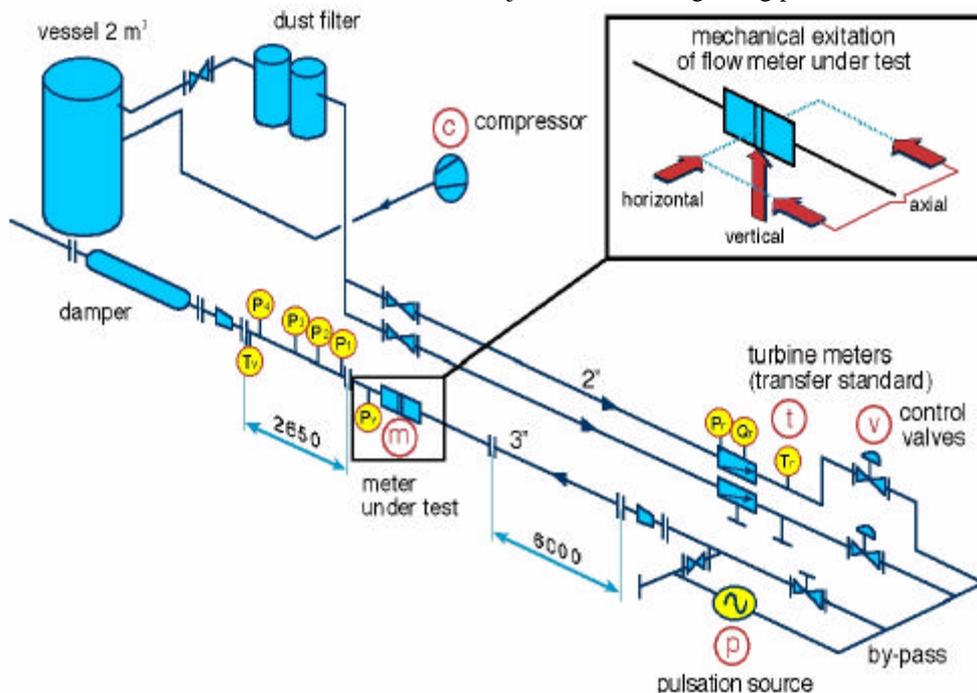


Figure 1 Pressurised AirFlow Test Facility for Installation Effects (PAFLOW) with mechanical excitation of flowmeter under test as shown in the inset.

3 IMPACT OF PIPE VIBRATIONS

The effect of pipe vibrations excited in vertical direction on the reading of a 3" vortex flowmeter with amplitude of 1g is shown in figure 2. The impact of vibrations on the reading of the flowmeter depends on the flow rate. At high flow rates, the excitation force of the bluff body due to vortex shedding is large, and therefore the impact of vibrations is small. At these high flow rates, the reading corresponds to the reference flow with an error of less than 2%. At low flow rates, the distorting of the sensor signal due to the vibrations becomes significant, leading to large errors in reading. Below a critical flow rate, the reading of the flowmeter locks to a value, of which the vortex frequency corresponds to the vibration frequency.

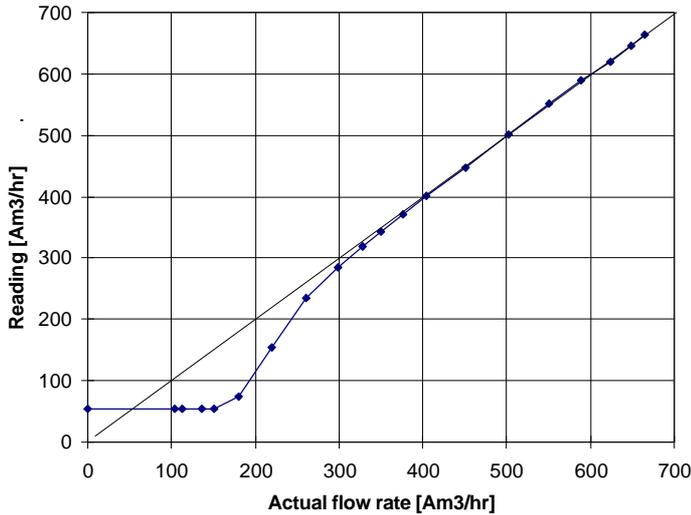


Figure 2. Reading vs. Actual flow rate when the flowmeter is exposed to vertical vibrations at 50 Hz, 1g amplitude.

At zero flow rates, this corresponds to the so-called no-flow reading. Since during no-flow there is no vortex shedding, the sensor is very sensitive for any vibration signal excited on the sensor, including external effects such as pipe vibrations. This is clearly shown in figure 3, where the sensor signal is shown for various flow rates.

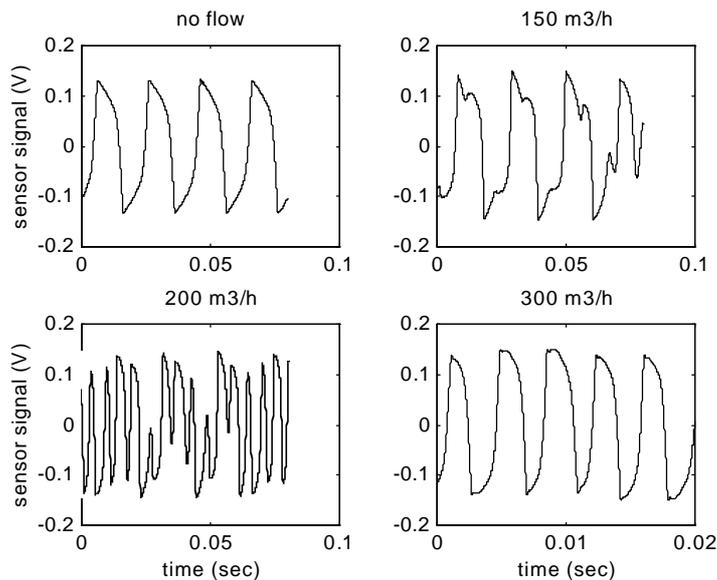


Figure 3 Conditioned signal when the flowmeter is exposed to vibrations of 50 Hz, 1g for different flow rates. **Note:** the time-scale of the last figure is different from the other three. For 150 and 200 m³/h the flow signal is heavily distorted by the pipe vibration.

The sensitivity in other directions, for different frequencies and different amplitudes for various industrial meter have been presented earlier by van Bokhorst et al. [2]. The sensor signal under flow conditions is a superposition of the vibration-induced signal and the flow induced signal as can be seen in figure 3. At low flow rates the vibration-induced signal is dominant. At higher flow rates, the amplitude caused by the actual flow increases and therefore the influence of the flow induced signal becomes clearer and the impact of the vibrations reduces, until at a certain flow rate (about 300 m³/h in this case) the effect of the vibrations on the signal is negligible. How the reading of the instrument is influenced by this phenomenon can best be seen from figure 4.

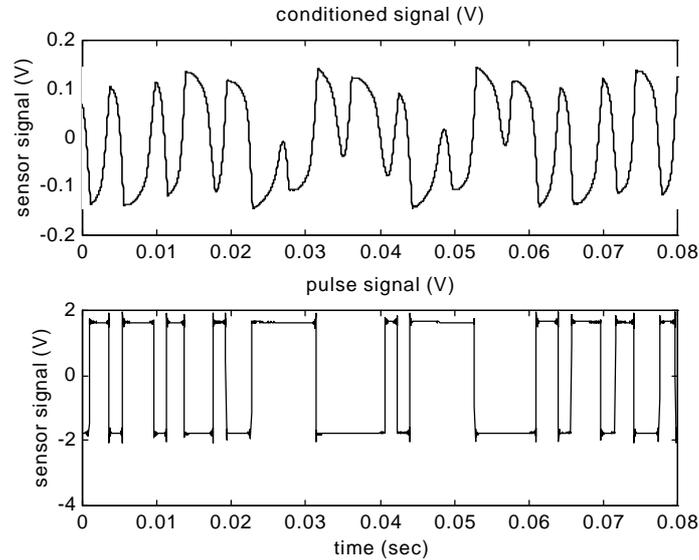


Figure 4 Conditioned and pulse signal when the flowmeter is exposed to vibrations of 50 Hz, 1g amplitude at 200 m³/h

At low flow rates the instrument will give a reading corresponding with the vibration frequency. In the transitional stage the conditioned signal that enters the Schmitt-trigger will be transformed into a pulse signal consisting of pulses of unequal lengths. As a result the pulse frequency is not corresponding to the actual vortex frequency nor the vibration frequency. Depending on the further signal processing in the instrument, the instrument will give an incorrect flow rate reading.

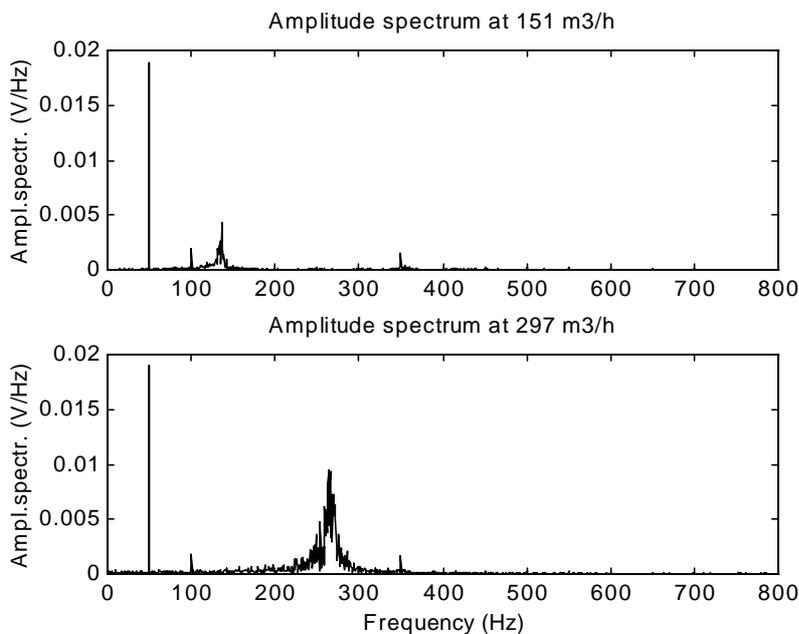


Figure 5 Amplitude spectrum of the sensor signal at a flow rate of 151 and 297 m³/h when the flowmeter is exposed to 50 Hz vertical vibrations, acceleration of 1g.

The frequency used by the instrument to display the flow rate will approach the real vortex frequency better as the flow signal increases in amplitude and the vibration induced signal becomes relatively less significant. The tests have been carried out with air at atmospheric conditions, which are most sensitive for vibrations. Both in case of high-pressure gas or steam and for liquid applications, the sensor signal is much stronger due to the higher density. However near the low-flow cut-off region, the sensitivity for vibrations remains. From the amplitude spectra of the sensor signal shown in figure 5 the vibration frequency and the vortex shedding frequency can easily be distinguished, the vibration frequency stands out like a needle, the vortex shedding frequency is less 'sharp', because it is influenced by the turbulent flow rate. While the amplitude of the vibration frequency remains unchanged, the amplitude at the vortex shedding frequency increases with flow rate, which also reduces the sensitivity for the pipe vibrations.

4 IMPACT OF FLOW PULSATIONS

The impact of flow pulsations on the reading of a 3" vortex flowmeter has been extensively discussed by Peters et al. [1]. The effect of pulsation flow on the performance of a vortex flowmeter is completely different from the effect of pipe vibrations. As a result of pipe vibrations, the sensor measures not only the dynamic force excited on the sensor by the periodic vortex shedding from the bluff body, but also the direct effect of external vibrations of the meter. In a pulsating flow, the vortex shedding process itself is impacted, which causes the frequency of vortex shedding to change and in some cases even lock-in of the vortex shedding frequency (f_v) with a multiple of half the pulsation frequency (f_p) can occur [1]. This is clearly seen in figure 6, where the effect of a pulsating flow of 290 Hz and a flow amplitude of 5% on the vortex reading is shown as a function of actual flow rate for a 3" vortex flowmeter. It appears that lock-in of the vortex shedding process can occur at specific pulsation frequencies, i.e. $f_v/f_p = 0.5, 1, 1.5$ or 2 . When the pulsation frequency is in the same region as the vortex shedding frequency of the vortex meter, large errors in reading up to -30% can occur as a result of lock-in, but also between the lock-in frequencies.

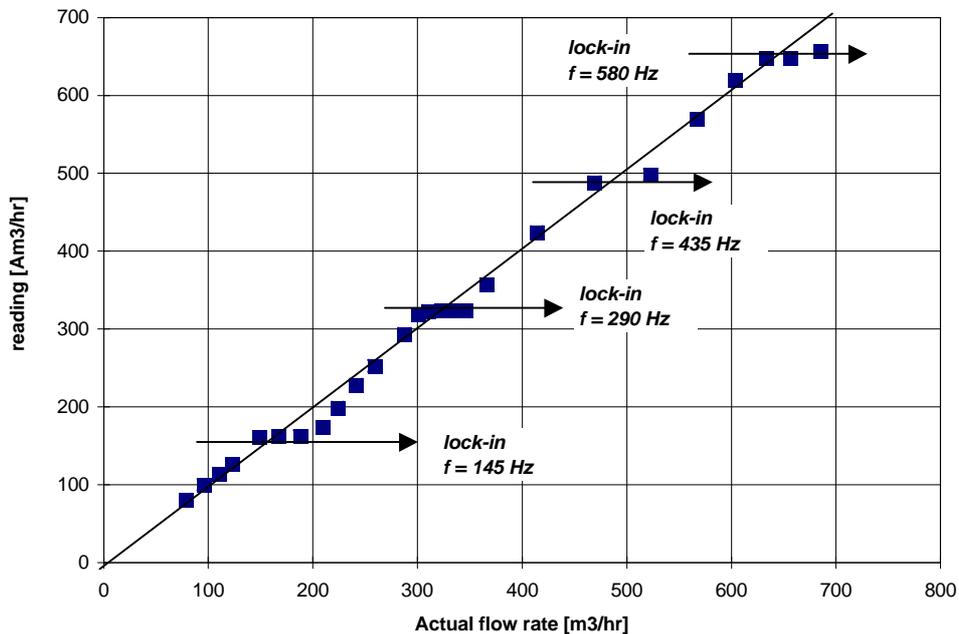


Figure 6 Reading vs. actual flow rate for a 3" vortex flowmeter in a pulsating flow of 290 Hz of amplitude of 5% of the mean flow (rms value).

Figure 7 shows that at low flow rates, the pulsations result in a frequency modulation with the pulsation frequency acting as a carrier. This results in the following peaks in the amplitude spectrum: f_v , f_p , $(f_p - f_v)$ and $(f_p + f_v)$. As the flow rate increases, f_v and $(f_p - f_v)$ approach each other. When they are very close, lock-in occurs at half the pulsation frequency. This means the vortex shedding frequency remains at half the pulsating frequency even though the actual flow rate (in absence of pulsating flow) should result in another frequency. During a large

range of flow rates, i.e. from 145 until 220 m³/h, the frequency spectrum looks alike. At higher levels of the pulsating flow, this lock-in period becomes even longer. Also, at high flow rates nonlinear interaction of the vortex shedding process and the pulsating flow results in a noisy signal with a broadband spectrum. Note that lock-in occurs already at very low pulsation amplitudes, i.e. 5% rms value. Earlier lock-in was observed at flow pulsation amplitude of 2% [1]. During lock-in, the peaks are very narrow, while in-between lock-in, the frequency peaks broaden.

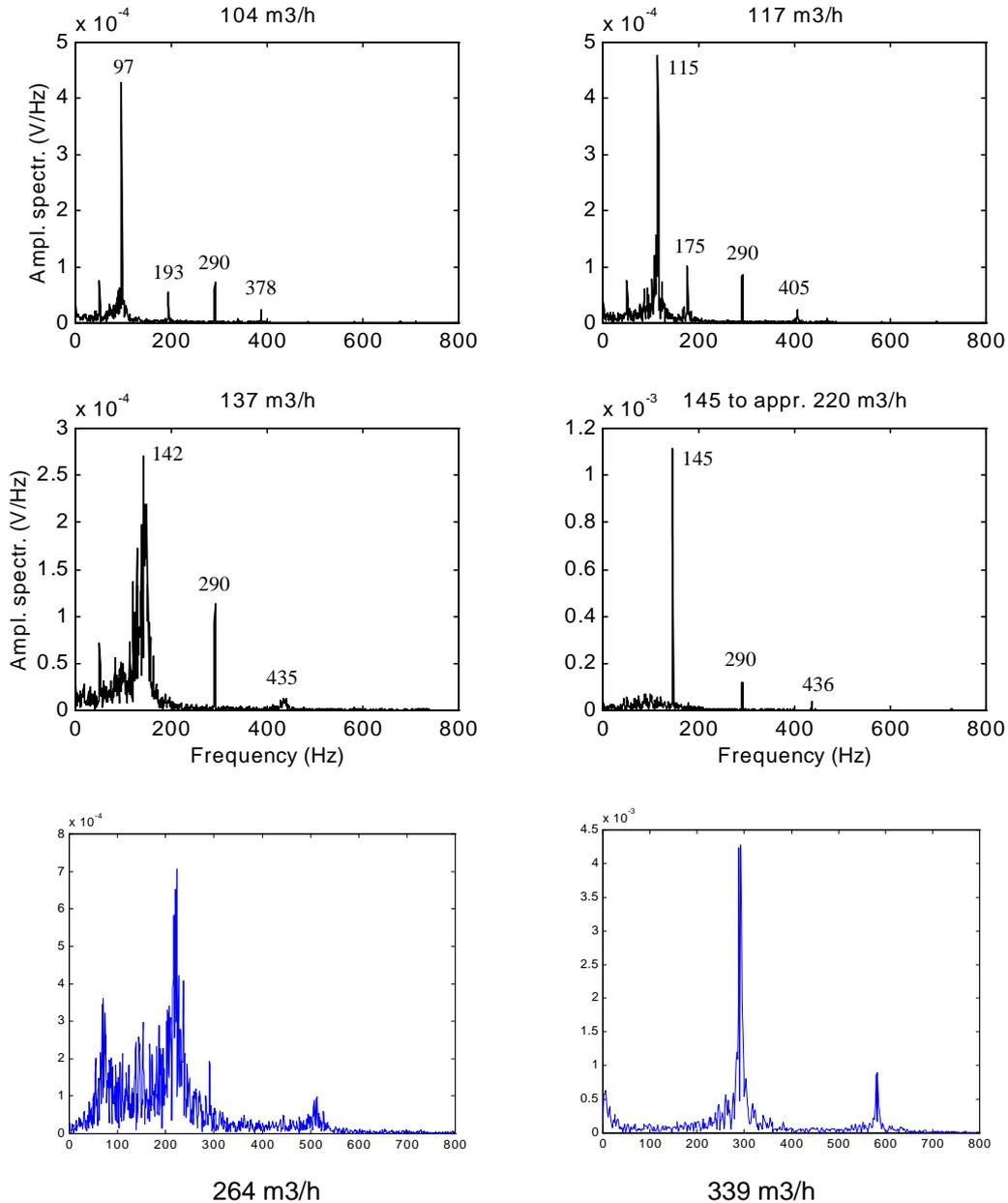


Figure 7 Amplitude spectra of the sensor signal for flow rates up to 339 m³/h corresponding to the conditions in figure 6, until the first and second lock-in at half and once the pulsation frequency are observed. **Note:** During lock-in the frequency spectrum is unchanged over a large range of flow rates, i.e. for the first lock-in in the range of flow rates from 145 m³/h to 220 m³/h, and for the second lock-in in the range 300 m³/h to 350m³/h. The spectrum is constant for this flow range except for the amplitude of the peaks, which increases with flow rate. At low flow rates, frequency modulation causes additional peaks, at high flow rates, nonlinear interaction results into a broadband spectrum.

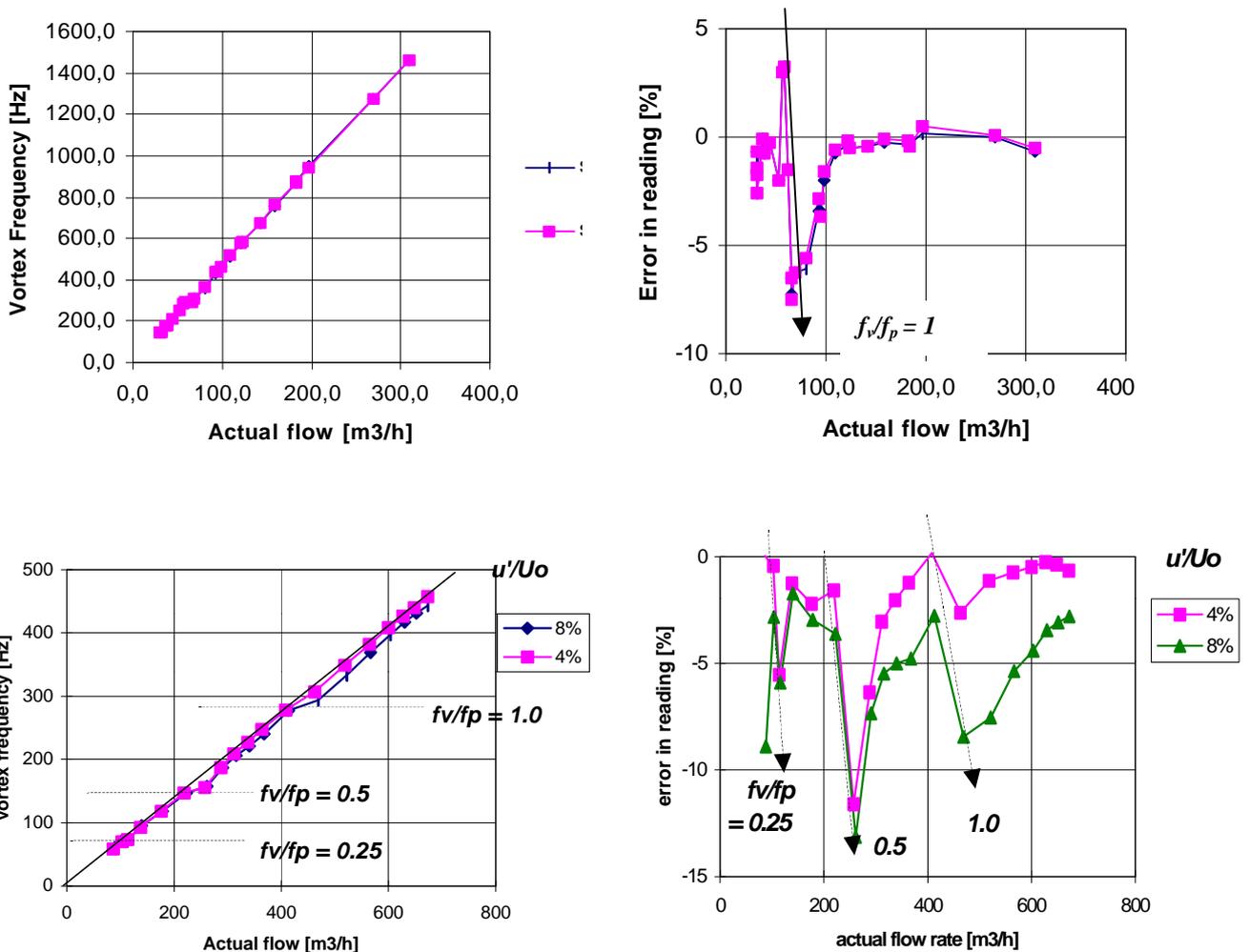
5 IMPACT OF METER SIZING

The effect of meter size on the lock-in phenomena has been determined for three commercial flowmeters of sizing 1.5" (DN40), 3" (DN80) and 4" (DN100) of one make. A different meter size not only changes the total flow range and the cut-off flow range, i.e. the minimum flow rate through the meter, but also the frequency range, see table 1. This will have a strong impact on the sensitivity of the vortex flowmeter for pulsating flows, since it was shown in section 4 that the lock-in phenomena mainly depends on the ratio f_v/f_p . All tests were carried out with pulsation frequencies of 50, 100 and 290 Hz.

Table 1: Operating range and frequency range of different size vortex meters tested.

Meter size	Q_{min} [m ³ /hr]	Q_{max} [m ³ /hr]	f_{min} [Hz]	f_{max} [Hz]
DN40	30	390	120	1520
DN80	70	800	50	700
DN100	160	1900	42	500

The effect of pulsating flow on the vortex frequency and the error in reading is shown in figure 12 for a DN40, DN80 and DN100 meter, respectively. The flow pulsation amplitudes imposed increased from 4% rms value for the D40, 4 and 8% for the DN80 up to 4, 8, 15 and 25% for the DN100. Since the range of operating frequencies changes with meter sizing, also the onset of lock-in in a pulsating flow changes. However, for all meter sizes, the errors in reading are similar for a given lock-in value f_v/f_p and pulsation amplitude. For example for $f_v/f_p = 0.5$ and a pulsation amplitude of 4%, the error in reading is around -10%, both for the DN80 and DN100. For $f_v/f_p = 1.0$ and a pulsation amplitude of 4%, the error in reading is around -7%, both for the DN40 and DN80. In figure 13, the error in reading of the vortex flowmeter in a pulsating flow of 290 Hz is shown for the three meter sizes.



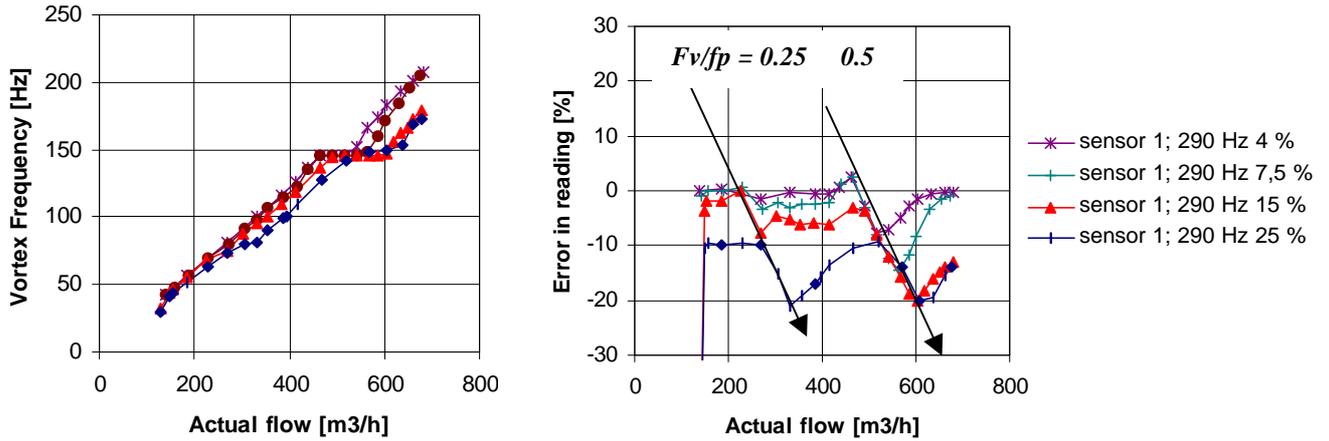


Figure 12: Vortex frequency and error of reading of DN40, DN80 and DN100 vortex flowmeter in a pulsating flow, $f_p = 290$ Hz at various amplitudes for one make vortex flowmeter. Lock-in is observed only at $f_v = f_p$ for DN40, at $f_v/f_p = 0.5$ and 1 for DN80 and at $f_v/f_p = 0.25$ and 0.5 for DN100.

The strongest lock-in occurs at $f_v/f_p = 0.5$ and the error in reading is rather independent of the meter size, but only on the pulsation amplitude and frequency. Also if the measurements at various pulsation frequencies are combined for one meter size, i.e. DN80, the strongest lock-in is observed when the ratio $f_v/f_p = 0.5$. This is shown in figure 14. Maximum errors in reading up to -55% are measured at a pulsation level of 25%. These measurements lead to an engineering criterion in which the error in reading of a vortex flowmeter in a pulsating flow depends on the frequency ratio f_v/f_p and flow pulsation amplitude, and is rather independent of the meter sizing. The errors are largest in the range $0.5 < f_v/f_p < 2$, and less than 2% for $f_v/f_p > 3$.

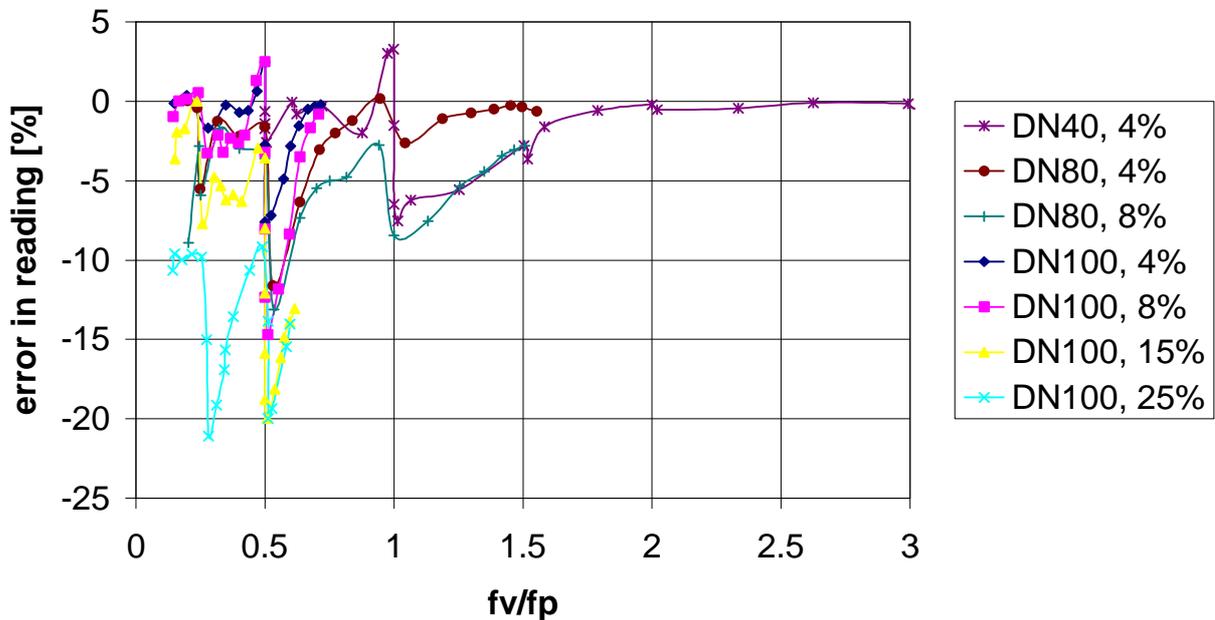


Figure 13 Error of reading of a DN40, DN80 and DN100 vortex flowmeter in a pulsating flow, $f_p = 290$ Hz at various amplitudes for one make vortex flowmeter. Lock-in is observed at $f_v/f_p = 0.25, 0.5$ and 1.

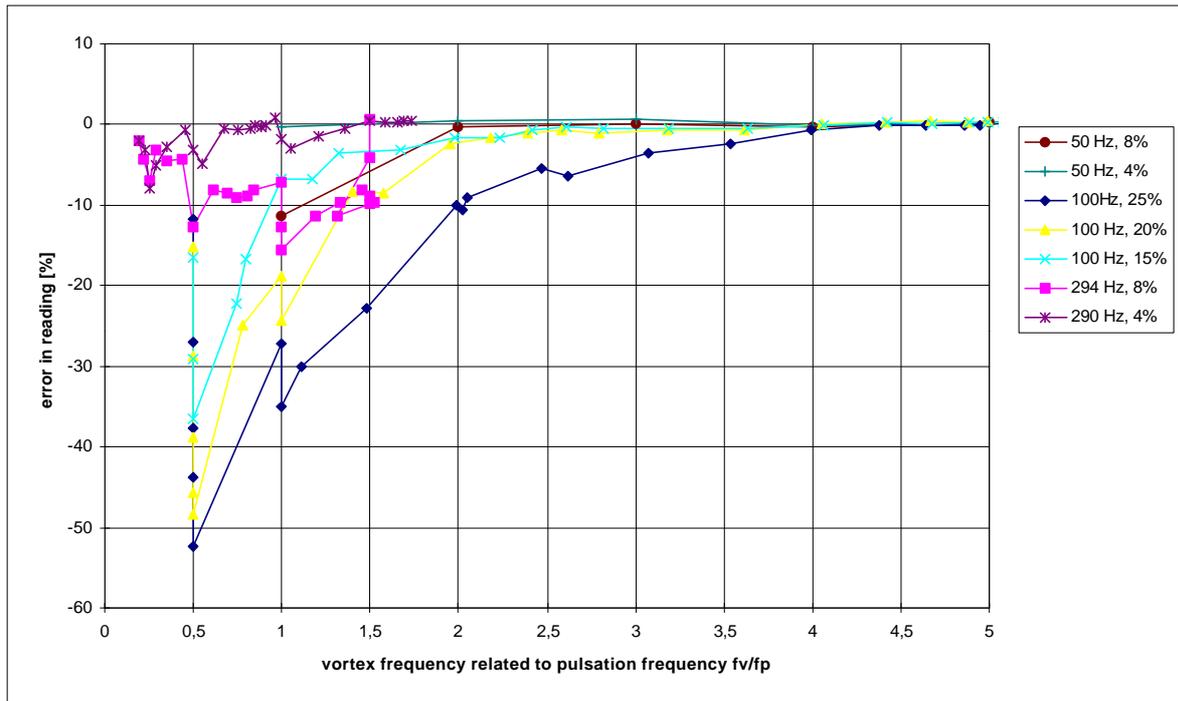


Figure 14 Error of reading of a DN80 vortex flowmeter caused by pulsating flow of various frequencies and amplitudes. The strongest lock-in occurs at $f_v/f_p = 0.5$.

CONCLUSIONS

From the experimental test on the effects of pulsating flow and vibrations on the accuracy of vortex flowmeters, it has been shown that the vortex flowmeter is very sensitive for these effects. The error in reading caused by these effects however are depending on frequency and amplitude of the disturbances. Pipe vibrations disturb the sensor signal in the sense that the sensor cannot discriminate between the vortex signal and pipe vibrations. Large errors in reading due to vibrations are measured when the vortex shedding is weak, i.e. in the low flow region, in particular at no-flow conditions and for low-density media. In the spectrum of the sensor signal, a sharp peak at the vibration frequency appears.

Pulsating flow affects the vortex shedding process in the sense that both the vortex shedding frequency can lock to the pulsation frequency and the amplitude of the vortices shed are modulated. As a result additional peaks arise in the spectrum of the sensor signal. Whether or not lock-in occurs depends mainly on the ratio between pulsation frequency and vortex frequency, i.e. when $f_v/f_p = 0.25, 0.5, 1$. Lock-in occurs already at very low pulsation amplitudes of 4% or less, but the pulsation amplitude determines the error in reading, which in general is negative.

From the measurements at different flow rates, pulsation frequencies and amplitudes and meter sizes, engineering criteria can be derived to make a proper selection of a vortex flowmeter, which can be applied in a pulsating flow. When the ratio $f_v/f_p > 3$, the error in reading is less than 2%, even in a strong pulsating flow. The information of the effect of pulsations and vibrations on the sensor signal can be used to reduce or eliminate the effect on the reading by means of digital signal processing [3].

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