

THE IMPACT OF FLOW DYNAMICS IN THE DESIGN OF FLOW METERS AND METERING STATIONS

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1. Introduction

Commercially available flowmeters are provided with a calibration certificate, based on stationary flow conditions and do not include the impact of installation effects like swirl, a-symmetry, and piping and flow dynamics. Flow pulsations, valve noise and mechanical pipe vibrations can have a considerable impact on flowmeter accuracy in gas as well as in liquid flows.

International standards like ISO, AGA and API, available for several flowmeter principles, sometimes refer to swirl, flow and piping dynamic effects, though they do not specify allowable amplitudes or frequencies.

Investigations on the impact of piping and flow dynamics on differential pressure, turbine, vortex and Coriolis flowmeters have been published at several occasions. Ultrasonic noise of control valves is well known as a potential source of errors on ultrasonic flowmeters.

The impact of mechanical pipe vibrations on vortex and Coriolis flowmeters can result in large errors if vibrations occur in the operating range of the flowmeter. Investigations on several commercially available flowmeters of this type have reported these phenomena for vortex and Coriolis flow meters

Several manufacturers, operating companies and engineering contractors have expressed their interest in developing a well-defined test for this type of applications. An *absolute* criterion for allowable pulsations or vibrations can hardly be defined as the impact on flowmeters differs for each flow metering principle and/or size. Therefore individual criteria should be developed for each type of flowmeter and its application.

TNO Flow Centre has defined a project proposal to develop a test for flow-dynamic effects on flowmeters for gas and liquid applications and manufacturers and operators are invited to participate.

In addition numerical codes like PULSIM [1] can be applied to investigate the design of a flow metering station with respect to the impact of pulsation sources like vortex shedding at T-joints, compressors and pumps. The layout of the flow metering station or the location of the flowmeter with respect to the pulsation source is optimised. A typical project, in combination with on-site verification measurements, is presented in this paper. It is proposed to include dynamic effects as pulsations, vibrations and noise in the design stage of flow metering stations to prevent systematic errors in flow metering due to installation effects.

2. Field experiences – examples of the impact of flow and piping dynamics on flowmeter accuracy

2.1. Case 1: Pulsation impact on a turbine and vortex flowmeter in a reciprocating compressor station

A station for natural gas storage and transport is supplied with five similar reciprocating compressors with a speed variation between 650 and 800 rpm. The station is extended with an additional reciprocating compressor with a variable speed between 600 and 1000 rpm to obtain the maximum flow of approximately 60.000 Nm³/hr. The gas is compressed from a suction pressure between 2600 and 7100 kPa to be stored in an underground storage at a discharge pressure between 4500 and 8600 kPa.

A pulsation analyses according to the API618 standard is required, which should also include an analyses of the pulsation impact on the flow metering station located in the suction piping. This study should reveal what measures are necessary to limit the maximum pulsations caused by parallel operating compressors. A schematic layout of the gas compression and metering station is shown in fig. 2.1

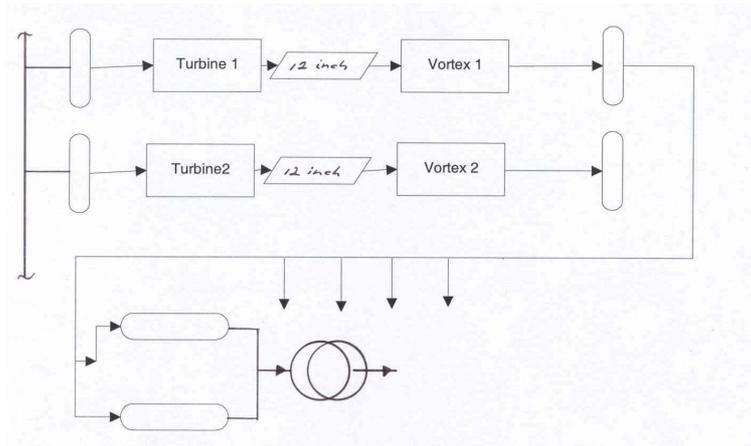


Figure 2.1 Schematic layout of compressor and metering station

The pulsation analyses are performed with our simulation package PULSIM, developed for the calculation of plane-wave propagation in pipe systems and fluid machinery. The 1-D approach has shown accurate results for low-frequency pulsations in pipe-systems restricted to a frequency $f < 0.586 c/D$, in which c is the speed of sound in the gas and D is the pipe diameter.

The pulsation analyses show that considerable pressure pulsations, above API618 limits, and corresponding pulsation induced vibration forces are caused by acoustic resonances between the compressors, mainly on suction side. As a result of the parallel operating compressors, running at different phase and/or speed, beating pulsations will excite the pipe system. The maximum amplitude of the beating pulsation is found by adding the individual pulsation amplitude caused by each compressor.

The flow pulsations at the flow metering station, upstream of the compressors on suction piping are varying between 20 % peak-to-peak for one compressor up to 100 % peak-to-peak for 5 compressors in parallel. This flow pulsation level will cause a considerable systematic error at the turbine and possibly also at the vortex flowmeter. The pulsation amplitude and frequency determine the error in the turbine flowmeter reading, which is due to rotor inertia. A best estimate based on the theory of Bonner and Lee [2] is that the turbine metering error ranges from +0.5 to +10%.

The analyses reveal that pulsations cannot be damped effectively by simple means, such as individual orifice plates at the pulsation dampers, without causing excessive pressure losses at increasing flow.

An additional damper volume, size 2.5 m length and diameter 0.65 m, is recommended to reduce the flow pulsation at the flowmeters to 2% pp for each individual compressor.

The new-installed compressor could be supplied with an acoustical filter, which dampens pulsation levels successfully over the entire operating envelope. Originally the filter consists of a two-chamber damper with two cylinders on each side of the compressor, which reduces the pressure pulsations within the API 618 criteria. Further reduction is required as to reduce the maximum flow pulsation at the flow meter, which is still 10 % pp. A secondary damper volume, size 2.5 x 0.55m, has been recommended to obtain a level of approximately 2 % pp.

An overview of the reduction in pulsation levels obtained with different recommendations is shown in the table below.

Modification	Maximum flow pulsations, U in % pp	Estimated systematic error In turbine meter
Original lay-out	110 % pp	< 10 %
Modification 1 with orifice plates at suction dampers (dP= 1%)	50 % pp	< 5 %
Additional volume bottle of 0.8 m ³ at each compressor plus orifice plates and modified piping for new compressor	11.5 % pp	< 0.5 %
Modification 2 with control valve on each suction line with a pressure drop of 5 %	30 % pp	< 1.0 %

Figure 2.2 Table showing the simulation results of various modifications

The corresponding systematic error at the turbine flow meter at this flow pulsation level is estimated at + 2.1 %, based on the manufacturer's data and assuming a sinusoidal pulsation. The systematic error at the vortex flowmeter cannot be determined simply as the relation between flow pulsation and error in reading depends on the individual meter design and the sensor used. Though an earlier investigation of different make vortex flowmeters has shown, that a pulsating flow affects the vortex shedding process, such that the vortex shedding frequency can lock to the pulsation frequency. The strongest lock in occurs, when $f_v/f_p = 0.5$, though lock-in also occurs at $f_v/f_p = 0.25, .5, 1.0, 1.5, 2.0$

Actual lock-in has not been noticed at the maximum flow pulsation occurring at 25 Hz of 2.6 m/s peak-to-peak at 6.0 m/s mean flow, which is 43 % pp.

The relation between vortex frequency and bluff body diameter is presented as:

$$f_v = Str \cdot v/D \text{ in which:}$$

- f_v : vortex frequency in Hz
- Str: Strouhal number 0.3
- v: flow velocity in m/s
- d bluff body diameter 0.3 pipe diameter

According to this expression the vortex frequency f_v for a mean flow velocity of 6.0 m/s is 20 Hz, which is not far from the pulsation frequency of 25 Hz. For the total flow range of 1.500 – 120.000 Nm³/h the vortex frequency for the 12-inch flowmeter varies between 5 and 40 Hz.

This is partially within the range of pulsation frequencies excited by the compressors running between 600 and 1000 rpm (10 – 16.6 Hz) and exciting mainly 2nd harmonic of compressor speed. It should also be noticed that fluctuation in pulsation and vibration levels occurs if compressors run at different speeds. The beating frequency of the pulsation is determined by the difference in compressor speed, as shown in the example fig. 2.5

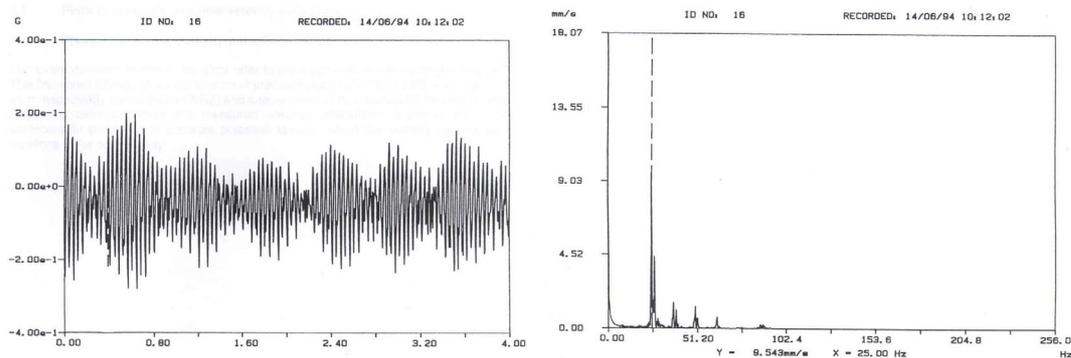


Figure 2.5 Example of a beating pulsation as a function of time (left) and frequency spectrum 0-250 Hz

The pulsation errors on vortex flowmeters are found to be mainly negative, especially at lock-in, though also positive errors occur if vortex frequencies are approaching towards pulsation frequencies.

The figures of actual flows of the flowmeters are only available as mean-hour flows, showing a deviation between turbine and vortex flowmeter of approximately +1.5 %. This confirms the theoretical positive systematic error of the turbine meter assuming the error in the vortex flowmeter is negative or neutral if no lock-in occurs.

The client has taken measures to decrease pulsation levels, as resulting from the recommendations in the pulsation analyses. In this way systematic errors have been reduced effectively to a level below 0.5 % over the entire operating envelope of the compressors.

2.2. Case 2: Field experience of a major operator in refinery projects

Shell recently described their experience [3] in three major refinery projects in which vortex flowmeters were specified as their main choice for flow monitoring, control and safeguarding. The application of flowmeters in these projects progressed slowly as a result of several problems encountered during installation and start up. The root causes of the problems were:

- Meter sizing not correct: too large i.e. line size

- Flow pulsations
- Pipe vibrations
- Incorrect piping geometry

The score for the three projects show that replacement of vortex flowmeters was necessary in 10-20 % of the cases: in total 180 out of 1060 meters have been replaced. In most of the cases described here this also required piping modifications. This implies that a costly program has to be performed, which in addition caused serious delay of the start-up of the plants. Other operators are reporting similar experiences.

As a result of these and similar experiences WIB, the International Instrumentation Users' Association, which include most of the major companies in process industry has started an investigation program on vortex flowmeters. The purpose of this program was in particular to focus on application-related subjects and installation effects like flow-profiles, pulsations, vibrations, temperature, pressure and viscosity. Vortex meters of six different make and various sizes have been included in the test program, of which results on pulsation and vibration impact have been reported earlier during Flomeko 2000 [4]

The evaluation results, in combination with experience of flow experts from WIB members have been used by TNO to develop application guidelines for vortex flowmeters.

These experiences show that there is a constant need for information on typical applications of flowmeters of all kind to be able to achieve the best performance dependent on the goals and objectives of the measurement. Flow monitoring, safety or custody transfer application have their specific demands with respect to process and installation conditions.

In addition to existing standards and application guidelines a flowmeter specific test certificate is a useful guide for operators to check if the intended flowmeter is suitable for the specific application. The objective of the test certificate or TNO product label is to qualify product on the basis of a well defined test, which includes several aspects of installation and process parameters for that specific flowmeter. The test certificate should be accompanied with a report, which describes test conditions and performance of the product in several aspects regarding flow and piping dynamics, flow profile, valve noise etc.

3. Installation effects in standards and guidelines – an overview

3.1 Standards and application guidelines

Much knowledge about the performance, application and engineering aspects of flowmeters in industrial applications such as the oil and gas industry is described in general standards and application guidelines

The standards are updated regularly to incorporate new knowledge obtained from laboratory investigations and applications in the field. The ISO 5167 for the 'Measurement of fluid flow by means of differential pressure devices' is still subject to revisions. The same applies to the ISO 9951 for the 'Measurement of gas flows in closed conduits by turbine meters'.

For other metering types ISO standards are relatively new, e.g. ISO 10790 for the Coriolis flowmeter, or still in development e.g. for ultrasonic flow metering. In addition to ISO Standards the ISO Technical Reports supply useful information on the application of flowmeters regarding special aspects, such as ISO TR3313 [5], which described the impact of pulsations on various flow-metering techniques. For refinery and petrochemical applications also the AGA reports and API Standards are applied worldwide.

In addition to manufacturer's installation guides, general standards and guidelines several large operating companies develop their own specifications like e.g. the Shell DEP-specs.

3.2 Periodic pulsations

It is remarkable that little information is to be found in manufacturer's installation guides and ISO Standards on flow dynamics regarding the impact of installation effects like fluctuating flow, periodic pulsations and valve noise on flow meter accuracy. The documentation sometimes refers to the sensitivity of a flowmeter for '*strongly fluctuating flow or pressure pulsations*' [ISO9951], however without mentioning allowable pulsation amplitudes or frequency ranges.

In the ISO technical report ISO/TR3313 the impact of periodic pulsating flow is described in somewhat more detail for various metering techniques. An overview of the criterion for different metering techniques in ISO Standards is presented in table 2.1

Flowmeter Technique	Applicable Standards	Pulsation impact in ISO/TR 3313	Pulsation Criterion in ISO/ TR 3313	Origin of pulsation Error
Orifice Venturi	ISO 5167 AGA Report 3 API 2530	+	$U_{all} = 5\% \text{ rms}$	Square-root error and gauge line errors
Turbine	ISO 9951	+	$U_{all} = 3.5\% \text{ rms}$	Inertia of the rotor
Ultrasonic	AGA Report 9 ISO TR 12765	+	-	Aliasing error
Vortex	ISO TR 12764	+	$U_{all} = 3\% \text{ rms}$	Lock-in
Coriolis	ISO 10790	+	-	Lock-in
Electro Magnetic	ISO	-	-	

Figure 3.1. Overview of dynamic flow aspects mentioned in international standards

The threshold for pulsating flow in ISO/TR 3313 is defined as $U'_{rms}/U_{mean} \leq 0.05$ or in terms of the equivalent DP (pressure loss) pulsation amplitude $\Delta p'_{p,rms}/\Delta p_{p,mean} \leq 0.10$. The specified allowable flow pulsation, U_{all} in the table above, is the threshold value for a sinusoidal pulsation for different metering techniques. Pulsation frequencies in industrial process installations range from fractions of a Hz to few 100 Hz or even over 1000 Hz, dependent on the type of source. An overview of frequencies and corresponding amplitudes is presented in the figure below

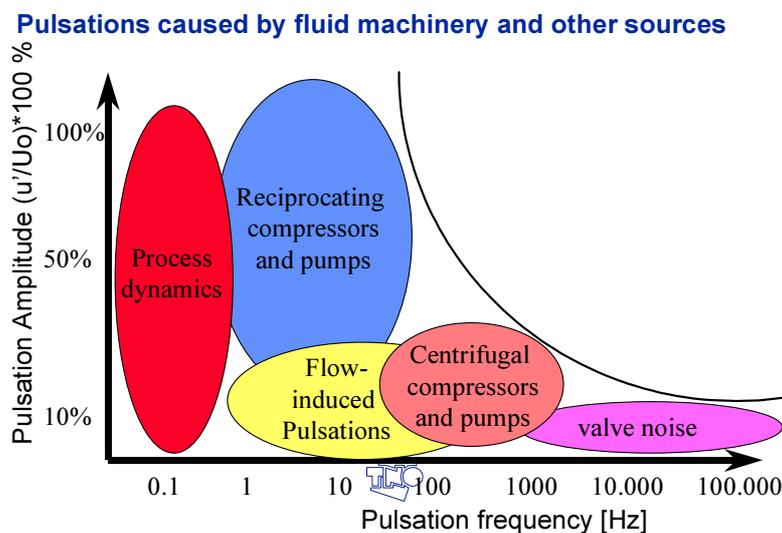


Fig 3.2 Pulsation levels versus frequencies caused by fluid machinery and other sources

An example of the impact of flow pulsations on vortex flowmeter is shown in the figure below for flow pulsation amplitudes of respectively 2 and 5 % rms at fixed pulsation frequency of 290 Hz, which is in the mid-range of the 3-inch vortex flowmeter ranging from 70-700 Hz.

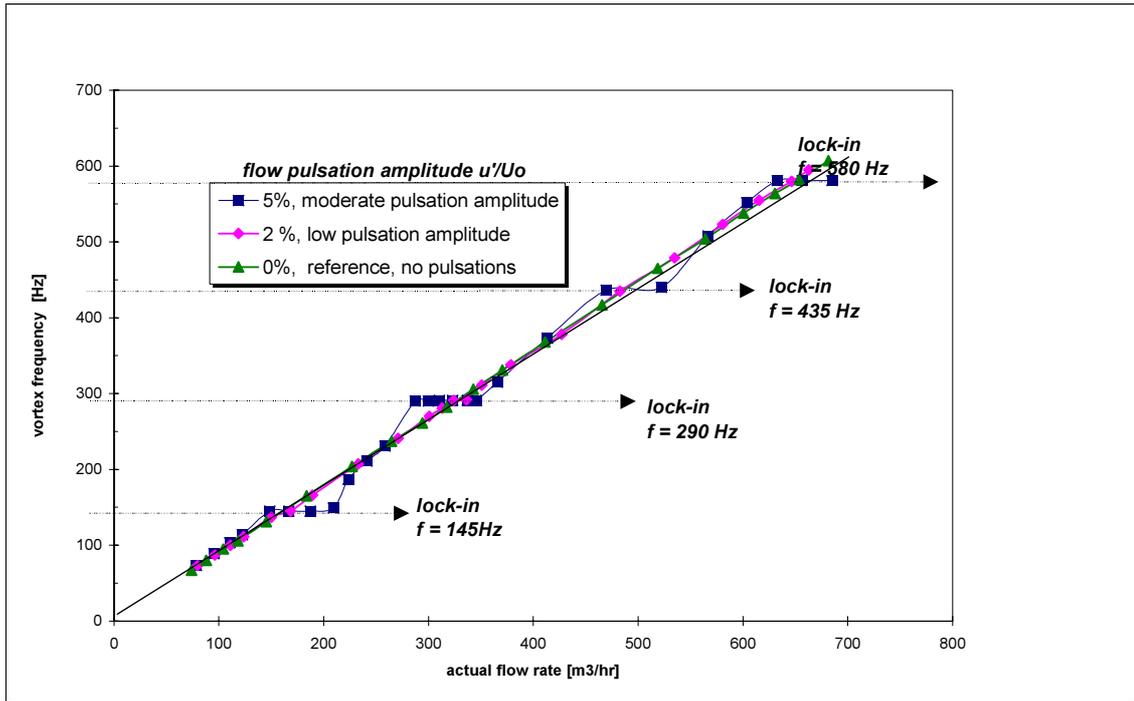


Figure 3.3 Impact of flow pulsations on a 3-inch (DN80) vortex flowmeter at $F_p = 290$ Hz

So even for a flow pulsation level of 2% rms a considerable impact on the flow meter accuracy is measured in case of a lock-in of the pulsation frequency with the vortex frequency or (sub) harmonics thereof. The flow pulsation amplitude is far below the specified level of 5% rms according to ISO/TR 3313, An overview of the impact of meter size and pulsation amplitude is summarised in the figure below for DN40-DN100 mm.

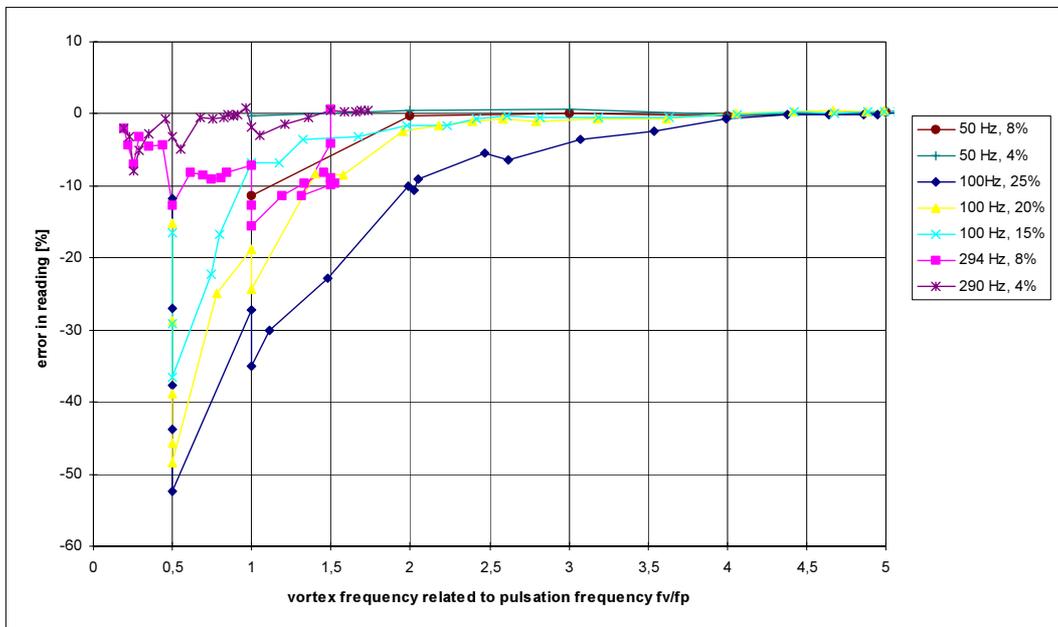


Figure 3.4. Systematic error in reading for 3-inch (DN80) vortex flowmeter

3.3 Randomly fluctuating flow: transients, flow-induced pulsations or valve-noise

A-periodic pulsations are caused by vortex shedding at T-joints, in shell and tube heat exchangers, at thermowells and in pipe reducers or fittings. Another mechanism of pulsation excitation is due to flow separation in turbomachinery (surge), in valves or in reducers due to high flow velocities. So various source mechanisms apart from compressors and pumps may be the cause of pulsations and vibrations in pipe systems and thus also in flow metering sections. Specific requirements with respect to locations of flowmeters and pipefittings should also be included in standards and installation guidelines.

High frequency valve noise due to valve actions is a well known as a potential source of misreading due to the fact that control valves generate ultrasonic noise, which is interfering with the flow sensor signals operating in the same frequency range typically between 50 and 500 kHz. Several attempts have been made to investigate in-line dampers for ultrasonic valve noise based on reflection and/or absorption of materials are added to ultrasonic flowmeters for the specific application of us flowmeters close to control valves. There is evidence that typical reduction by 20 dB in the ultrasonic range can be achieved without excessive pressure losses. In addition the use of appropriate signal analysis applied to the raw time signal can result in effective reduction and separation of valve noise from the actual sensor signal.

3.4 Mechanical pipe vibrations.

The ISO Technical report for vortex flow metering (ISO/TR 12764) states: "vibration of the vortex meter and associated piping should be within the levels recommended by the manufacturer". However out of five different make vortex meters investigated in the WIB-project only one specifies a limit for an allowable vibration level of 0.25g. In one of the tests performed on these flowmeters the actual flow rate through the meter is zero and the exciter is swept from 20 to 2000 Hz by increasing the frequency at a sweep rate of 0.5 octave per minute. The flow meter under test is imposed to vibrations in three directions: axial, horizontal and vertical.

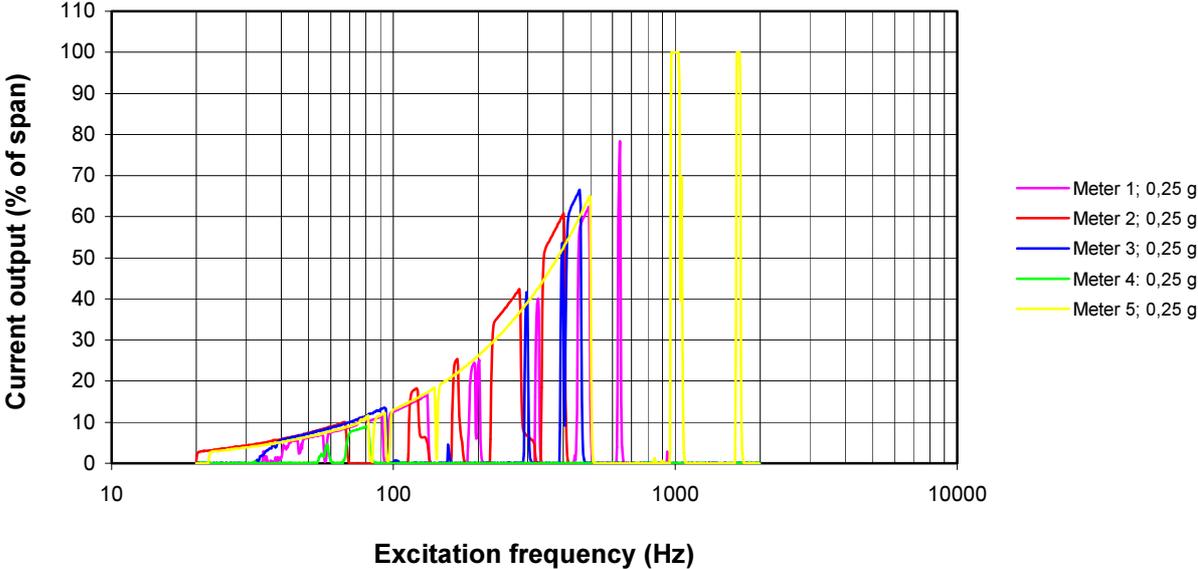


Figure 3.4. Impact of pipe vibrations, amplitude of 0.25 g, in horizontal direction on 5 different make vortex flowmeters at zero flow conditions

The test result shows that all five different make vortex flowmeters are sensitive for vibrations in all directions. Even at rather low amplitude of 0.25 g the current output shows a considerable error in the flow range from 5-100% of the span dependent on frequency of the vibration and the excitation direction. This excitation level of 0.25 g is below the allowable vibration level, assumed as acceptable for pipe systems from cyclic stress point of view (20 mm/s) for frequencies above 20 Hz.

In the 2nd test the impact of fixed vibration amplitudes, from 0.25 g to 1.5 g, on the flowmeter reading has been measured for a flow range from 50 to 800 Nm³/h.

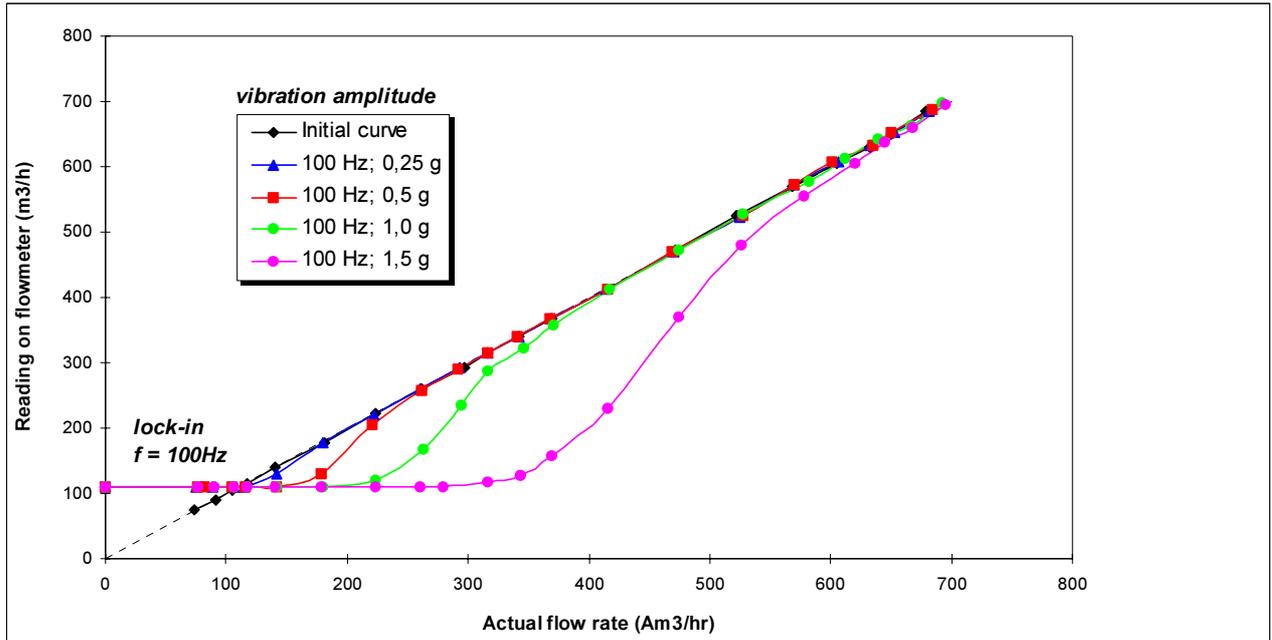


Figure 3.5. Impact of pipe vibrations on vortex flowmeters under flow conditions with vibration amplitudes from 0.25 g to 1.5 g in horizontal direction

The reading of the flowmeter is plotted against the actual reading of the reference flowmeter at normal operating conditions (initial curve) and next with a vibration at a fixed frequency of 100 Hz.

Also Coriolis flow meters are found to be sensitive for mechanical vibrations occurring in the operating range of the flow meter. In the ISO Standard 10790 (2nd ed. 1999-05-01) on Coriolis flowmeters chapter 3.3.8 mentions the possible impact of "Hydraulic and mechanical vibrations". This Standard states that the manufacturer should specify the operating frequency range to "enable assessment of possible influences of processes or other external mechanically imposed frequencies".

Though the standard does not specify limits regarding allowable vibration or pulsation amplitudes and frequencies.

It is known from various investigations [6] that flow pulsations as well as external mechanical vibrations can result in erroneous flowmeter readings due to interaction with the steady flow induced motion of the Coriolis tube.

Therefore for Coriolis flowmeters both the impact of flow pulsations and mechanical vibrations should be included in the test certificate

3.5 Swirl and a-symmetry in the flow profile

The piping geometry and configuration upstream of the flow meter can result in disturbances from the ideal axial flow profile in a turbulent flow. The deviation such as a-symmetry and swirl in the mean velocity profile can result in a significant deviation and thus a systematic error in the reading of the flowmeter. The effects depend on the degree of a-symmetry and swirl and the sensitivity of the specific flowmeter. Differential pressure type, turbine, ultrasonic and vortex flowmeters are all sensitive to deviations from the ideal profile.

The impact of upstream disturbances on the nominal K-factor for vortex flowmeters, as investigated in the WIB project is summarised in table 2.4.1 showing the deviation from an ideal situation with an upstream straight pipe section of 70 D.

Figure 3.6. Impact of upstream straight pipe length on the K-factor for 5 different makes vortex flowmeters

Disturbance	Location of upstream disturbance		
	5D upstream	10D upstream	40D upstream
90° single elbow		+0.4% <E< + 1%	+0.1% <E< + 0.4%
Two 90° elbows out of plane		-0.6% <E< + 0.7%	-0.1% <E< + 1%
Reducer	-0.2% <E< + 1.4 %	-0.1% <E< + 1%	

Regarding the impact of swirl or a-symmetry in the flow pattern much more attention is paid to these installation effects in manufacturer's documentation and standards. There is sufficient information available to recommend straight length of piping after a single or a double-bend configuration. Though also in this case recommendations show a considerable spread for the same piping configuration [7]

3.6 Flashing and cavitation

The relatively high fluid velocities that can occur in vortex and Coriolis meters can cause high-pressure losses inside the meter, which may result in flashing and/or cavitation. The reduction of the local pressure in a liquid system may result in a local pressure below the vapour pressure, thus resulting in the formation of gas bubbles (flashing), which will change the fluid characteristics. This consequently results in an irregularity in the vortex shedding on the bluff body, which will have an impact on the accuracy of the flow measurement.

Flashing is often followed cavitation, which can be described as the implosion of gas bubbles, resulting in erosion of the bluff body.

The ISO/TR 12764 describes the possible effects of cavitation in vortex flow meters in chapter 7.2.2 and annex C. An example of a cavitation test on a 3-inch vortex flowmeter in the TNO Water Test Facility is shown in figure 3.6.1.



Figure 3.7. A 3-inch dual bluff body vortex flow meter located in the TNO Flow Centre Water Test Facility

The Coriolis meter is also sensitive for cavitation, which may cause measurement errors and result in damage of the sensor as mentioned in ISO 10790. This again may be of concern if the flowmeter is installed in a low-pressure system, which is close to vapour pressure of the liquid or for Non-Newtonian fluids and slurries, which have a high viscosity and pressure loss.

As a rule of thumb the following expression for the minimum line pressure P_{min} results from the installation guidelines derived from the WIB project on vortex flowmeters:

$$P_{min} = 2.7 * dp + 1.3 * P_{vap} \text{ with:}$$

- P_{min} : minimum line pressure at 5D downstream , kPa
- dp : pressure loss across the flowmeter, kPa
- P_{vap} : vapour pressure of the liquid at operating conditions, kPa

3.7 Summary of important installation effects on different flowmeters

The impact of dynamic flow and piping installation effects depends on the specific sensitivity of the flow metering technique for the effect and the application. The required accuracy and repeatability of a turbine or vortex flowmeter for custody transfer applications differs considerably from an

application for control or safeguarding. Also the requirements for application of a custody transfer measurement of an ultrasonic flowmeter in a gas control and metering station differs from an application in flow control. An overview of the importance of various installation effects on different types of flowmeters, based on working principles is given in the table below.

Installation effect >>>	Periodic low frequency pulsations	Transients due to valve actions	High Frequency Valve noise	Mechanical Vibrations	Cavitation	Flow profiles: Swirl A-symmetry
Metering technique:						
Orifice/DP transmitter	++	+	-	-	-	++
Vortex	++	+	-	++	+	+
Ultrasonic	+	+	++	-	-	+
Turbine	++	+	-	-	-	+
Coriolis	++	+	-	++	+	-

4. A test certificate proposal

We have evaluated the interest of manufacturers and operators in the development of a test certificate for flow and piping dynamic effects on flow meters in a brief questionnaire. Approximately 100 questionnaires have been send to various clients, mainly in Europe, of which the total response was 25 % from 20 different companies. The development of a certificate was qualified as valuable by various operating companies (100%), whilst they also declared their willingness to support the development of such a certificate. The reply from manufacturers shows a similar response: 90% qualified the test certificate as valuable and are also willing to co-operate and support such a certificate. Positive reactions have been received from major manufacturing companies like Fisher Rosemount, Endress&Hauser, Instromet, Daniel, Danfoss and Yokogawa.

An overview of the installation effects, which should be included in the test for respectively gas and liquid applications, is shown in the tables 4.1 and 4.2

Table 4.1 Installation effects to be included for flowmeter application in gases

Metering technique	Periodic pulsations	Transients due to valve actions	Start-up/shut down	Valve noise	Mechanical Vibrations	Wet gas	Flow profiles: Swirl A-symmetry
Orifice/DP transmitter	50 %	45%	20%		25%	5%	45%
Vortex	40%	30%	20%		25%	5%	45%
Ultrasonic	45%	35%	30%	40%	25%	5%	45%
Turbine	45%	45%	20%		35%	5%	45%
Coriolis	55%	55%	20%		45%	5%	45%
Thermal mass	20%	10%				5%	5%

Table 4.2 Installation effects to be included for flowmeter application in liquids

Metering technique	Periodic pulsations	Transients due to valve actions	Start-up	Shut down	Cavitation	Mechanical Vibrations	Gas bubbles in liquid
Orifice /DP transmitter	35%	45%	15%	15%	35%	35%	
Vortex	65%	65%	25%	15%	55%	70%	10%
Ultrasonic	55%	55%	25%	20%	35%	55%	15%
Turbine	35%	35%	20%	20%	15%	25%	
Coriolis	70%	65%	30%	25%	65%	75%	
Inductive	45%	45%	15%	10%	35%	35%	
PD	10%	10%			10%	10%	

The overview represents the view of manufacturers, engineering and operating companies; there is not much deviation between the opinions of the parties involved. We have highlighted the 'top three' installation effects in the above mentioned tables. It is clear that for gas applications the periodic low-frequency pulsations, valve actions and flow profiles are mentioned as the most important installation effects. For ultrasonic flow meters valve noise of control valves is classified as being equally important as periodic pulsations.

For liquid applications the mechanical vibrations are qualified as being as important as pulsations and transients, especially for the application of Coriolis and vortex flowmeters. In addition the impact of cavitation for the last two categories of flow meters is mentioned by more than 50% of the respondents.

In a few cases operating companies mentioned wet gas applications as well as the occurrence of gas bubbles in liquids. The effects of pollution and erosion were also raised by some of the operating companies.

The main objective of the TNO Product Label, which goes with the certification, is to provide a basis for communication on one or more specific aspects of the product. The certification is based on a contract between the manufacturer and TNO Certification without other parties involved. This independent TNO branch, which handles the contractual aspects supplies and controls the TNO product label. The TNO TPD Flow Centre is responsible for the technical aspects, including the specification of the test conditions and conducting the test.

The test certificate for a specific type of flow meter will be based on well-defined flow and piping dynamic effects, as occurring in practice, under well defined flow conditions.

For the test on pulsation and vibration impact the frequency range and the range of amplitudes in the test can be well defined in relation to values experienced in practice.

A standard low frequency pulsation test can be defined as follows:

Flow pulsation amplitudes:	5, 10, 25 and 50% of the mean flow
Pulsation frequencies:	5, 10, 25, 50, 100, 250 Hz
Flow range:	0-100 %

A standard vibration test should cover the following range of amplitudes and frequencies:

Vibration amplitudes:	0, 0.25, 0.5 and 1 g amplitude
Pulsation frequencies:	5, 10, 25, 100, 250, 500, 1000 Hz
Flow range:	0-100 %
Additional test at zero flow:	1-1000 Hz for 0.25 g

5. Proposal for improvement of design of flow metering stations

In particular for fiscal metering, any disturbance at the location of the flow meter leading to measurement uncertainty needs to be eliminated from an optimal design. This does not only hold for the flow profile, which should be fully developed at the location of the meter, but the flow should also be steady, i.e. without low frequency flow pulsations and high frequency noise and a minimum of transient effects. Swirling flow and mechanical vibrations should be avoided for all conditions. Although different flow meters respond differently to these distortions, there is no type of meter, which is fully insensitive for all distortions. For example, Ultrasonic flow meters have shown to be sensitive for valve noise and flow profiles, while turbine meters are very sensitive for swirling, transient and pulsating flow. Vortex and Coriolis flow meters appear to be sensitive for pipe vibrations. During calibration of the instruments, the standard procedure is a test under fully developed, steady flow in a quiet environment, which can be significantly different from the actual conditions under which the meter has to perform. Therefore we propose the following two-step approach:

1. Define a calibration test for installation effects which can be imposed in a reproducible manner and for realistic dynamic conditions (frequencies and levels) and perform these tests prior to installation. This test should be carried out either at the manufacturer, operator or an independent test laboratory, but always under inspection of an independent witness. The result should be a certificate related to a specific type and make of instrument, which specifies the conditions under which the instrument was tested and the effect on its accuracy under these dynamic conditions.

2. Determine the level of dynamic conditions that occur at the location of the instrument in a flow metering station during the detailed design phase. Several conditions should be evaluated:

Flow profile, this can be obtained from a CFD analysis of the flow through the meter run. With such an analysis, also the level of swirl at the flow meter can be determined.

Transient and pulsating flow, this can be obtained from a dynamic flow analysis of the flow meter station. During such an analysis, causes of transient and dynamic flow should be taken into account such as valve opening and closing, flow induced pulsations, compressor or expanders. All operating conditions leading to different meter runs to be opened and closed should be evaluated during the design. Since in many cases closed meter runs lead to the existence of closed side branches, flow induced pulsations are frequently observed in these installations, and have for example led in the past into ghost reading of turbine meters in closed meter runs [8]

Flow noise, generated by control valves and bends or reducers. In particular the high frequency noise above 50 KHz generated by control valves should be predicted in a design stage. This analysis can be carried out when geometrical details of the control valve are given and the flow and pressure distributions in the metering station are known.

Currently, TNO TPD has various software tools available to determine in the design stage whether any installation effects may lead to misreading of the instrument.

CFD simulation packages such as Fluent are being used on a day-to-day basis to determine flow profiles in pipe systems after disturbances.

Dynamic flow phenomena can be determined with the help of the TNO proprietary code PULSIM (pulsation simulation) which is capable to determine both transient and pulsating flow in pipe systems, as well as flow and pressure distribution in piping networks. The code is also capable to model the effect of flow-induced pulsations at T-junctions and side branches.

Mechanical vibrations of pipe systems caused by unsteady flow can be determined with the finite element package ANSYS. The dynamic forces resulting from the dynamic flow excite the pipe at bends, reducers and closed valves, leading to strong vibrations.

Flow noise can be predicted in a design stage with the software package SID, which has recently been developed at TNO in a European project with the University of Stockholm and Eindhoven.

By using these software tools, the installation effects acting on an instrument can be determined in a quantitative way already in the design stage. Whether or not the instrument is affected by this disturbance, will depend on the type and make of instrument, and should be evaluated separately as mentioned in the previous section.

This may result into optimization of the flow metering station when the type of flow meter is already known. For example the main aim will be minimizing swirl and dynamic flow in case of turbine meters, while noise may be of critical importance for ultrasonic and pulsation and vibrations for vortex meters (only accepted for fiscal metering in Germany).

A few examples of using these tools are shown in figure 4.1 – 4.3

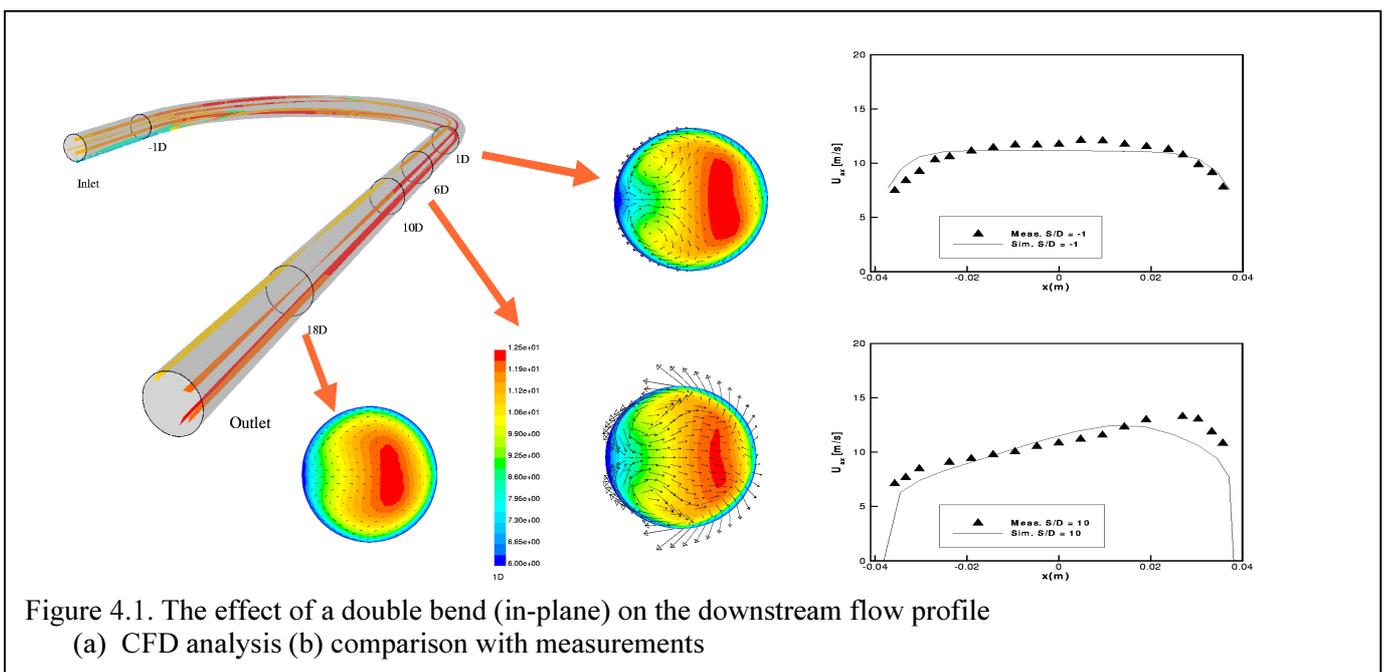
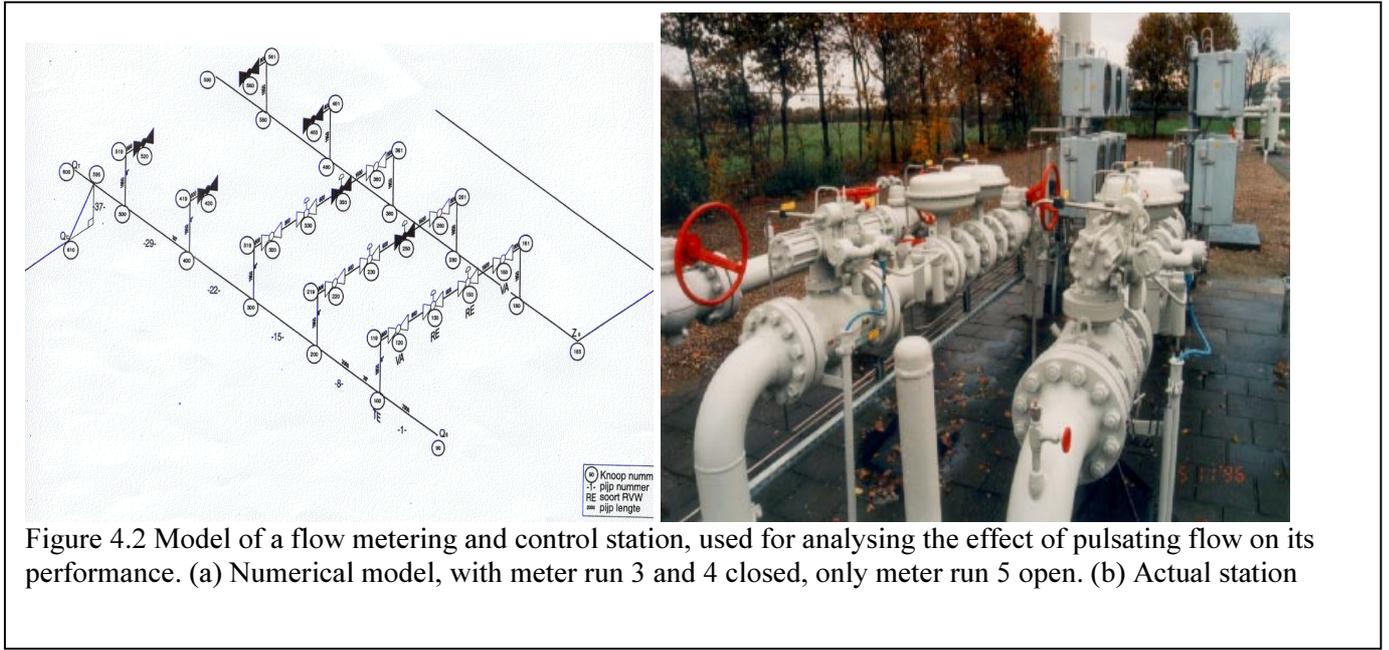


Figure 4.1. The effect of a double bend (in-plane) on the downstream flow profile
(a) CFD analysis (b) comparison with measurements



In figure 4.1, the flow profile of a steady flow through a double bend in plane is presented at several locations downstream of the second bend. Clearly the profile is distorted, and even at 18 D downstream of the bend, a fully developed profile is not recovered yet. The simulation was validated with experimental data, as shown in figure 4.1b.

In figure 4.2, a flow metering station is presented which has been modeled with PULSIM to analyze the effect of flow-induced pulsations. The numerical model of the station is shown in figure 4.2a. The results are shown in figure 4.3. Both pressure and flow pulsations at any location in the piping network can be calculated, in particular at the flow meter. Also dynamic forces on the pipe sections are determined, which can be fed into ANSYS to determine the piping vibrations. In this way the existing dynamic flow conditions at the location of the flow meter can be determined for any process condition during the design stage. With these tools, also optimization of the location of the flow meters can be done.

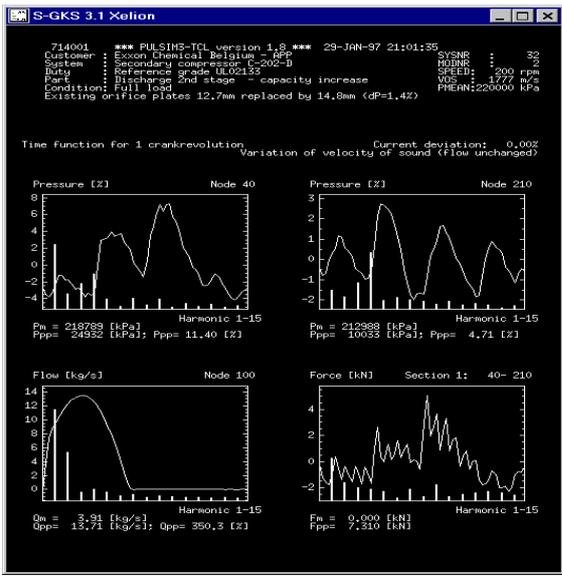


Figure 4.3 Example of output generated with a PULSIM simulation (a) pressure (b) velocity (c) forces

6. Conclusions and recommendations

Field experience [3, 8, 10] has shown that flow and piping dynamics can have a considerable impact on the accuracy of flowmeters. The systematic errors on flow meters like turbine, Coriolis, vortex and ultrasonic can be positive or negative and depends on flow pulsation amplitude and frequency. Lock-in effects on vortex flowmeters can result in large errors if the pulsation frequencies are in the range of the vortex frequencies.

The ISO/TR3313 (3rd edition – 1998) provides guidelines for low-frequency pulsations on flow metering techniques like differential pressure, turbine and vortex flowmeters, though Coriolis and ultrasonic flowmeters are not mentioned. Also the impact of mechanical pipe vibrations, which is important for Coriolis flowmeters, is not mentioned in this guideline.

In our opinion a certificate for flowmeters regarding flow and piping dynamic effects is in the interest of both manufacturers and operators. It enables the manufacturer to prove that his equipment is insensitive for dynamic effects below defined threshold amplitude and within a specified frequency range. It allows the operator to get more insight in the impact of flow dynamic phenomena on a specific meter and enables him to choose a flowmeter fit for his application. Various manufacturers and operators as shown in the enquiry described in this paper support the development of such a certificate. TNO TPD Flow Centre is developing this test certificate and is looking for partners to join this project.

It is also in the interest of operators to locate flowmeters such that the impact of flow and piping dynamics is minimised. This can be achieved by appropriate design of flow metering stations, such as to avoid flow induced pulsations at T-joints and prevent resonances in closed side branches [9]. The PULSIM code has proven to be an effective software tool to serve this goal not only for flowmeters close to compressor stations but also for flow induced pulsations and transients due to valve actions.

For other installation effects like swirl, a-symmetric in flow patterns and valve noise other CFD codes are applicable to assist in the design of a flow metering station.

TNO TPD Flow Centre is developing a project proposal to define the guidelines for an appropriate design and operation of flow metering stations regarding flow and piping dynamics. We want to develop these guidelines and define proposals for design calculations to be applied to new and existing flow metering stations in co-operation with operators based on our common experience from various projects.

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