BACHELOR

Towing a body through a fluid

Meesen, A.R.G.

Award date:
2012

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Towing a body through a fluid

A.R.G. Meesen

November 2012
R-1813-S
Abstract

At InnoSportLab in 'De Tongelreep' research is done on the swimmers of the Dutch national team. The setup that will be important for this project is the towing system. It can pull swimmers through the water while measuring the force needed. In this project research has been done on the force fluctuations on the swimmer.

First, a well characterized experiment in the water channel at TU/e has been done on a well documented object: a sphere. It is known that the drag coefficient of a static sphere in a uniform flow is 0.47. The measured drag coefficient in this experiment is 0.9. This difference might be explained because here measurements were done on a tethered sphere and the value of 0.47 comes from a static sphere.

At Reynolds numbers from $2 \cdot 10^4$ two Strouhal numbers are expected. A low one at 0.2 because of vortex shedding and a higher one around 3 because of instability of the boundary layer. The lower Strouhal number can indeed be identified from the spectra of the ball, the higher one can not. There are other frequencies in the spectrum, but it is not sure where these come from. They are not high enough to be associated with the high Strouhal number or with the eigenfrequency of the system.

At De Tongelreep experiments have been done at speeds of 1.3 m/s and 2.6 m/s. At these speeds the drag is expected to be respectively 24 N and 95 N. The drag coefficient is expected to lie between 0.25 and 0.28 for a towing speed of 1.3 m/s and between 0.32 and 0.39 for 2.6 m/s. The calculated drag coefficient is 0.21 at 1.3 m/s and 0.39 at 2.6 m/s. At 1.3 m/s this is slightly lower than the expected value and for 2.6 m/s it’s quite high. Because only two or three measurements at each speed were performed, it’s hard to say if these values are reliable.

The frequencies calculated from wavelet transforms are around 0.2 Hz for 1.3 m/s and around 0.4 Hz for 2.6 m/s. When it is assumed that these frequencies are the result of vortex shedding and that the Strouhal number is 0.2 too, the corresponding length scale is 1.3 m. From this it can’t be excluded that vortex shedding plays a role. There are other frequencies visible, but the origin is unknown.
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Chapter 1

Introduction

Because I am addicted to swimming since I was four years old, it’s a logical choice that my bachelor thesis should have something to do with that. At InnoSportLab in ‘De Tongelreep’ research is done on the swimmers of the Dutch national team. All kinds of research is performed here, for example registering 3D-images of swimmers to predict shoulder injuries. However, the setup that will be important for my project is the towing system. It can pull swimmers through the water while measuring the force needed. It is now used to measure the drag of swimmers and swimwear. It turns out that the force is always fluctuating and that very little is known about that. So this will be the topic of my research. I will try to find out what the origin and nature of these fluctuations is.

The closest physicist’s abstraction of a swimmer is a sphere. So first a well characterized experiment in the water channel at TU/e will be done with a sphere. The experiment will be somewhat different from the towing system at De Tongelreep, because the sphere will be more or less static in the water channel and the water will flow around it instead of the other way around. The sphere will not be totally static, but that will be explained in section 3.

It is known that the forces on a fixed sphere in a uniform flow will not be constant. This is because the sphere will shed vortices in its wake\cite{1} and because the boundary layer can become unstable. At Reynolds numbers from $2 \cdot 10^4$ the Strouhal number reaches a constant value of 0.19. There is also a higher Strouhal number which lies between 3 and 4. From this the shedding frequency of the vortices is expected to lie between 0.3 Hz and 0.6 Hz for the low Strouhal number and between 5 Hz and 11 Hz for the high Strouhal number. In this experiment the Reynolds number will lie between $2 \cdot 10^4$ and $3 \cdot 10^4$. In this region the drag coefficient of a fixed sphere in a uniform flow based on frontal area is 0.47\cite{2}.

Some research has already been done on towed swimmers. According to Vennel\cite{3}, the drag of a totally immersed towed swimmer satisfies $D = 14V^2$. So at towing speeds of 1.3 m/s and 2.6 m/s the drag is expected to be respectively 24 N and 95 N. In this article it can also be seen that the drag coefficient at 1.3 m/s should be around 0.27 and at 2.6 m/s around 0.33. To be able to calculate the drag coefficient, the projected frontal area of the swimmer is needed. From article \cite{4} this is estimated to be 0.14 m².

In the water channel and at De Tongelreep experiments will be done at different flow and towing speeds and with different spring constants in the water channel. This way it can be examined if the flow or towing speed influences the fluctuations. The different speeds will also
be used to calculate the drag coefficient of the sphere and the swimmer. The setups used have their own mechanics and of course an eigenfrequency. For the setup in the water channel this eigenfrequency can be calculated and by using different spring constants it can be investigated if a certain outcome is the result of the movement of the ball or of the internal mechanics of the system. For the towing system in De Tongelreep the eigenfrequency is unknown and can’t be changed.
Chapter 2

Theory

In this chapter the theory relevant for the project will be discussed. The basics of fluid dynamics are assumed to be known by the reader. For those who are not familiar with fluid dynamics, the theory is included in appendix A.

2.1 Shedding frequency

Sakamoto did research on the shedding frequency of vortices from a sphere. In figure it can be seen that the shedding frequency depends on the Reynolds number and that two frequencies can coexist. The low Strouhal number is associated with the periodic shedding of vortices, the high Strouhal number with the instability of the boundary layer.

![Figure 2.1: Strouhal number as a function of Reynolds number.](image-url)
2.2 Added mass

When a body moves through a fluid, the fluid will move around the object. When the body accelerates, the fluid must accelerate too. Thus, accelerating a body in a fluid involves three forces. Drag, the force to accelerate the body forward and an additional force to accelerate the fluid backwards. Since force equals mass times acceleration, the additional force can be thought of as an imaginary added mass of the body.

\[
F = \frac{1}{2} C_D \rho AV^2 + ma + C_a \rho Va
\] (2.1)

The first term on the right side of equation (2.1) represents drag. How much mass must be added depends on the volume and shape of the body. The shape-dependent part is expressed as the added mass coefficient, \( C_a \). The mass of the body plus the added mass \((m + C_a \rho V)\) is often called the virtual mass.

The added mass of a sphere can be calculated when the flow is a potential flow, then it is \( M_a = \frac{2}{3} \pi R^3 \rho \). So a sphere of one kilogram in water will have an added mass of approximately half a kilogram and the virtual mass will be 1.5 kilogram. Not much research has been done on added mass in flows with high Reynolds numbers where it’s no longer a potential flow. However, a recent study\(^5\) shows that for different sized balls in air, the added mass is not dependent on Reynolds number.

2.3 Drag on a swimmer

Research has been done on the drag on human swimmers\(^3\). To investigate this, they pulled a mannequin through the pool at different depths. From this research the graph in figure 2.2 resulted. It is clear that for a swimmer towed near the surface the drag is much higher than when he is totally immersed. This is the result of wave drag experienced at the surface. From the graph it can be seen that for a swimmer totally immersed, the drag is expected to meet the formula \( D = 14V^2 \). 
CHAPTER 2. THEORY

2.3. DRAG ON A SWIMMER

Figure 2.2: Fit of the drag of a swimmer as a function of towing speed. The ‘+’ and solid curve is the total drag averaged over tows at 0.2-0.0 m deep. The ‘x’ and solid curve is the total drag averaged over tows at 1.0-0.8 m deep. The dots and chain dashed line are for the intermediate depths.

The drag coefficient (based on frontal area) has also been determined in this article, a graph can be seen in figure 2.3. Again, it is clear that the drag coefficient is much higher when the swimmer is closer to the surface, due to wave drag.

Figure 2.3: Drag coefficient, based on frontal area, versus velocity.
2.4 Wavelet transformation

A wavelet transformation can be a better way to analyze the spectrum than the well known Fourier transform. With Fourier analysis there is a trade off in the choice of window size. A longer time window improves frequency resolution, but it results in a poorer time resolution. On the other hand, a shorter time window improves time localization, but this gives a poorer frequency resolution. Wavelet analysis uses long time intervals when low frequencies need to be analyzed and shorter regions when high frequencies are involved.

In the continuous wavelet transform (CWT), the analyzing function is a wavelet. Here the Morlet wavelet is used. The CWT compares the signal to shifted and compressed (or stretched) versions of the wavelet. By comparing the signal to the wavelet at various scales and positions, a function of two variables is obtained. For a scale parameter $a > 0$, and position parameter $b$, the CWT is:

$$C(a, b, f(t), \psi(t)) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \psi^*\left(\frac{t - b}{a}\right) dt$$

(2.2)

By continuously varying the values of $a$ and $b$, the CWT coefficients $C(a, b)$ are obtained. The higher the coefficient $C$ belonging to a certain scale and position is, the more the analyzed function resembles the wavelet at that point. For example, a high coefficient at scale 3 and position 30 means that at $t = 30$ s, the analyzed function resembles the wavelet with scale 3. This scale corresponds to a certain frequency, so now it is known which frequency is present at $t = 30$ s.

The wavelet transform can be plotted, time on the horizontal axis, the scales on the vertical axis and the coefficients displayed as a color scale in this coordinate system. In section 4.1.3 an example can be seen, a red color means a great resemblance to the wavelet at that point. So when a lot of red dots are seen at a certain scale it means that this frequency is present throughout the whole measurement. When a red dot is only visible at a certain time, it means that this frequency was only present for a short amount of time.
Chapter 3

Experimental setup

During this project two experiments have been performed, these will be discussed in the present chapter. One experiment was done in the water channel at the TU/e and the other at De Tongelreep. In both experiments a basic understanding of the force fluctuations is wanted. Therefore the frequency of these fluctuations is identified. It will also be checked if the measured drag and drag coefficients are consistent with literature.

The Reynolds numbers lie in the region $10^4$ to $3 \cdot 10^4$ for the experiments in the water channel. For the experiments in De Tongelreep they lie between $0.5 \cdot 10^6$ and $1.3 \cdot 10^6$. It is not possible to get these numbers to coincide, because the flow speed of the water channel and the diameter of the ball can’t be increased further.

3.1 Towing system

At InnoSportLab measurements have been performed on a towing system. An object or person can be towed through the swimming pool at a set speed while measuring the force exerted on the swimmer.

In this experiment a swimmer is pulled at 1.3 m/s and 2.6 m/s. Obviously the length of the measurements is limited, because after a while the edge of the swimming pool is reached. At 1.3 m/s the measurements are about 25 seconds long and at 2.6 m/s only about 15 seconds.

3.1.1 Drag coefficient

The drag is equal to the mean force on the swimmer, which can be measured. The drag should correspond to the formula mentioned in chapter 2.3, $14V^2$. The drag coefficient can be deduced from the drag according to this formula: $C_D = \frac{F_D}{\frac{1}{2} \rho AV^2}$, in which $F_D$ is the drag, $\rho$ is the density of the fluid, $A$ is the frontal area of the swimmer and $V$ is the towing speed. In this experiment $\rho = 998$ kg/m$^3$ and $A = 0.14$ m$^2$, estimated from the article by P. Zamparo[4].

For a velocity of 1.3 m/s the drag is expected to be 24 N and the drag coefficient between 0.25 and 0.28, for 2.6 m/s the drag is expected to be 95 N and the drag coefficient between 0.32 and 0.39, see figure 2.3.
3.1.2 Frequencies

The ultimate goal of these force measurements is to understand more about the force fluctuations on the swimmer. Therefore the frequencies of these fluctuations are calculated. It is unknown what to expect of this, because no research has been done yet on this topic. It could be that vortex shedding plays a role here, just as with a sphere in a uniform flow. One can then assume that the Strouhal number is also the same, namely 0.2. This way the corresponding length scale can be calculated using the definition of the Strouhal number: \( L = \frac{SrV}{f} \), in which \( V \) is the towing speed and \( f \) is the measured frequency.

3.2 Water channel

The experimental setup used in the water channel can be seen in figure 3.1. A neutrally buoyant sphere is used with a diameter of 10 cm and a mass of 0.52 kg. It is placed in the water channel and attached to a bar using a thin line. When the ball pulls on the string, due to the water flow, the bar will bend. To measure how much it bends, a mirror is attached to it. A laser beam is pointed at the mirror and reflects onto a sensor. The sensor measures the place of the laser spot, which corresponds to the bending of the bar.

Figure 3.1: Schematic display of the experimental setup in the water channel.

3.2.1 Spring constant and added mass

The setup used here has its own internal mechanics and could influence the measurements. The setup is a spring-mass system, so the formula \( F = k(x - x_0) \) holds, with \( k \) the spring constant and \( x_0 \) the equilibrium position. A spring-mass system obviously has an eigenfrequency, depending on the mass and the spring constant. To determine if an outcome is the
result of the movement of the ball or of the internal mechanics of the system, two spring constants will be used. The spring constant of the bar can be changed by clamping it at a different point, one will be referred to as the ‘long’ bar and one as the ‘short’ bar.

The spring constant can be calculated when the deflection of the bar is known as a function of the force acting on the bar. This is measured for both the long and short bar and plotted in figure 3.2. The spring constant of the long bar is 50 N/m and for the short bar it is 201 N/m.

![Figure 3.2: Graph of the deflection of the long bar (left) and the short bar (right) as a function of force, including a fit through the points.](image)

The mass of the mirror and the bar is easily determined, it is 0.2 kg. The mass of the ball is harder to define. Because the ball is accelerating and decelerating the whole time, added mass may play a big role here, but no research has been done on the topic of added mass in an oscillating system. Because the only study found on this topic is [5], it will be assumed that the added mass is \( M_a = \frac{2}{3} \pi R^3 \rho \), as described in section 2.2. The total mass of this system will then be \( M = 0.2 + 0.52 + 0.26 = 0.98 \) kg.

Now the eigenfrequencies of the bars can be calculated using \( \omega = \sqrt{\frac{k}{m}} \). So the eigenfrequency of the long bar is 1.1 Hz and that of the short bar 2.3 Hz.

### 3.2.2 Drag coefficient

The drag coefficient of the sphere can be calculated by measuring the drag, which is the mean force exerted on the ball, at different flow speeds. The drag coefficient can be found by plotting \( V^2 \) on the x-axis, \( \frac{F_D}{\frac{1}{2} \rho A} \) on the y-axis and calculating the slope of the graph. According to Vogel [2], the drag coefficient of a sphere based on frontal area at Reynolds numbers between \( 10^4 \) and \( 10^6 \) is 0.47.

### 3.2.3 Frequencies

The Fourier transform is applied to measurements of the force on the ball, so the spectrum can be generated. From this spectrum the frequency (or frequencies) of the force fluctuations
can be calculated.

The Reynolds numbers in this experiment lie in the region $10^4$ to $3 \cdot 10^4$. From figure 2.1 the low Strouhal number is expected to be approximately 0.2 and the corresponding shedding frequency lies between 0.3 Hz and 0.6 Hz. The high Strouhal number lies between 2 and 4 and the corresponding frequencies between 3 Hz and 11 Hz.

It is expected that two frequencies are visible in the spectrum, one between 0.3 and 0.6 Hz and one between 3 and 11 Hz. Another frequency that might be visible in the spectrum is the eigenfrequency of the system.
Chapter 4

Results

In this chapter the results from the experiments in the water channel and at InnoSportLab, explained in chapter 3, are shown.

4.1 Water channel

In this section the results from the sphere in the water channel will be presented. Measurements have been done at different speeds for both spring constants. A typical measurement of the movement of the ball can be seen in figures 4.1 and 4.2. It is clear that there is a mean force, a lot of fluctuations and a clear frequency of these fluctuations.
CHAPTER 4. RESULTS

4.1. WATER CHANNEL

Figure 4.1: Graph of the movement of the ball attached to the long bar at a flow speed of 0.28 m/s.

Figure 4.2: Graph of the movement of the ball attached to the short bar at a flow speed of 0.28 m/s.
4.1.1 Drag coefficient

In this experiment the force on the ball is measured for 5 minutes and then averaged to get the drag on the ball. This is repeated for different flow speeds. According to section 3.2.2 the drag force should be proportional to the square of the velocity. In figure 4.3 it can be seen that this is indeed the case. The slope of the two graphs in figure 4.3 represents the drag coefficient of the ball, this gives $C_D = 0.9$ for both the long and the short bar.

![Figure 4.3: Graph of the average force on the ball and the flow speed of the water channel.](image)

4.1.2 Frequencies

On the measurements of the force a Fourier transform is applied, so the different frequencies of the movement of the ball can be visualized. The frequencies are listed in tables 4.1 and 4.2 and an example of a Fourier transform can be seen in figure 4.4. The rest of the spectra can be found in appendix C.

For the long bar, a frequency between 0.38 and 0.65 can be found in every measurement. The Strouhal numbers of these frequencies are also listed in table 4.1. This is clearly the expected low Strouhal number of 0.2. For the short bar this Strouhal number can also be identified, now with a frequency between 0.41 and 0.68, these are listed in table 4.2. The low Strouhal number is also plotted as a function of velocity in figure 4.5.

The high Strouhal number is not visible in the measurements and neither is the eigenfrequency of the setup. When the calculation is reversed, the added mass can be calculated from the measured frequency. Then the added mass is around 1 kg for the long bar and around 3.3 for the short bar.
## 4.1. Water Channel

<table>
<thead>
<tr>
<th>Flow speed (m/s)</th>
<th>Frequency (Hz)</th>
<th>Frequency (Hz)</th>
<th>Frequency (Hz)</th>
<th>Strouhal number</th>
</tr>
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<tbody>
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<td>0.17</td>
<td>0.38</td>
<td>0.81</td>
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<td>0.20</td>
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<td>0.55</td>
<td>0.90</td>
<td></td>
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<td>0.28</td>
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<td></td>
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<td></td>
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<tr>
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<td>0.26</td>
<td>0.24</td>
<td>0.64</td>
<td>0.90</td>
<td>0.25</td>
</tr>
<tr>
<td>0.26</td>
<td>0.65</td>
<td>0.80</td>
<td></td>
<td>0.25</td>
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</tbody>
</table>

Table 4.1: Frequencies and Strouhal numbers calculated from the spectra of the long bar. The Strouhal number is calculated with the frequencies between 0.38 and 0.65 found in every measurement.

<table>
<thead>
<tr>
<th>Flow speed (m/s)</th>
<th>Frequency (Hz)</th>
<th>Frequency (Hz)</th>
<th>Frequency (Hz)</th>
<th>Strouhal number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>0.68</td>
<td>1.27</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>0.24</td>
<td>0.28</td>
<td>0.59</td>
<td>1.18</td>
<td>0.25</td>
</tr>
<tr>
<td>0.21</td>
<td>0.19</td>
<td>0.49</td>
<td>1.11</td>
<td>0.23</td>
</tr>
<tr>
<td>0.17</td>
<td>0.41</td>
<td>1.01</td>
<td></td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 4.2: Frequencies calculated from the spectra of the short bar. The Strouhal number is calculated with the frequencies between 0.41 and 0.68 found in every measurement.

![Figure 4.4: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.20 m/s. The frequencies indicated with a red line are 0.47 Hz and 0.89 Hz.](image-url)
CHAPTER 4. RESULTS

4.1. WATER CHANNEL

Figure 4.5: The calculated Strouhal number as a function of velocity for the long bar (red) and the short bar (blue).

4.1.3 Wavelet transform

To illustrate the wavelet transform explained in section 2.4, it is applied to a measurement of the ball (long bar, 0.20 m/s), the result can be seen in figure 4.6. The lower line in the graph corresponds to a frequency of 0.92 Hz, the higher line to 0.47 Hz. This is in good agreement with the frequencies found in section 4.1.2, namely 0.47 Hz and 0.89 Hz.

Figure 4.6: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.20 m/s. The lower line corresponds to a frequency of 0.47 Hz, the higher line to 0.92 Hz.
4.2 Towing system

Measurements have been done at a towing speed of 1.3 m/s (3 measurements) and on 2.6 m/s (2 measurements). The length of the towed swimmer is approximately 1.8 m. In graphs 4.7 and 4.8 a typical measurement can be seen. At the beginning the swimmers needs to adapt to the towing and is not yet horizontal. By the time the swimmer is adapted and horizontal, the end of the swimming pool is near end therefore the end of the measurement. In these figures it can be seen that only the last 5-10 seconds, and at 2.6 m/s even less, the force is more or less constant. This mean force at the end of the measurement can be associated with the drag on the swimmer. Just as with the sphere, fluctuations can be seen here and a frequency of these fluctuations, although the frequency is less clear here.

![Graph of force vs. time for towing system measurement](image)

Figure 4.7: Measurement of the force on a pulled swimmer at 1.3 m/s.
CHAPTER 4. RESULTS

4.2. TOWING SYSTEM

Figure 4.8: Measurement of the force on a pulled swimmer at 2.6 m/s.

4.2.1 Drag coefficient

To be able to check if equation $A.4$ holds in this experiment, the mean value of the force over the last part of each measurement is calculated, which represents the drag on the swimmer. The average drag calculated at 1.3 m/s is 25 N and 184 N at 2.6 m/s, the drag measured in individual measurements can be seen in table 4.3.

The velocity is doubled, so if drag is proportional to $U^2$ the force should be four times as large. It is clear that this is not the case here, the measured force at 2.6 m/s is much higher. Thus, the drag doesn’t meet the expected formula of $14V^2$ explained in section 2.3.

The drag coefficient can be calculated at both towing speeds, it is 0.21 at 1.3 m/s and 0.39 at 2.6 m/s, see table 4.3 for individual measurements. At 1.3 m/s this is slightly lower than the expected value (see section 3.1.1) and for 2.6 m/s it’s quite high.

<table>
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<th>Flow speed (m/s)</th>
<th>Drag (N)</th>
<th>Drag coefficient</th>
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<td>1.3</td>
<td>25.9</td>
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<td>1.3</td>
<td>23.6</td>
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<td>1.3</td>
<td>25.7</td>
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<tr>
<td>2.6</td>
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</tr>
<tr>
<td>2.6</td>
<td>180.7</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 4.3: Calculated drag and drag coefficient of measurements from De Tongelreep.
4.2.2 Wavelet transform

In this case a Fourier transform is of no use, because the fluctuations are very much dependent
of time. Therefore a wavelet transform is applied to the measurements done at De Tongelreep,
this way the time information isn’t lost. The transform is applied to the whole measurement
and to only the last ‘constant’ part of the measurement. The wavelet used is the Morlet
wavelet. An example of a wavelet transform on the end of the measurement can be seen in
figures 4.9 and 4.10. The frequencies visible in the transforms of the end of the measurements
are listed in table 4.4. The rest of the results can be found in appendix D.

Figure 4.9: Wavelet transform of the movement of the swimmer at a towing speed of 1.3 m/s.
The lowest line corresponds to a frequency of 0.87 Hz, the second line to 0.28 Hz and the
highest line to 0.16 Hz.

Figure 4.10: Wavelet transform of the movement of the swimmer at a towing speed of 2.6
m/s. The line corresponds to a frequency of 0.40 Hz.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Flow speed (m/s)</th>
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<td></td>
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<tr>
<td>D.8</td>
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<td>0.36</td>
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</table>

Table 4.4: Frequencies calculated from the wavelet transform of the end of the measurements from De Tongelreep.

Let’s assume that the fluctuations here also result from vortex shedding and that the Strouhal number is also 0.2, as explained in section 3.1.2. At a towing speed of 1.3 m/s a frequency around 0.2 Hz is visible in all three measurements. At 2.6 m/s a frequency of approximately 0.4 Hz is visible in both measurements. These frequencies look as if they are similar, because when the speed doubles, this frequency doubles too. The corresponding length scale is 1.3 m.
Chapter 5

Discussion and conclusions

In this chapter the final remarks are made about the performed experiments. Some results are better than others and obviously more research is needed.

5.1 Water channel

The original idea to perform measurements in the water channel was to identify the origin of force fluctuations. Because much more research has been done on a sphere than on a swimmer, this should have been easier. To some extent it was, some results confirmed what was expected based on literature, but also new questions arose.

The low Strouhal number of 0.2 was identified in the measurements, so it is clear that vortex shedding has an effect on the force fluctuations. On the other hand, the high Strouhal number was nowhere to be seen and also the eigenfrequency of the setup wasn’t visible. Yet other frequencies than the one corresponding to the low Strouhal number can be identified in the spectrum and it is unknown what the origin of these is.

Because the eigenfrequency of the setup wasn’t visible in the spectra, the calculation for added mass was reversed. When the added mass is calculated from the measured frequency, its around 1 kg for the long bar and around 3.3 for the short bar. This shows that added mass is a complicated topic and it’s not clear yet what the influence of it is in an oscillating system.

Another mystery left unsolved is the drag coefficient of the sphere. According to literature it should be 0.47, but the two experiments with the long and short bar are in good agreement at 0.9. This difference could be the result of a different way of experimenting. The value of 0.47 is based on a static ball in a uniform flow, whereas in this experiment the sphere could move around in the water channel.

5.2 Towing system

The intention here was also to identify the origin of the force fluctuations. The drag on the swimmer and the drag coefficient have been determined before, but about the force
fluctuations on a swimmer nothing was known beforehand.

The calculated drag coefficients of 0.21 and 0.39 are near the expected values, but to little measurements have been done to be certain. Especially because the drag doesn’t seem to be proportional to $V^2$.

From the wavelet transforms, different frequencies are identified. At 1.3 m/s the frequency of 0.2 Hz jumps out and at 2.6 m/s a frequency of 0.4 Hz is visible. It might not be a coincidence that the second frequency is twice as high, just as the speed, but this should be checked with more measurements at different towing speeds. The calculated length scale of 1.3 m does not immediately ring a bell about vortex shedding from a certain part of the body, but it could not be excluded that vortex shedding plays a role here.

To improve the measurements at De Tongelreep it might be useful to videotape the measurements. Then it can be seen if the swimmer is horizontal and the speed can be calculated more accurately. Also some fluctuations might be explainable because the swimmer moves, but that can’t be seen now.

5.3 Final remarks

The original purpose of this project was to find the origin of force fluctuations on a towed swimmer. Unfortunately, this proved to be too hard to do in only three months. Yet some progress has been made. For the force fluctuations on a sphere, it has been proven that vortex shedding plays an important role and for the towed swimmer a way to analyze the data was explored. This project was a good start into understanding the force fluctuations on a towed object or person, but much more research is needed.
Bibliography


Appendix A

Theory

In this chapter the basics of fluid dynamics will be explained.

A.1 Reynolds number

The Reynolds number is a dimensionless number which characterizes a flow. Two important things can be determined with this number. First, it can be used to determine whether a flow is laminar or turbulent. Second, when the Reynolds numbers of different flows are the same, the flow patterns will also be the same. Of course this is only true when the geometry is also the same. This is quite handy when working with scale models. The Reynolds number is defined as:

\[
Re = \frac{\rho VL}{\mu} = \frac{VL}{\nu}
\]  

(A.1)

in which \(\rho\) is the mass density of the flowing medium, \(V\) is the characteristic speed, \(L\) is the characteristic length, \(\mu\) is the dynamic viscosity and \(\nu = \mu/\rho\) is the kinematic viscosity.

A.2 Boundary layer

To ensure that a flow satisfies the no-slip condition, a boundary layer has to be introduced, which is due to viscous effect. In potential theory these effects are neglected. A potential flow is an irrotational flow of a non-viscous, incompressible and homogenous fluid, an ideal fluid. In most practical cases \(Re \gg 1\), which implies that viscous effects are only significant near the body. At greater distances the flow can be taken to be non-viscous. The viscous area around the body is then called the boundary layer. This layer takes care of a smooth transition from the main flow speed to zero at the surface of the body.

When the flow is around a curved body, there will be a pressure gradient according to Bernoulli:

\[
\frac{dp}{dx} = -\rho V \frac{dV}{dx}
\]  

(A.2)
An accelerating flow is associated with a negative pressure gradient and a decelerating flow is linked with a positive gradient. When \( \frac{dp}{dx} > 0 \) there is a chance of separation of the boundary layer. The separation point is located where \( \frac{\partial u}{\partial y} |_{y=0} = 0 \). This implies that the shear stress on the surface is zero. After this point, it can occur that some fluid will flow backwards to the separation point.

### A.3 Flow around a blunt body

The flow around a blunt body can be dominated by boundary layer separation, this is represented in figure [A.1]. This flow has two stagnation points, in A and in B, the flow accelerates from A to B and decelerates from C to B. Thus, in C the pressure will be minimal and in A and B the pressure will be at its maximum. In the range from C to B there will be a chance of separation. With a streamlined body the chance of separation is quite small, because \( \frac{dp}{dx} \) will be relatively small, but with a blunt body \( \frac{dp}{dx} \) will be big and hence the chance of separation is much higher.

The separation and form of the wake-flow will be determined by the Reynolds number. The flow around a circle-cylinder can be seen in figure [A.2] for different values of the Reynolds number. For \( Re < 5 \) the flow is very viscous and symmetric. For \( 5 < Re < 40 \) there are two vortices at the back of the cylinder. Those vortices are stationary and are trapped between the streamlines. For \( Re > 40 \) there will appear a periodic shedding of vortices, such a wake flow is called the Von Kármán vortex trail. The vortices shed alternately, so the direction of rotation switches with every vortex. The frequency of shedding can be characterised with the Strouhal number, defined as:

\[
S_r = \frac{fd}{V} \tag{A.3}
\]

In which f is the vortex shedding frequency, d is the diameter of the sphere and V is the flow speed.
A.4 Drag

Drag will be very important in this project, it refers to the force which acts on an object in the direction of the flow velocity. The overall drag on an object consists of two components, skin friction and pressure drag. Both come from viscous effects. Skin friction is more important at low Reynolds numbers, while pressure drag is more important at high Reynolds numbers.

Skin friction is the consequence of the viscous mechanism by which a fluid exerts a force on a surface. It always exerts its force parallel to the surface. Obviously, it will be more significant in more viscous situations, thus at low Reynolds numbers and it will be higher when a body exposes more surface to the flow.

Pressure drag is indirectly also a result of viscosity. It occurs because due to separation, the dynamic pressure on the front is not counterbalanced by the pressure on the rear. As explained in section A.2, energy needs to be invested into accelerating fluid to get around the object. This energy is not being returned to the object in decelerating fluid near its rear, but is dissipated in the wake. Pressure drag can be reduced by designing the rear as a long and tapering tail. Fluid now gradually decelerates and little or no separation occurs.

Figure A.2: Wake flow of a cylinder at different regimes of Reynolds numbers.
Pressure drag mainly reflects inertial forces, so it is roughly proportional to surface area and to the square of velocity. The drag coefficient is inversely proportional to these factors, so where pressure drag dominates, the drag coefficient will not vary widely. Skin friction on the other hand is a direct matter of viscous forces and is proportional to linear dimensions and velocity. Thus where skin friction dominates, the drag coefficient will be inversely proportional to the Reynolds number.

The dimensionless drag coefficient is defined as:

\[ D = \frac{1}{2} C_D \rho S V^2 \]  

(A.4)

Here \( C_D \) is the drag coefficient and it is a function only of the Reynolds number. This means that equality of Reynolds numbers implies equality of the drag coefficient.

There are several ways to define the area \( S \) in equation [A.4]. The most common definition is the frontal area \( (S_f) \) of an object, its maximum projection onto a plane normal to the direction of flow. The corresponding drag coefficient will be \( C_{Df} \). Another area is the wetted area \( (S_w, C_{ Dw}) \). The third definition is the two-thirds power of volume as a reference area \( (S_v, C_{Dv}) \). A figure for drag coefficient is only of use when the reference area is indicated.

In figure [A.3] the drag coefficient can be seen as a function of Reynolds number for a sphere. There is a critical value of \( Re_{critical} \sim 5 \cdot 10^5 \) where \( C_D \) drops suddenly. This can be explained because at this point the boundary layer flow shifts from laminar to turbulent. In a turbulent boundary layer the pressure gradient is bigger, so it is harder for separation to take place.

Figure A.3: Drag coefficient (based on frontal area) as a function of Reynolds number (based on diameter) for a sphere. (Fig. 5.4 in [2])
Appendix B

Calibration

The two tables in this section show the measurements used to calibrate the system. The measurements are also plotted in figure B.1.

<table>
<thead>
<tr>
<th>Mass (±0.001 kg)</th>
<th>Voltage (V)</th>
<th>Deflection (±0.5 · 10⁻³ m)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>0.070</td>
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<td>13.5</td>
</tr>
</tbody>
</table>

Table B.1: Measurements used to calibrate the system with the long bar.

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<th>Voltage (V)</th>
<th>Deflection (±0.5 · 10⁻³ m)</th>
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<td>-</td>
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</tbody>
</table>

Table B.2: Measurements used to calibrate the system with the short bar.
Figure B.1: Graph of the measured voltage as a function of force for the long bar (left) and the short bar (right).
Appendix C

Fourier transform

The spectra of the measurements in the water channel which are not displayed in section 4.1.2 are shown here.

Figure C.1: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.17 m/s. The frequencies indicated with a red line are 0.38 Hz and 0.81 Hz.
Figure C.2: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.23 m/s. The frequencies indicated with a red line are 0.55 Hz and 0.90 Hz.

Figure C.3: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.28 m/s. The frequency indicated with a red line is 0.84 Hz.
Appendix C. Fourier Transform

Figure C.4: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.19 m/s. The frequencies indicated with a red line are 0.45 Hz and 0.82 Hz.

Figure C.5: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.21 m/s. The frequencies indicated with a red line are 0.49 Hz and 0.87 Hz.
Figure C.6: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.23 m/s. The frequencies indicated with a red line are 0.22 Hz, 0.52 Hz and 0.89 Hz.

Figure C.7: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.23 m/s. The frequencies indicated with a red line are 0.21 Hz, 0.54 Hz and 0.92 Hz.
Figure C.8: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.26 m/s. The frequencies indicated with a red line are 0.24 Hz, 0.64 Hz and 0.90 Hz.

Figure C.9: Spectrum of the movement of the sphere attached to the long bar at a flow speed of 0.26 m/s. The frequencies indicated with a red line are 0.65 Hz and 0.80 Hz.
Figure C.10: Spectrum of the movement of the sphere attached to the short bar at a flow speed of 0.28 m/s. The frequencies indicated with a red line are 0.68 Hz and 1.27 Hz.

Figure C.11: Spectrum of the movement of the sphere attached to the short bar at a flow speed of 0.24 m/s. The frequencies indicated with a red line are 0.28 Hz, 0.59 Hz and 1.18 Hz.
Figure C.12: Spectrum of the movement of the sphere attached to the short bar at a flow speed of 0.21 m/s. The frequencies indicated with a red line are 0.19 Hz, 0.49 Hz and 1.11 Hz.

Figure C.13: Spectrum of the movement of the sphere attached to the short bar at a flow speed of 0.17 m/s. The frequencies indicated with a red line are 0.41 Hz and 1.01 Hz.
Appendix D

Wavelet transform

The wavelet transforms of the measurements from De Tongelreep, which are not displayed in section 4.2.2 can be found here. Also a list of frequencies calculated from the wavelet transforms of the entire measurements is shown.

Figure D.1: Wavelet transform of the movement of the swimmer at a towing speed of 1.3 m/s. The lowest line corresponds to a frequency of 0.42 Hz, the highest line to 0.22 Hz
Figure D.2: Wavelet transform of the movement of the swimmer at a towing speed of 2.6 m/s. The lowest line corresponds to a frequency of 0.44 Hz, the second line to 0.24 Hz and the highest line to 0.12 Hz.

Figure D.3: Spectrum of the movement of the swimmer at a towing speed of 1.3 m/s. The lowest line corresponds to a frequency of 0.52 Hz, the highest line to 0.13 Hz.
Figure D.4: Spectrum of the movement of the swimmer at a towing speed of 1.3 m/s. The lowest line corresponds to a frequency of 0.71 Hz, the highest line to 0.21 Hz.

Figure D.5: Spectrum of the movement of the swimmer at a towing speed of 1.3 m/s. The lowest line corresponds to a frequency of 0.40 Hz, the highest line to 0.12 Hz.
Figure D.6: Spectrum of the movement of the swimmer at a towing speed of 1.3 m/s. The lowest line corresponds to a frequency of 0.38 Hz, the highest line to 0.21 Hz.

Figure D.7: Spectrum of the movement of the swimmer at a towing speed of 2.6 m/s. The lines correspond the the frequencies 0.43 Hz, 0.29 Hz, 0.18 Hz and 0.11 Hz (from lowest to highest).
APPENDIX D. WAVELET TRANSFORM

Figure D.8: Spectrum of the movement of the swimmer at a towing speed of 2.6 m/s. The line corresponds to a frequency of 0.36 Hz.

<table>
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</tr>
<tr>
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</tr>
</tbody>
</table>

Table D.1: Frequencies calculated from the wavelet transform of the entire measurements from De Tongelreep.