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INTELLIGENT FLOWMETERING - MAXIMUM PROFIT OF AVAILABLE INFORMATION-

F.M. Braal, W.J. Bouman and C.H.L. Limpens
Flow Centre
TNO - Institute of Applied Physics (TPD)
Delft, The Netherlands

ABSTRACT

This paper deals with the development of a diagnostic system for flowmeters, that does not only make flowmeters work optimal under the toughest conditions, but can also diagnose the condition of instrument, process and installation. The paper describes the promising results of a pilot project for vortex flowmeters. Investigated items are vibrations, pulsations and cavitation. Making the flowmeter insensitive to these disturbances makes it possible to measure lower flow rates than before.

Keywords: process diagnostics, digital signal processing, vortex flowmeters, pulsations, vibrations, cavitation.

INTRODUCTION

The operational conditions of flowmeters are never ideal. Unwanted and often unknown or at least not quantified process disturbances and installation effects like vibrations and pulsations influence the sensor signal and cause problems for a lot of the current flowmeters. The current signal processing techniques are not designed to distinguish which part of the signal is related to the flow rate and which part is caused by other phenomena. Furthermore, the design is not set up to get the maximum of information out of the signal. However, the unfiltered sensor signal contains the information needed, to solve the major part of the problems.

The Flow Centre of TNO-TPD is developing a new ‘smart’ method of signal processing, that, combined with the digital signal processor of the next generation of flowmeters, decreases the meters sensitivity to these disturbances. Not only that, it uses the information to turn the meters’ former disadvantages into its benefits: the meter can be used to diagnose the same conditions, it suffered from before.

The potential of this new feature is obvious: because of its reduced sensitivity, the meter becomes more reliable, its operating range can be expanded and it can diagnose the condition of instrument, process and installation. Therefore it can be used to have a better understanding of what's going on in that part of the process and become an effective tool for predictive maintenance, instead of measuring only the flow rate.

VORTEX FLOWMETERS

The Flow Centre of TNO-TPD proved, in a research programme on different makes vortex flowmeters, that many meters are considerably sensitive for vibrations and pulsations[i ii]. With the current state of the art of digital signal processors, it should be possible to solve this problem and we started an investigation.
The research programme comprised a wide range of disturbances, including pulsating flow, pipe vibrations and cavitation. Encouraged by the promising results, we are developing a tool that allows the vortex meter not only to measure the correct flow rate under the toughest conditions, but also to diagnose the existence and levels of these conditions. A tool that will later also be adapted for other flowmeters.

Vibrations

The current signal processing in most vortex flowmeters is based on the signal in the time domain and works as follows: the sensor signal is filtered, conditioned and then lead through a Schmitt-trigger, to transform the sinusoidal signal into a pulse signal (see figure 1). By counting the number of pulses per time unit, the frequency is calculated and via a constant factor the flow rate can be derived.

However, the sensor also picks up vibrations and the component caused by vibrations is simply added to the component caused by the vortex shedding. This causes the flowmeter to count the wrong number of pulses per time unit and therefore results in a wrong flow rate (see figure 1).

The effect of vibrations on the sensor signal depends on the ratio of the amplitude of the component caused by vibrations and the amplitude of the component caused by the vortex shedding. The lower this ratio, the lower the impact. The amplitude of the component caused by vibrations remains constant with increasing flow rate, the component caused by the vortex shedding however, increases with flow rate. This means that the effect of vibrations is higher at low flow rates. When the flow rate is zero, vibrations can cause the vortex meter to give a flow rate reading, that is corresponding to the vibration frequency.

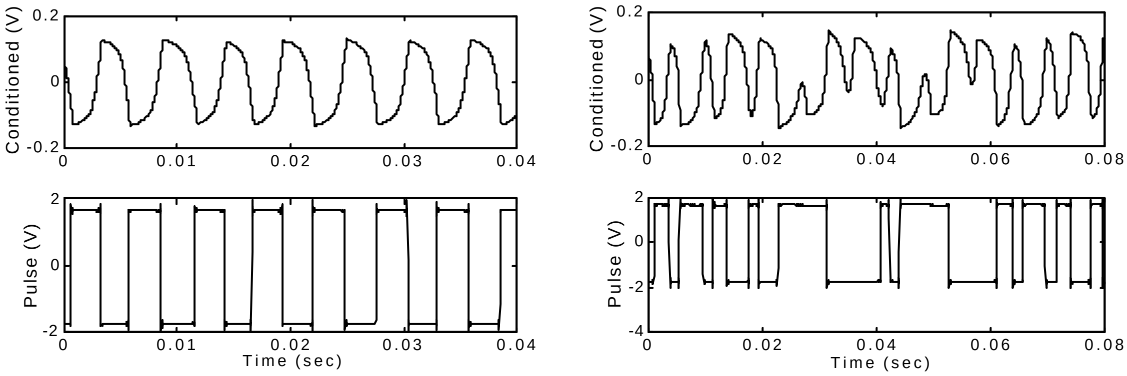

Figure 1: Left: Conditioned sensor signal and pulse signal under ideal conditions (air at 200 m^3/h) **Right**: Conditioned sensor signal and pulse signal when exposed to vertical vibrations of 50 Hz (1g) (air at 200 m^3/h).

The current signal processing is based on the signal in the time domain, meaning it cannot determine, which part is caused by flow and which part by vibrations. Therefore the conditioned signal still contains the vibration component.

In the frequency domain however, it is possible to distinguish the two components, even if the vibration component has a much larger amplitude then the one related to the flow rate. It is also possible to distinguish between the two components when the vibration frequency and the vortex shedding frequency are very close (see figure 2).

The developed tool cannot only eliminate the effect of the vibrations on the reading of the flowmeter, but can also diagnose that the meter is exposed to vibrations with a certain frequency and severity. This leads to a higher awareness, what's going on at the location of the meter. The tool will furthermore be able to monitor a considerable change in the measured vibration frequency or severity. This way, the meter can indicate an installation defect or predict the degradation of the installation.

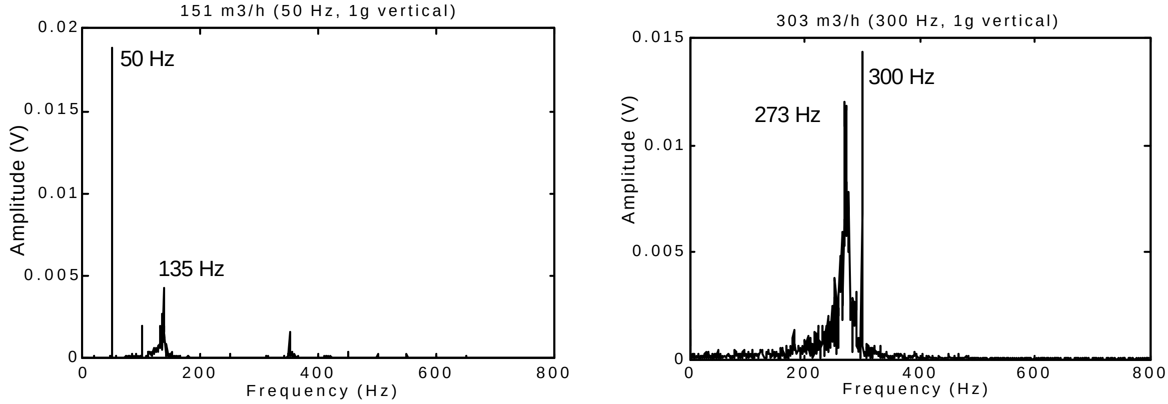

Figure 2: Spectrum of the sensor signal for vertical vibrations (medium is air).

Pulsations

Pulsations influence the meter in a different way than vibrations. Vibrations 'fool' the sensor. The sensor considers the vibrations as forces caused by the vortex shedding. Pulsations however are real flow rate variations that interfere with the vortex shedding. Modelling this phenomenon leads to a non-linear expression. For low flow rates, however, the expression is similar to frequency modulation, which figure 3 shows.

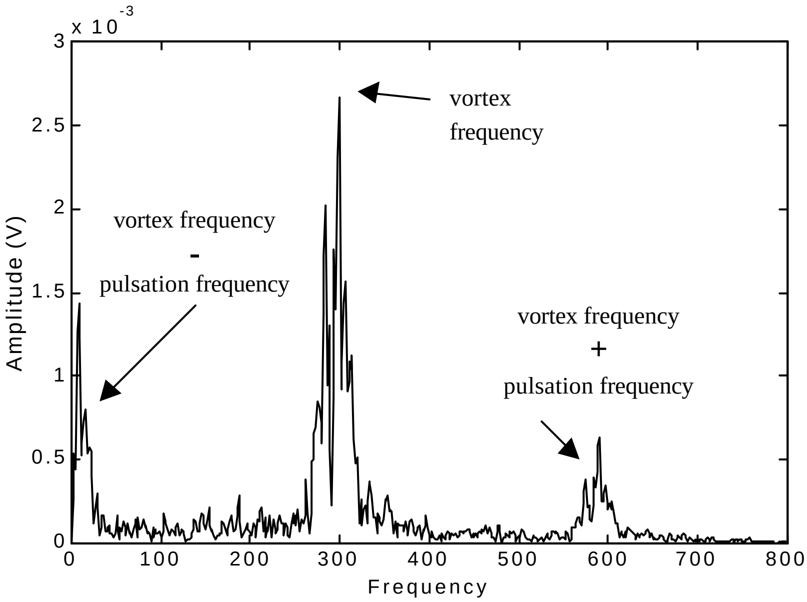

Figure 3: Sensor signal of vortex flowmeter at 339 m^3/h and 290 Hz pulsations.

For high flow rates the non-linearity of the expression really shows and the signal becomes more chaotic, which the frequency spectrum in figure 3 demonstrates. Using theoretical models and 'smart' signal processing, it's possible to make the meter almost insensitive to pulsations.

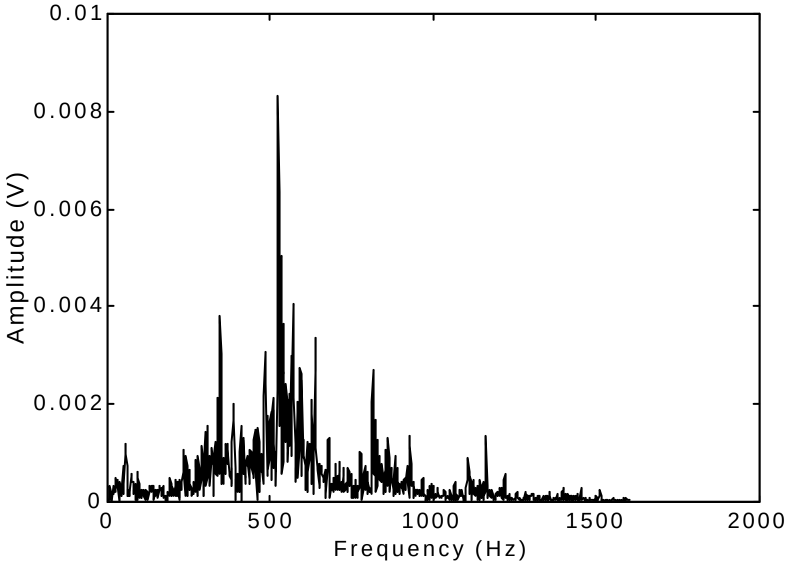

Figure 4: Sensor signal of vortex flowmeter at 600 m^3/h and 290 Hz pulsations.

Nevertheless, there is a problem, that is still hard to solve and that is the lock-in problem. Lock-in means that the vortex shedding frequency locks in to ½, 1, 1½ or 2 times the pulsation frequency. At lock-in, the vortex shedding frequency and thus the reading of the flowmeter stays constant, independent of the flow rate over a certain range (see figure 5).

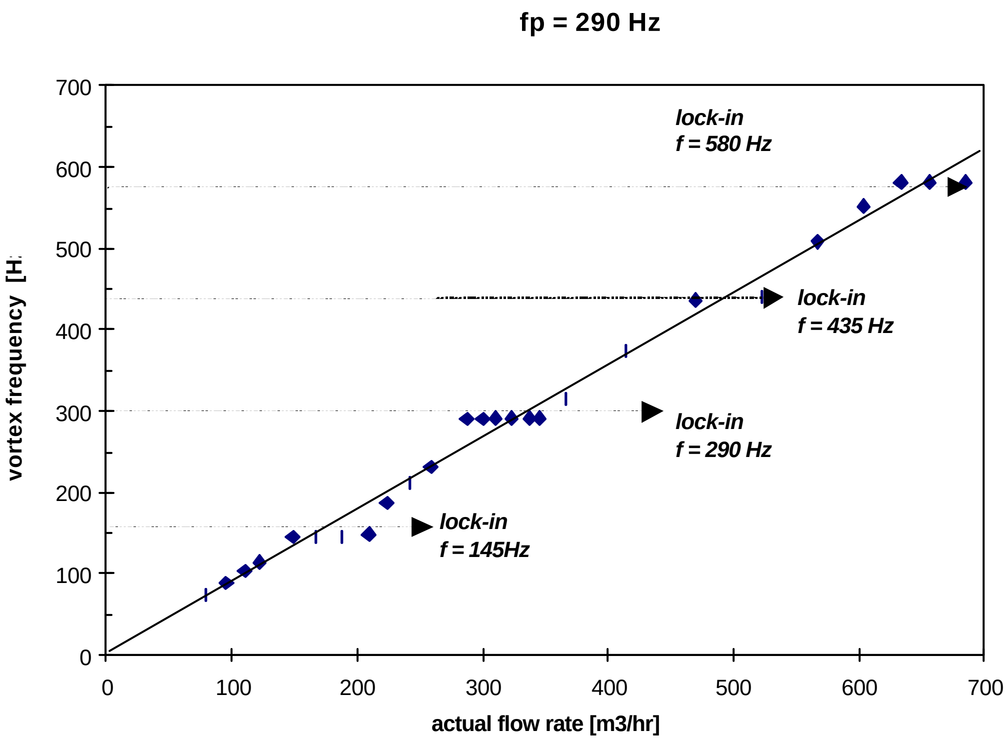

Figure 5: Lock-in of the vortex frequency to ½, 1, 1½ and 2 times the pulsation frequency (290 Hz)

Figure 6 shows the amplitude spectrum of a vortex meter, exposed to flow pulsations with a frequency of 290 Hz. The spectrum shows a lock-in at half the pulsation frequency, at 145 Hz. In this case the appearance of the spectrum remains unchanged from 145 to 220 m^3/h.

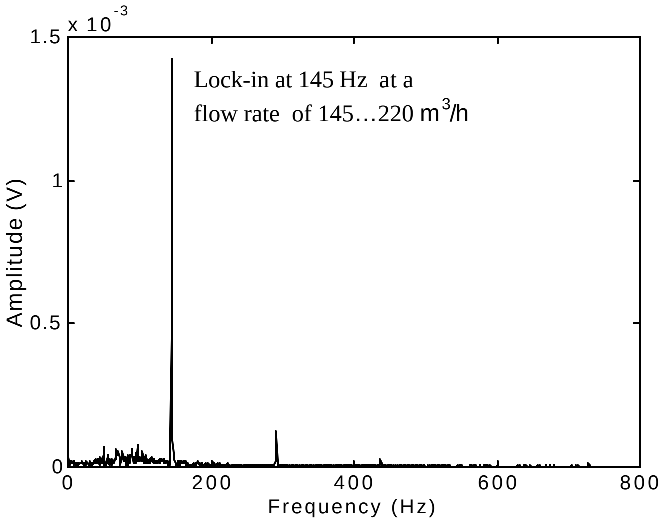

Figure 6: Amplitude spectrum of lock-in at 145 Hz from 145 to 220 m^3/h.

Although we did not yet succeed to measure the correct flow rate during lock-in, the new diagnostic system it is possible to indicate that the output of the meter should not be trusted and that the problem is probably lock-in at that frequency. The current flowmeters would not recognise this situation as a problem and it would give a flow rate of about 150 m^3/h even though the flow rate might be 220 m^3/h (an error of –30 % !).

Combination of vibrations and pulsations

Imposing disturbances and investigating the effect on the signal is not the most difficult part. It's more challenging to process a signal that is disturbed by a combination of unknown phenomena and then still being able to diagnose the case correctly. To see if the developed diagnostic system is able to do this, we imposed vertical vibrations of 50 Hz and 1g acceleration and 290 Hz (approximately 4 % amplitude) on the vortex flowmeter at the same time.

The following figures show the spectrum before (left) and after (right) filtering out the effect of vibrations on the signal. The left figure contains the effects of vibrations as well as pulsations. The pulsations can hardly be recognised from this figure. After filtering out the vibrations, the frequency modulation due to the pulsations of 290 Hz becomes evident. The diagnostic system first recognises the vibrations of 50 Hz (and higher harmonics) and after filtering, it recognises the main peak due to the flow rate as well as the pulsations of 290 Hz.

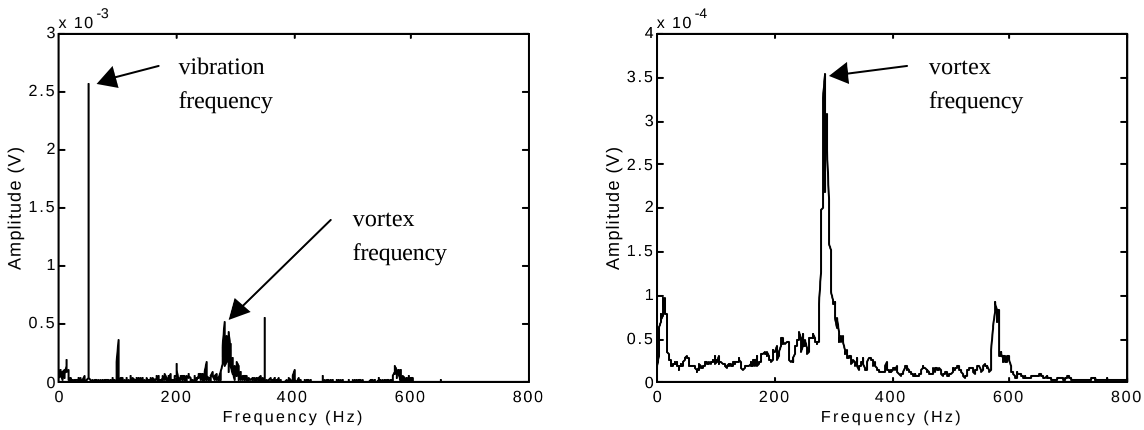

Figure 7 Left: unfiltered sensor signal, suffering from 50 Hz (1g) vertical vibrations and 290 Hz pulsations (flow rate of 327 m^3/h). **Right:** Processed sensor signal, where the effect of vibrations have been removed, showing only the modulation of 290 Hz around the main vortex shedding frequency.

Cavitation

Besides the possibilities for conditions like vibrations and pulsations, another striking result is, that application of sophisticated signal processing makes it possible to still measure the correct flow rate, while the meter is submitted to severe cavitation. Of course cavitation is an unwanted phenomenon and should be avoided. It's does not only cause severe erosion, but it causes the current vortex flowmeters to measure incorrectly under these circumstances, showing strongly varying unpredictable behaviour. This could not only raise a lot of questions with the operator, it could even cause that part of the process to shut down if the meter is used for control. Figure 8 shows how chaotic the (time) signal of the unfiltered sensor is. The amplitude of the signal is varying a lot, not only for data acquisition at a high frequency (102.4 kHz), but also at a much lower frequency (800 Hz).

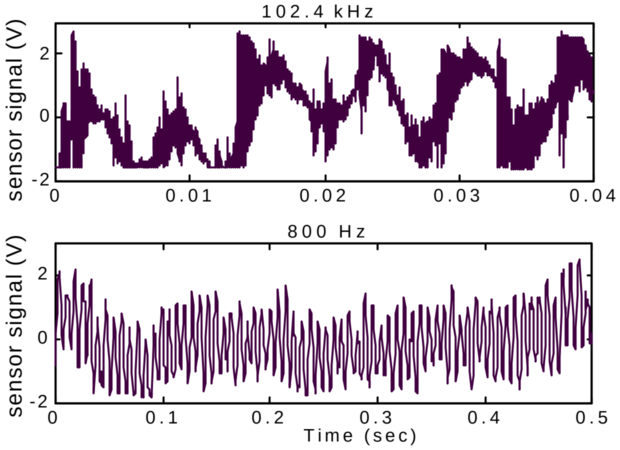

Figure 8: Sensor signal meter, experiencing cavitation

In the frequency domain however, the flow rate can still be determined with an accuracy of at least a few percent (see figure 9). The diagnostic system can also diagnose that the meter is exposed to cavitation.

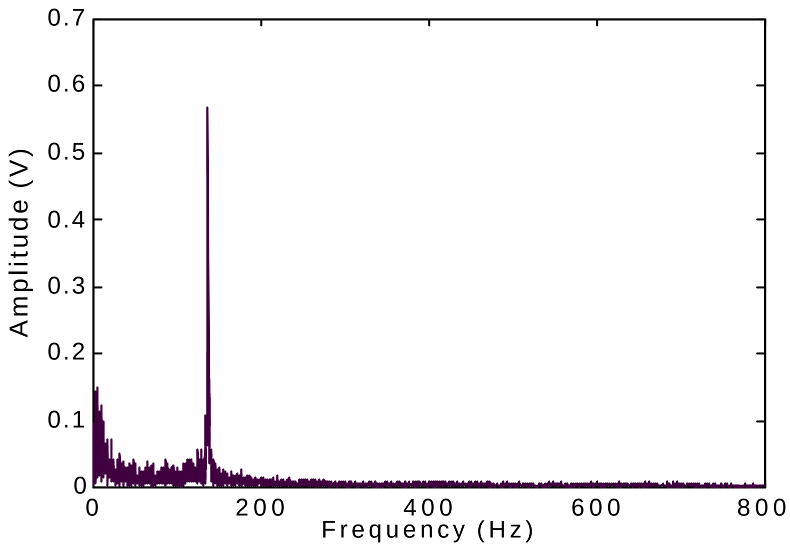

Figure 9: Amplitude spectrum of sensor signal, meter experiencing cavitation

Although cavitation is unwanted, that doesn't mean it won't occur. Using the diagnostic system described in this paper makes it possible to still measure the correct flow rate while the vortex meter is suffering from severe cavitation and also identifies the phenomenon as cavitation. This means the flowmeter gives a 'cavitation alarm', but keeps operating correctly so the problem can be solved, minimising the damage done to the bluff body, installation and process and without losing control.

Low flow

At lower flow rates, there is a bad signal noise ratio, due to vibrations and other disturbances. For this purpose, a low flow cut-off can be set within the software of the current vortex flowmeters. Below this low flow cut-off the output is forced to zero and there is no information below this flow rate. If the low flow cut-off is set to zero or set too low, it's unknown if the output reading is caused by flow or by other phenomena (like vibrations).

To give an idea, the low flow cut-off of a 2" vortex flowmeter is usually set at about 40 m^3/h for gas applications (meter flow velocity ≈ 5.5 m/s). This means there is no information available between 0 and 40 m^3/h.

Knowing what part of the signal is related to the flow rate and what part is caused by other phenomena, the meter can be designed to measure much lower flow rates, being less dependent on the signal noise ratio. The following picture shows the amplitude spectrum of the unfiltered sensor signal, caused by air with a flow rate of 1.7 m^3/h at a line pressure of 4 bar, meaning a meter flow velocity of 0.24 m/s and a Reynolds number of approximately 5000. The measured peak frequency is 5.3 Hz.

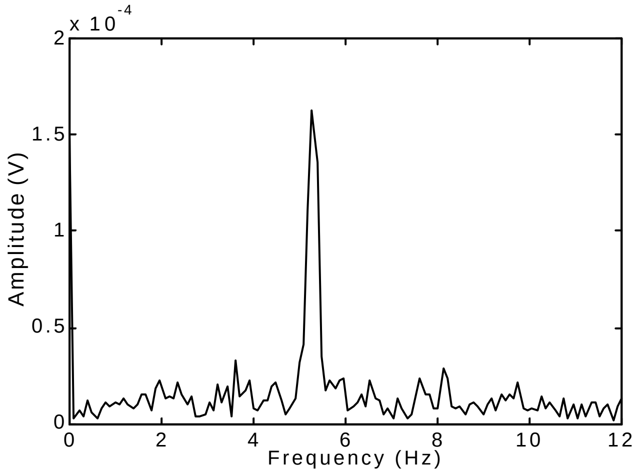

Figure 10: Sensor signal from 2” vortex flowmeter, air at a flow rate of 1.7 m^3/h and a line pressure of 4 bar, meaning a velocity of 0.24 m/s and Reynolds number 5000.

The frequency of 5.3 Hz means an error of about 16 % compared to the expected frequency based on the nominal meter factor [p/l] (K-factor). This is however not the actual error, because the meter factor is only valid in the area where K is approximately constant (Re>20,000). For low Reynolds number as here, the meter factor strongly depends on the flow rate. With a digital signal processor it is possible to integrate the shape of the K-factor in the meter, leading to a better accuracy. For these low flow rates, the repeatability is less than in the higher range. However, in this area, it is not important to measure with the highest accuracy, but to know if there is a flow going through the meter and that the reading is not disturbed.

Other research subjects

This new technique allows the meter to detect whether the medium going through the meter is liquid or gas and adjust its' settings accordingly. This means the new vortex flowmeter will also become more a 'plug & play' instrument.

Also the possibility of monitoring wear of or deposition of material on the bluff body is currently being studied as well as detection of back flow.

THE DIAGNOSTIC SYSTEM

TNO-TPD developed and is developing diagnostic systems for a broad application field, ranging from glass furnaces to consumer machines. Therefore, the results of the research on vortex flowmeters could already be implemented in a diagnostic system.. This section starts to discuss the diagnostic information provided by this system in more detail. Next, the diagnostic algorithms of the system will be discussed. This issue addresses the approach which has been taken to fill the diagnostic system with relevant expertise knowledge.

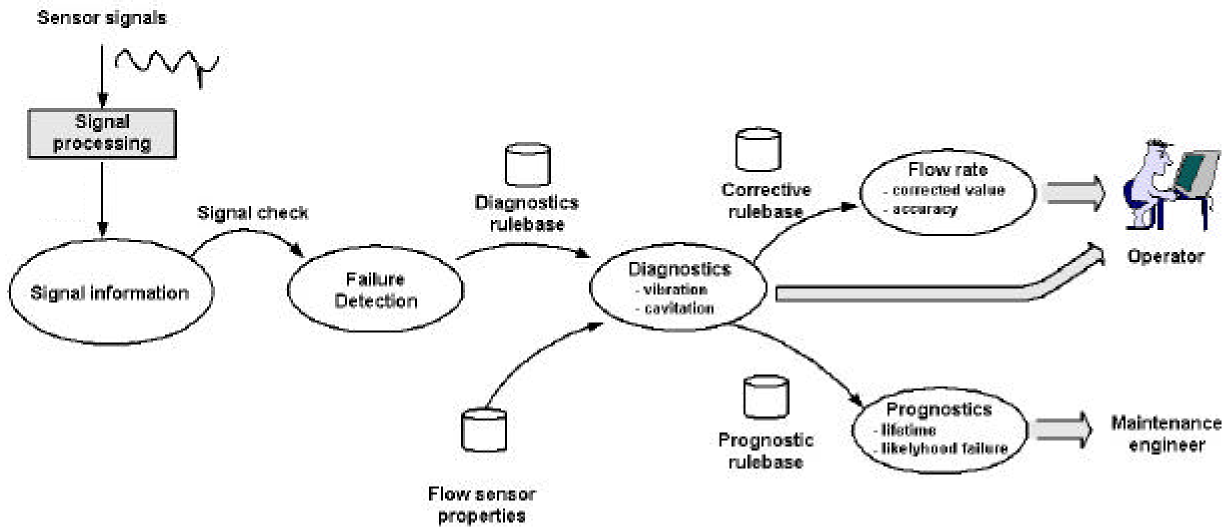

Figure 11: System setup showing the main diagnostic modules.

Considering the results provided by the diagnostic system, the user is interested in several types of diagnostic information. The first and most important type of diagnostic information is whether failure conditions have been detected or not. The monitoring module of the diagnostic system is providing this information. This module is based on signal processing algorithms of the raw sensor values. Successively, the characteristics of the sensor signal are compared with the characteristics of normal operation. Based on the deviation, the reliability of the sensor signals is determined and failure detection might be given.

Failure detection is the first module of the system. In addition, three more modules have been set up. The second module is related to diagnostics: when failure conditions have been detected, the user would like to know the cause of the problem. The current system contains algorithms to detect vibration, pulsation and cavitation. The diagnostic calculations start with the measured signal characteristics. If these characteristics coincide with the characteristics of one of the disturbances, this disturbance is very likely to be the cause of the problem. The algorithms are based on the time domain as well as the frequency domain to avoid leaving out crucial information. The algorithms have been set up in such way that combinations of disturbances can be detected as well.

The third module of the diagnostic system is calculating corrected values for the flow signal. As long as no problems have been detected, the conventional algorithms can be used to calculate the flow value. When a failure has been detected, and the cause has been found by diagnostics, other algorithms will be used. The central part of these algorithms is to separate the signal into a component caused by the flow and a component caused by the process disturbance. Next, the first component is used to calculate a more reliable value for the measured flow. In addition, the confidence level of the calculated flow rate is determined as well.

Finally, the fourth module, provides prognostic information. This information includes the detection of long-term trends of the measured flow signals and the disturbances and could in future even contain prediction of the lifetime of the flowmeter. The prognostic information is especially useful for predictive maintenance use. The predictions are based on algorithms, which keep track of the condition of the flow sensor.

Filling the diagnostic system

The diagnostic system is based on the relations between the possible process conditions and disturbances on one hand and the effect on the flow signal characteristics on the other hand. These relations are structured and formulated by means of rules. For example, the diagnostic module contains rules about the effect of pulsations on the variation of the sensor signal. The prognostic module on the other hand might contain rules to describe the effect of operational hours on the accuracy of the sensor. All rules are combined into rule sets, which are filled with expertise knowledge.

The quality of the diagnostic system highly depends on the quality of the information, which has been fed to the system. Therefore, filling the rulebase is an important activity, which has been given special attention. In general, the available knowledge has a wide diversity. First of all, experimental data are used to find empirical relations between variables. These relations can be best expressed in black-box models. However more types of information are available, for example by physical relations, rules of thumb (fuzzy rules) and decision trees. Because of the lack of complete physical knowledge of the effects of all the phenomena, the employed system combines different sources of ‘knowledge’ about the flow rate measurement, such as empirical relations, physical knowledge and human experience. The different sources result in different descriptions of the relation between variables. Physical knowledge can be best expressed in technological models, models based on experimental data can be best expressed in black-box models and human experience in fuzzy models.

With this approach, the diagnostic algorithms can be refined gradually. The first result is a coarse system, which describes most relations in a qualitative way. With this system, it is already possible to distinguish normal operation from situations with pulsations and vibration, based on the raw sensor signals. Currently, a selection of the rule bases is made to be modeled in more detail in a quantitative way. These refinements aim to derive corrected flow values on one hand and make diagnostics for other tough conditions on the other hand.

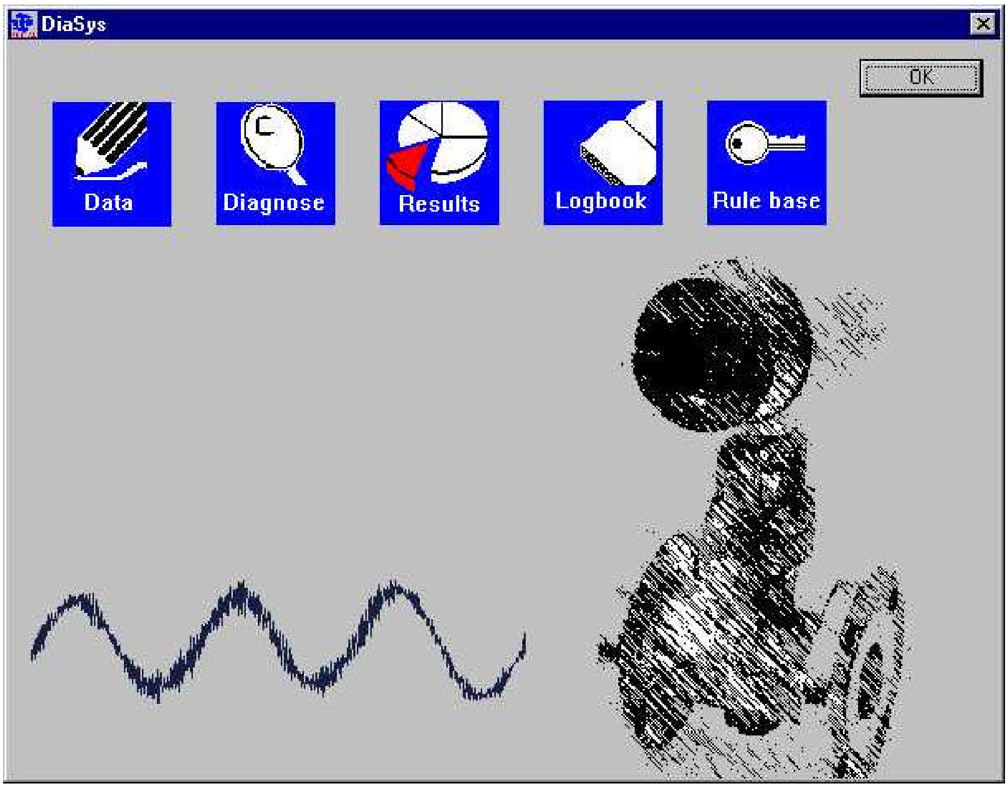

Figure 12: Front page of the Vortex Diagnostic System.

CONCLUSIONS, REMARKS AND FURTHER RESEARCH

This pilot project for vortex flowmeters shows, that these new signal processing techniques produce a number of new possibilities. By analysing the raw (unfiltered) sensor signal online, not only its application range can be expanded, a whole new functionality can be added to the flowmeter, namely a diagnostic system, including instrument, process and installation diagnostics.

Another idea to increase the functionality of the meter is to integrate other sensors like temperature, pressure and acceleration sensors in the meter. This could not only make other instruments superfluous, but the combination of sensors could lead to more valuable diagnostic variables.

Fingerprinting of as well process as instrument expands the possibilities for predictive maintenance. This prevents the disadvantages of scheduled maintenance and reduces the chance of disastrous breakdown maintenance.

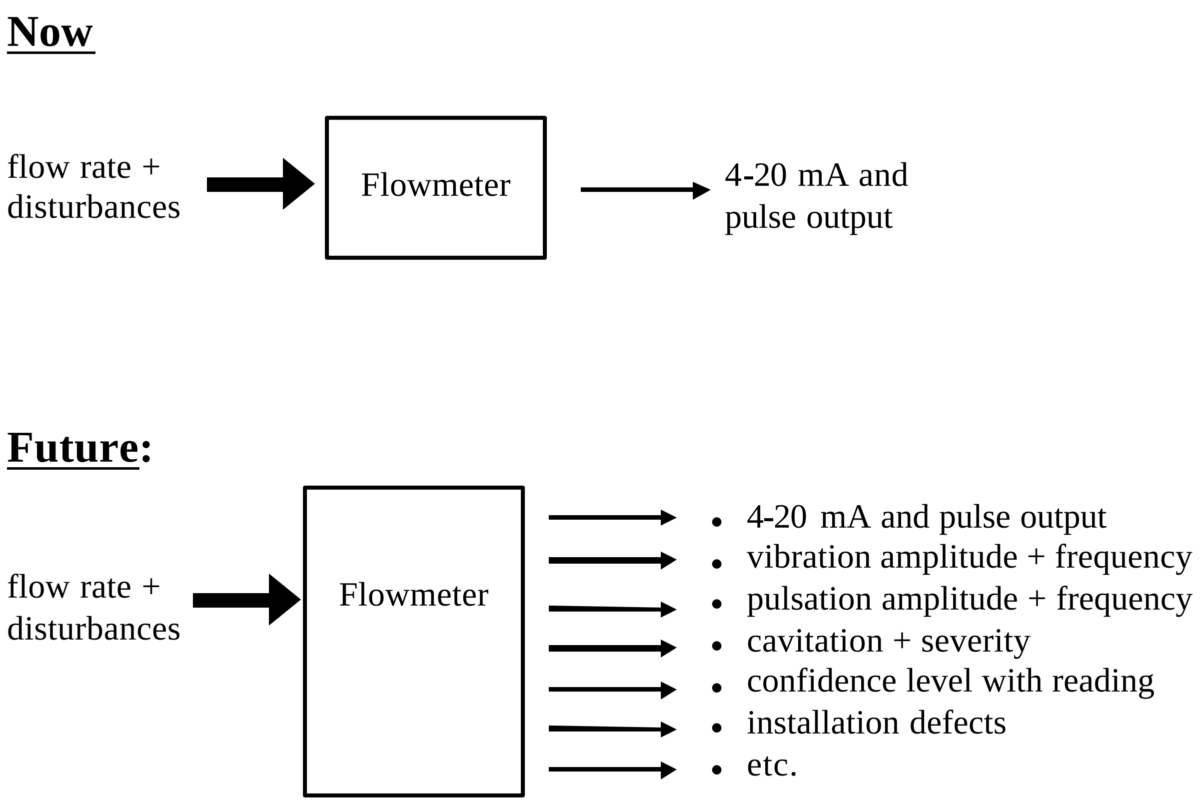

Figure 13: The current and future flowmeter

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[i] 'Impact of pulsations on vortex flowmeters' by M.C.A.M. Peters, E. van Bokhorst and C.H.L. Limpens . Proceedings of FLOMEKO '98 Lund, Sweden 15-17 June 1998
[ii] 'Impact of pipe vibrations on vortex flowmeters under operating conditions' by E. van Bokhorst, M.C.A.M. Peters and C.H.L. Limpens. Proceedings of 4th Int. Symposium on Fluid Flow Measurement (CD-ROM), June 1999, Denver USA