Vortex Shedder Sing-Around Flow Meter

Emma Persson

Luleå University of Technology
MSc Programmes in Engineering
Electrical Engineering
Department of Computer Science and Electrical Engineering
Division of EISLAB
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Emma Persson
Department of Computer science and electrical engineering
Luleå University of Technology

September 30, 2008
Abstract

The need to measure flow rates in fluids is large in the world today. Many are the applications where a more or less accurate measurement is needed, e.g. gasoline pipe, district heating, medical flows and flows in the manufacturing industry. One way to measure flow velocities that is commonly used is with vortex shedding flow meters. These flow meters detect the vortices behind a bluff body in a flow in different ways, one way is by transit time ultrasonics. Since, normally, the sing around-ultrasonic is a more accurate way to measure flow velocity the theory behind this thesis is that a vortex shedder flow meter with sing-around ultrasonics should be more accurate than the ones with transit-time.

A vortex flow meter is modeled with FEMLAB to give simulated data for the signal processing, and then the data is processed in MATLAB. The zero-crossing algorithm and the fast Fourier transform are applied to find the vortex frequency. In this stage it seems as if the sampling frequency is too small to detect the vortex frequencies. The final step is to make a vortex flow meter to confirm the theoretical model. The bluff body is built around ultrasonic transducers from D-flow technology AB. The flow meter is inserted to the water laboratory at Luleå University of Technology and measurements are done that is later evaluated and compared to the simulation results.

In the real model the vortex frequency is discovered for the lower velocities, but the signal processing used in this thesis is not sufficient to give accurate frequencies for the higher velocities. Two big conclusions are made, that the theoretical model is not good enough and that the vortex frequency is present in the measured signal but could not be found with the algorithms at hand.
Preface

This thesis is written as a part of the Degree of Master of Science in Electrical Engineering at Luleå University of Technology. It was written at the Department of Computer science and electrical engineering during 2008.

I would like to thank my supervisor Jan van Deventer for the support during my work on this thesis. I would also like to thank Carl Carlander and D-Flow Technology AB for their help with the measurements. Finally I thank Mats and the rest of my family and friends for their support throughout this work.
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Chapter 1

Introduction

1.1 Background

Vortex shedding is widely used for flow measurements and there is a number of ways to detect the vortices. Many of these flowmeters have accuracies around ±1% down to a specified Reynolds number \(^1\), and below that number the accuracy is poor, if even stated in datasheets. Lynnworth et. al has done some experiments with a bluff body vortex shedder and ultrasonic sensor and come up with something that might be possible to use down to Reynolds number as low as 1000 with good accuracy [1]. This is the idea that is further investigated in this work.

In [1] they used transit-time ultrasonics to measure the frequency of the vortices created by the bluff body, and as an extension the possibility to use sing-around ultrasonics is investigated in this thesis. Normally when measuring volume flow the sing-around technique shows an improvement in accuracy compared to the transit-time technique, so if it is possible to use sing-around even for vortex measuring then a more accurate flowmeter can be developed.

Previous work has investigated that a vortex shedder can be used for both the vortex shedding and density measurement [1]. That work also concluded that the best shape of the bluff body for this task is an elongated bluff body, which is what is used in this thesis.

1.2 Objective

The main objective of this master thesis is to design and build an ultrasonic sing-around gas flowmeter. This flowmeter will measure the vortex frequency behind a bluff body and use this information to calculate the flow velocity.

\(^1\)Read more about Reynolds number in appendix A
The specific objective of this master thesis is to investigate if it is possible to get an accurate velocity measurement by measuring the vortex frequency with ultrasound. The accuracy and repeatability should be made to match the accuracy of the flowmeters available on the market today.

The main idea that will be investigated is to measure the flow velocity downstream from the vortex shedder with sing-around ultrasonics. Since there are vortices in the flow this velocity will be fluctuating and also not be equal to the flow velocity upstream the bluff body. The fluctuations in the measured velocity should be equivalent with the vortices and by finding the frequency of the fluctuations the vortex frequency will be found. According to flow theory vortex frequency is linearly proportional to the flow velocity upstreams of the bluff body [2].

This thesis is part of a research idea whose long term goal is to make a compact and accurate air mass flow sensor, which measures volume flow rate, density and temperature.

1.3 Thesis outline

In chapter 2 there is an overview of different ways to measure flows. The focus is on vortex flow meters, but a few other methods are mentioned as well.

Chapter 3 is covering the fluid dynamic simulations.

In chapter 4 the signal processing is described. The result from the simulations is also analyzed and discussed.

In chapter 5 the experimental setup is described. The signal processing of the measurement result are also analyzed in this chapter.

Chapter 6 includes the conclusion.
Chapter 2

Flow measurement

The need to measure flow rates in fluids is large in the world today. Many are the applications where a more or less accurate measurement is needed, e.g. gasoline pipe, district heating, medical flows and flows in the manufacturing industry. In some applications it is enough to measure only the volume flow rate while other applications needs the mass flow rate. The mass flow rate is preferable in applications where the density is varying due to changes in pressure or temperature.

Here follows a short description of different flow measurement techniques that are available on the market today.

2.1 Vortex flowmeter

A vortex flowmeter uses the vortex shedding technique to measure the velocity of the flow. The velocity can then be used on its own, to calculate the volume flow rate, or be combined with a density measurement to calculate the mass flow rate.

2.1.1 Vortex shedding - the principle

The shedding of vortices in a flow is one of the world’s more classical problems, the phenomena was first studied by Leonardo da Vinci in the 16th century. A bluff body that is immersed in a flow will cause vortices to be shed downstream of the bluff body (see fig. 2.1). The vortices will be shed on alternate sides of the bluff body and the frequency is proportional to the flow velocity as

\[ f = S \frac{v}{d} \]  

(2.1)

where \( S \) is the Strouhals number, \( f \) is the vortex frequency, \( d \) is the width of bluff body and \( v \) is the average flow velocity. The linear behaviour can also be seen in figure 2.2, which is the expected frequencies for different velocities. These
calculations involves the Strouhal number, which is constant for a wide range of Reynolds numbers, $Re^1$.

The vortex frequency is the measured value and can be acquired with different types of sensors. Pressure sensors, lift detectors and ultrasonic sensors are the most common ones [6]. Table 2.1 shows different accuracies for some commercial flowmeters. It can be seen that the accuracy is similar for different techniques, ±1%.

### 2.1.2 Detecting vortices with pressure transducers

One way to detect the vortex frequency is to use pressure transducers. The vortex shedding will cause pressure changes in the flow. Pressure transducers either on the side of the vortex shedder or in the pipe walls detects the pressure fluctuations and calculates the vortex frequency. One commercial example of this kind of flowmeter is the Foxboro Vortex 84 meter from Foxboro inc [3].

### 2.1.3 Detecting vortices by lift detection

The lift is a force that is acting on the bluff body, the force is perpendicular and proportional to the velocity. If the bluff body is not attached in one end and fastened in the other the body will try to move due to the lift. This stress can be detected by piezoelectrical sensors in the fastened end of the bluff body [6]. A commercial flowmeter which utilizes this technique is the digital YEWFLO flowmeter from Yokogawa [4, 7].

### 2.1.4 Detecting vortices with ultrasonic transducers

Most of the ultrasonic vortex flowmeters today makes use of the fact that the vorticity in the flow will modulate the phase and frequency of the ultrasonic signal.

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1Read more about the Strouhal number and Reynolds number in appendix A
The phase and amplitude modulation is proportional to the vortex frequency\[8\]. The ultrasonic transducers are placed downstream from the bluff body and the measurements are perpendicular to the flow. One company utilizing this technique is Racine [5].

### 2.1.5 Vortex mass flowmeter

The vortex shedding flowmeters can be combined with a densitometer and then become a mass flowmeter. Mass flow rate, $\dot{M}$, is

$$\dot{M} = \rho Q$$

where $Q$ is the volume flow rate and $\rho$ is the fluid density. For best result with this mass flowmeter the densitometer should be situated as close to the volume flow rate measurement point as possible since the density of a gas is dependent on temperature and pressure. If the pressure or temperature changes between two measurements, the mass flow reading becomes inaccurate. One of the more common ways to measure the density is by a resistance temperature detector, RTD,
inside the bluff body [5]. The RTD will measure the temperature and calculate the density from that.

Another approach with vortex mass flowmeters is to use the bluff body as a wave guide for ultrasonic waves. If the waveguide is immersed in a fluid the density of the fluid will affect the behaviour of the ultrasonic torsional signal in the waveguide. The changes of the signal is then proportional to the density of the fluid. The best shape of the waveguide is a diamond shape, but the bluff-polygon also gives a good result [1].

### 2.2 Other flowmeters

#### 2.2.1 Ultrasonic flowmeters

Ultrasound is sound waves with frequencies greater than the audible range, from 20kHz and upwards. Sound waves needs a medium to be able to travel and the medium also modifies the sound wave in different ways. These modifications can be either time-shift or frequency-shift of the signal, and they are used to determine different properties of the fluid.
Doppler flowmeters are frequency-shift flowmeters. The received frequency of the sound is different from the transmitted one due to the Doppler-effect. The Doppler-effect is that a sound beam that is reflected against a traveling source alters its frequency depending on the speed of the source. The fluid needs to contain particles or air bubbles to be able to reflect the ultrasonic sound. Doppler flowmeters have accuracy down to $\pm 1\%$ [9].

Time-shift flowmeters are transit-time or sing-around types where the velocity of the ultrasound depends on the velocity in the flow and whether the ultrasound is traveling upstream or downstream. The flow velocity is

$$v = \frac{kL}{2} \left( \frac{1}{t_1} - \frac{1}{t_2} \right)$$

(2.3)

where $k$ is a calibration factor, $L$ is the length between the sensors, $t_1$ is the time for an upstream traveling beam and $t_2$ is the time for a downstream traveling beam. The best transit-time flowmeters have an accuracy of about $\pm 0.5\%$ [10].

The difference between transit-time and sing-around

The main difference between the transit-time and sing-around ultrasonic techniques are the way the transit-times are collected. In the transit-time case the upstream time is measured once, and then the downstream time is measured. After that the velocity is calculated before the next pair of transit-times are sampled. In the sing-around case there are a number of upstream times measured to get an averaged $t_1$, and then an equal number of downstream times are measured to get an averaged $t_2$. This gives a lower sampling rate but also a measured flow velocity that is less sensitive to minor variations in the flow velocity.

2.2.2 Thermal mass flowmeter

There are different ways to use thermal conditions to measure the mass flow rate. One way is to measure the temperature in two places in the fluid. Between these two points a heater is heating the flow with a known amount of heat. The difference between the two temperature sensors give rise to a differential voltage which is proportional to the mass flow rate.

Another way to measure the mass flow with temperature is to keep a known heat profile in the flow through the sensor. The mass flow is then proportional to the voltage needed to keep that heat profile constant.

The mass flow rate is dependent on the heat transfer properties of the fluid. If the fluid in the flow changes some corrections in the meter is also needed.

Thermal mass flowmeters have accuracies similar to the vortex mass flowmeter, down to accuracies around $\pm 1\%$ [11].
2.2.3 Coriolis mass flowmeter

By leading a flow into a oscillating u-shaped pipe the flow will make the u-shape twist slightly and give a phase shift between inlet and outlet. This phase shift will render the mass flow.

Coriolis flowmeters have accuracy down to $\pm 0.35\%$ [12]. However, coriolis flowmeters aren’t suitable for all flows. They give a pressure drop in the flow, which is inadvantegeous in some flows. It also needs to bend the flow path, which can be bad in small areas, and the flowmeter is an intrusion in the flowpath. If anything fails the flow has to be shut down before the flowmeter can be removed, while an ultrasonic clamp on flowmeter can be removed without any intrusion to the flow.

2.3 Conclusion

The conclusion that can be drawn from this chapter is that most of the gas flowmeters on the market have accuracies around $\pm 1\%$ except for the coriolis mass flowmeter which has considerably better accuracy. There are pros and cons with all of the different flow measurement techniques. Which is chosen depends more on personal preferences and the application than anything else. The pros with a vortex flowmeters are that many people are already used to the vortex shedding technique. By using the ultrasonic sing-around flow technique better accuracy might be achieved. Let’s start looking on how to design the flowmeter by using computer simulations of fluid flows through a vortex flowmeter.
Chapter 3

Simulations

Prior to the design of a new flowmeter, we must gain an understanding of how the flow velocity profile looks is needed. The simulated signal is also needed later to be able to test the signal processing MATLAB code. Flow simulations in FEMLAB are used to simulate the flow and get the flow velocity. The flow velocity is exported to MATLAB and used as a simulated measurement signal in the signal processing of chapter 4.

3.1 FEMLAB simulations

Comsol Multiphysics, better known as FEMLAB, is a program that helps in simulation of a multitude of physical problems. It uses the finite element method to approximate the solution of complex differential equations. The finite element method takes the surface over which the solution is wanted and divides it into small surfaces, a grid. In all the small surfaces the differential equation can be linearized and the boundary conditions from one surface is used as boundary to the next surface. In this way an approximate solution for the entire surface can be calculated.

The first step in simulating the flow in FEMLAB is to make a geometrical model of the pipe. Since the vortex flow is mostly a two-dimensional phenomena, [6], the geometric model will be made in two dimensions to keep the simulation time down. When the geometric model is finished, it is time to set the boundary and surface conditions. One of the boundaries is set as inflow with a fully developed velocity profile, and another as outflow. All other boundaries has “no slip”, which means that they are walls. For the surface conditions the Navier-Stokes equation is used, where the fluid density and dynamic viscosity are set as constants.
Navier-Stokes equation on general form:

\[
\rho \frac{\partial \mathbf{u}}{\partial t} - \nabla \cdot [-p \mathbf{I} + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \mathbf{F},
\]

(3.1)

\[
\nabla \cdot \mathbf{u} = 0
\]

(3.2)

where \( \mathbf{u} \) is the velocity field, \( p \) is the pressure and \( \mathbf{F} \) is the forces acting on the flow, such as gravity.

Using the viscosity, \( \eta \), and density, \( \rho \), of air together with the dimension on the pipe which will be used in the experimental setting causes a convergence error in the numerical calculations performed by FEMLAB. To be able to perform the calculation a dimensionless number will be used, instead of using the viscosity, pipe dimensions and density of the experimental setup the equivalent Reynolds number will be used. Two fluid flows will be considered equal, for simulation purposes, if their Reynolds number is equal [13].

To be able to do the simulation without the convergence error Navier-Stokes equation will be made dimensionless as follows.

\[
\frac{\partial \mathbf{u}^*}{\partial t^*} - \nabla \cdot \left( \frac{1}{Re} (\nabla \mathbf{u}^* + (\nabla \mathbf{u}^*)^T) \right) + (\mathbf{u}^* \cdot \nabla) \mathbf{u}^* + \nabla p^* = \mathbf{F}^*
\]

(3.3)

\[
\nabla \cdot \mathbf{u}^* = 0
\]

(3.4)

Where \( \mathbf{u}^* = \frac{\mathbf{u}}{U}, t^* = \frac{t}{L}, Re = \frac{UL_p}{\eta}, p^* = \frac{p}{\rho U^2} \) and \( \mathbf{F}^* = \frac{L}{\rho U^2} \).

### 3.2 Flow velocity simulation

The flow around a bluff body in a pipe has been simulated in FEMLAB as described in section 3.1. The flow simulation actually gives the point velocity at every point in the flow at every simulated time instant. Each of these point velocities has a component in the x-direction and one component in the y-direction. The summation of point velocities in the x-direction along a line in the flow gives a one-dimensional approximation of the mean flow velocity between the ultrasonic sensors. The red line in fig. 3.1 parallel to the flow is divided in two hundred points. At each time instant the velocity at each of the two hundred point is summed and divided by 200 to give a mean velocity at that time instant. The mean velocities are combined to give a time-dependent signal.

The simulations were done with two different sampling rates. First with 5 ms spacing to give a sampling frequency of 200Hz, and then with 200\( \mu \)s, which gives a sampling frequency of 5000Hz. The first frequency was chosen because it was the
maximum sampling frequency of the velocity that the state of the art sing-around flowmeter from D-flow could do at the moment of this project start. The greater frequency was used to give a more exact simulation of the ultrasonic signal, which takes about 200µs to travel between the two transducers.

Figure 3.1: Flow velocity simulated in FEMLAB.

Figure 3.2 shows some simulated velocities sampled with 200Hz. As can be seen there are fluctuations around a mean velocity in all of the simulation. These fluctuation should be representing the vortex frequency, and the next chapter is about different ways to examine the signal to get the frequency.

3.3 Simulations of ultrasonic signals

The ultrasonic signals are not simulated directly since the signal that is going to be used is the velocity measured by the flowmeter rather than the ultrasonic signal itself. The velocity is simulated with a sampling rate of 5000Hz since it takes approx 200 µsec for an ultrasonic burst to travel from one of the transducers to the next.

The big difference between sing-around and transit-time is the number of measurements that are used for each calculation of the velocity. Transit-time does only
measure once upstream and then once downstream and weighs the two together to get a velocity sample. Ideally the velocity can then be sampled at approx. 2500Hz. The sing-around uses more ultrasonic measurements to calculate the velocity. The velocity is then an average of the measurements over time and is thus less sensitive to occasional erroneous measurements. This is almost always a good thing, but when it comes to vortex shedding it can remove the fluctuation in the signal that is to be used to detect the vortex frequency. In figure 3.3 the difference between sing-around (fig. 3.3(a)) and transit-time (fig. 3.3(b)) can be seen. There is a lot more fluctuation in the transit-time case and it has a bigger amplitude. With sing-around, the small amplitude of what is supposed to be the vortices can make it hard to discover the vortex frequency correctly since some of the vortices can be mistaken for noise.

3.4 Differences between simulations and real world

The big difference between the simulations and the real world is that the real world is in 3D. Since the vortex shedding is a mostly 2D-phenomena this is normally not a big problem. In this case however, the ultrasonic transducers are placed in the middle of the flow, embedded in the vortex shedder. The need to simulate the full
model in 3D is quite large because of the placement of the sensors, but it takes a lot of computer power and time so it is not feasible in this case. The transducer might be hidden behind the vortex shedder, but it may also introduce some errors to the measurement.

Another thing that is not accounted for in this model is that the ultrasonic transducers are piezoelectric sensor which are sensitive to pressure changes. This means that both the pressure changes from the flow and the pressure changes from the ultrasonic waves will have to be accounted for. The model described in the previous paragraph is not really valid for a ultrasonic signal since it only shows the velocity profile in the flow. It is also averaged in time, the approximation that both an upstream burst of sound and a downstream one has the same time-of-flight is the opposite to the real world where it is the difference between those two time-of-flights that is the wanted signal.
Chapter 4

Signal analysis

When the flow velocity has been simulated it is time to analyze the result. Since the wanted data is the vortex frequency it seems like a good idea to analyze the frequency spectrum of the signal, but first another method will be tried, the zero-crossing method.

4.1 Zero crossing algorithm

The idea behind this algorithm is that it should be possible to describe the velocity signal as a sinusoid [14]. If the mean of the signal is removed the sinusoidal will oscillate around zero, going from positive to negative once each period. If each such passage from positive to negative is counted then the frequency will be equal to the number of passages during one second.

The resulting frequencies from the flow simulations calculated in this way can be seen in table 4.1. The wanted result would be something like the plot in figure 2.2, that the frequency is linearly proportional to the velocity. The simulated velocities does not show any kind of linearity. However, the number of simulated velocities are quite a few and some more might be needed to draw any certain conclusions.

4.2 Frequency spectrum analysis

One common way to find the frequency content in a sampled signal is by the discrete Fourier Transform, DFT. With the Fourier Transform every signal can be written as a sum of sinusoids, and the DFT is the discrete counterpart to the Fourier transform.
Table 4.1: The frequencies from the simulated signals, calculated with the zero-crossing method.

<table>
<thead>
<tr>
<th>Simulated velocity, m/s</th>
<th>Frequency from zero-crossing, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>12</td>
<td>83</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
</tr>
</tbody>
</table>

\[ X(\mu) = \frac{1}{N} \sum_{n=0}^{N-1} x(n)W^{-\mu n}, \mu \in \mathbb{Z}, W = e^{2\pi i/N} \quad (4.1) \]

where \( X_\mu \) is the discrete Fourier transform and \( x(n) \) is the sampled signal.

The discrete Fourier transform tells how much there is of each frequency between \( f = 1 \) and \( f = \mu/2 \). The upper limit \( \mu/2 \) is because the fact that the Fourier transform is symmetric. By taking the absolute value of the DFT a magnitude plot can be made to show the frequency content of the signal. To enhance the peaks of the DFT a power spectral density (PSD) can be made. This is easily and most commonly made by squaring the magnitude of the DFT.

\[ S_f(\mu) = |(X(\mu))|^2 \quad (4.2) \]

where \( S_f \) is the PSD and \( X(\mu) \) is the DFT.

4.3 Analysis of simulated velocities

The simulated velocities were analyzed with the built-in FFT-function\(^1\) in Matlab and then the PSD was calculated as described in previous section. It showed quite soon that the offset of the velocity caused some problem since it was considerably larger than the oscillation caused by the vortices. The offset gives a maximum of the PSD at 1Hz for all velocities. This shows quite well by comparing the two figures 4.1(a) and 4.1(b) where two PSDs has been done on the same signal. First the PSD was made on the signal with the offset still there (fig. 4.1(a)), then the offset is removed by subtracting the mean of the signal from the signal and then the resulting PSD is in fig. 4.1(b). In all the following signals the offset has been removed before the DFT was calculated.

\(^1\)The fast Fourier transform, FFT, is an effective algorithm used to calculate the DFT in computers
The PSD has been calculated on different velocities, both those that have been simulated with transit-time simulation and those simulated with sing-around simulation. The transit-time simulated signal is sampled with 2500Hz and thus the PSD has frequencies up to 1250Hz, while the PSD of the sing-around signal, sampled with 200Hz, only has frequencies up to 100Hz. In the transit time PSD:s there is quite clear peaks at two different frequencies, shown in tab. 4.2. This shows that there is some connection between the velocity and the frequency, double the velocity gives an almost doubled frequency. Since almost all of these frequencies are above 100Hz, they do not show up in the sing-around. A typical case can be seen in fig. 4.2 where the PSD:s for the simulated velocity 10m/s is shown. This leads to the conclusion that since the sing-around does not have that fast sampling rate the vortex phenomena will not show on the PSD. To be able to see the vortices on a PSD with sing-around technique the sampling frequency must be at least twice the greatest vortex frequency expected in the flow.
Figure 4.2: The PSD:s for the simulated velocity of 10m/s
Chapter 5

Measurements

5.1 The experimental setup

The tests will be performed in the water laboratory at LTU. The flowmeter, that is described in the next section, will be installed in an air flow system as shown in fig. 5.1. Water will be pumped from one tank to another. When the water is leaving the first tank air will be drought into it and generating an air flow, which will be measured. The reference flow rate will be calculated from the weight of the water that is in the second tank after the run is finished. It will only be possible to make measurements of one flow velocity at a time.

5.1.1 The flow meter construction

The flowmeter consists of a pipe that is 51mm in inner diameter at the inlet and then narrowed down to 31mm between the sensors, see fig. 5.3. The plan was to do the measurement with a straight pipe that made of plexiglas to be able to visualize the flow if needed, but it turned out to be too short to get a good ultrasonic signal. Instead an aluminum pipe is used. In each end of the pipe is an ultrasonic sensor and to one of the sensors a bluff body is attached. The sensors and bluff body will be further described in the following sections. Figure 5.2 shows some photos of the flow meter.

5.1.2 The bluff body

Lynnworth et. al have made computational fluid dynamic predictions to conclude that an elongated bluff body has the most constant Strouhal number over a wide range of Reynolds numbers compared to other shapes of bluff body [1]. This kind of bluff body is also suitable to use as an ultrasonic density meter to make a complete mass flow meter system as described in section 2.1.5. The bluff body
5.1.3 Ultrasonic sensors and electronics

The ultrasonic sensors that are used are two sensors from D-flow Technology AB. The sensors are placed in the middle of the flow and thus the flow is measured along an axial path. The electronics connected to the sensor are also from D-flow and measures the transit time with sing-around technique. The reason to why the transit time is measured instead of the velocity is that it increases the sampling frequency, which will now be 324Hz and should be sufficient to detect the vortices. Normally the velocity is calculated from the transit time so when the calculation of the velocity is removed the time between each transit time is shorted and thus the sampling frequency is higher. Hopefully the vortex frequency is visible even if the measured quantity is the transit time instead of the velocity.
5.1.4 Measured velocities

The velocities that are measured and the expected vortex frequencies are listed in table 5.1. The maximum velocity that can be measured in the lab is 12.5 m/s thereby setting the upper limit.

Each velocity will be measured 6 times and each measurement will last 35 seconds.

5.2 Measurement results

Fig. 5.4 shows segments of the measurements for different velocities. Each segment is two seconds long. It seems that for velocities higher than 5 m/s the frequency
Figure 5.3: 2D FEMLAB model of pipe used in measurements.

Table 5.1: Velocities to measure. The expected frequency is calculated from eq. 2.1 with a Strouhal number of 0.2.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Pipe Reynolds number ($Re_{pipe}$)</th>
<th>Expected vortex frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1935</td>
<td>10</td>
</tr>
<tr>
<td>2.5</td>
<td>9678</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>19355</td>
<td>50</td>
</tr>
<tr>
<td>7.5</td>
<td>29035</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>38715</td>
<td>100</td>
</tr>
<tr>
<td>12.5</td>
<td>48390</td>
<td>125</td>
</tr>
</tbody>
</table>
in the signal is not getting any higher. But instead some of the peaks are much larger than the average signal, just a few for the lower velocity, and then there are more large peaks in the higher velocities.

Fig. 5.5 shows the entire measurement for some signals. Here it is clear that the larger the velocity, the higher number of large peaks.

There are three different ways of finding the flow velocity that will be tested on the measurement data. The first one is by finding the mean value of the measured signal. This method is tested to see if it is possible to see the correct flow velocity directly instead of measure the vortex frequency and calculate the velocity from that. The second, zero-crossing algorithm, and third, fast Fourier transform, are both trying to find the vortex frequency and then calculate the velocity from that.

5.3 Zero crossing algorithm applied to measured values

The zero crossing algorithm described in sec. 4.1 is applied to one-second long chunks of the measured signal. For each measurement there are 35 calculated frequencies, one for each second. The mean of these 35 frequencies is taken as the measured frequency. The measured frequencies can be seen in fig 5.6. It seems as if there is some common frequency for the lower velocities, but when the velocity is raised the frequency does not follow in the same way. This is most likely because of the fact that the frequency of the measured signal is not raised, as stated in section 5.2. However, for the lower velocities the measured frequency is closed to the expected one.

5.4 Spectrum analysis of measured values

When doing a FFT in MATLAB it is done with a N-point window. The best way to do this is to choose N equal the sampling frequency. Choosing a smaller window gives a spectrum that has a maximum at \( f = 0 \) Hz and then is rapidly decreasing as the frequency is increasing. Choosing a bigger window gives aliasing effects which is not desired in this case. Since the sampling frequency in this case is 324, N is chosen to be 324.

To be able to do a 324-point FFT on the entire measured signal it has to be divided into 324 samples long sections. A FFT is performed on the section, and then the PSD is calculated from that as described in sec. 4.3. The mean of the PSDs for all the section are then used as the frequency spectrum for that specific measurement. Fig. 5.7 shows typical spectra for each of the seven different flow velocities. These signals are unfiltered, the only thing that has been done to
them is that the larger peaks (see fig. 5.5) has been removed. It looks as if the spectra consist of many different frequencies, and just taking the frequency with the maximum amplitude does not give the correct vortex frequency.

Filtering the signal with Butterworth-filters does not give that much better result. What this filter is actually doing is that it removes the low-frequency components (high-pass) or high-frequency components (low-pass). In the measured signal the wanted frequencies differs from 10 to 125 depending on which velocity that is measured. The fact that the signal is sampled with 324Hz gives that the measured frequency can be maximum 162Hz to avoid aliasing effect. That does not leave many frequencies left to filter out with a lowpass filter, and there is not much gained by filter out the very lowest frequency components either. Fig. 5.8 shows the difference between an unfiltered signal and a signal that is filtered with a 10th order Butterworth-filter with cutoff-frequency at 130Hz. The only difference is that this frequencies above 130Hz is almost minimized.

5.5 Conclusion

Three different signal processing algorithms are evaluated in this chapter. First the mean-value algorithm which gave a linear relation between transit-time and the real velocity. This method is however not that very accurate but shows on the advantage of sing-around technique to be able to remove small variations in the signal.

The second algorithm that is tested is the zero-crossing algorithm. This algorithm gives good results for the lower velocities, but not that good result for the higher velocities.

The final algorithm is the fast Fourier transform. It seems that it is hard to find the correct vortex frequency with this method.

In the next chapter there will be a more thorough analysis of the results, and also some comparison with the theoretical results.
Figure 5.4: The measured transit times, plotted during two seconds.
Figure 5.5: The measured transit times for the highest velocities
Figure 5.6: Velocities from measurement. The frequency has been calculated with zero crossing and then multiplied with a constant which is $d/St$, bluff body diameter over the Strouhal number, according to eq. 2.1.
Figure 5.7: Segment averaged Fast Fourier Transform of different measured velocities
Figure 5.8: Comparison of Fourier spectra for the same signal, filtered and unfiltered. The expected frequency is approx $57\text{Hz}$.
Chapter 6

Conclusion

It was seen in chapter four that it can be hard to detect the vortex frequency with sing-around ultrasonic systems because of the low sampling frequency. The measured signal does however show that it might be possible to find the correct frequency, and thus the correct velocity, at least for lower velocities with the zero-crossing algorithm.

The Fourier transform of the simulated signal vs. the measured one gives similar results. Both PSDs have a lot of frequencies, and no really distinct peak that clearly states the vortex frequency. The PSDs in the measured case are different for the different velocities so it might be possible to find the correct vortex frequency with extensive signal processing. One idea to be tried in future work is to bandpass-filter the signal in very short frequency intervals and then search for the vortex frequency in those filtered signals. This might imply that one must know approximately the flow velocities and thus the turn-down ratio will be small.

The biggest reasons for the discrepancy between the theoretical model and the measurement are the differences in geometry and the fact that the ultrasonic signal was not included in the model. In the theoretical model the pipe was modeled as a straight pipe, while in reality the meter body was narrower than the pipe upstream and downstream of the meter. This makes the vortices be more concentrated to the middle of the pipe where the ultrasonic signal is. In the theoretical model the ultrasonic signal is omitted since the measured signal is the velocity, as declared in section 3.4. The biggest down-side of the approach taken is this model is that the ultrasonic beam is assumed to travel between the sensors in no time instead of the 200 µs that it is actually traveling. This gives some error to the theoretical model. In future models the transit time between the sensors should be considered in one way or the other.

The final conclusion of this thesis is that the theoretical model in this work is not that very good and that the vortex frequency might be detected with better signal processing.
Appendix A

About the Strouhal and Reynolds numbers

A.1 The Strouhal number

The Strouhal number is a dimensionless number that is used as a constant for calculation of the velocity from vortex frequency. It is named after the Czech physicist Vincenc Strouhal. The number is constant for a large range of Reynolds numbers. The value varies for different shapes of the bluff body, but in simulations a value of 0.2 can be used since its range is between approximately 0.15 and 0.23 for different bluff bodies [15].

A.2 Reynolds number

Reynolds number is a dimensionless number which describes the ratio between inertial and viscous forces in a fluid as

\[ Re = \frac{\rho v d}{\eta} \] (A.1)

where \( \rho \) is the fluid density, \( v \) the velocity, \( d \) the characteristic dimension of pipe and \( \eta \) the dynamic viscosity. It is named after professor Osborne Reynolds.
Bibliography


