Why skates skate

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Why skates skate

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Abstract

A method was proposed to measure the thinness of water, ice and air under a skate blade during ice skating. The set-up has been improved using a motor and an improved printed circuit board. The set-up did not yet lead to compelling evidence for such a lubricating layer yet. Several future improvements have been recommended.

A system has been constructed to move the skate with a constant speed between 2 cm/s and 80 cm/s which lead to data similar to earlier results.

Contents

Chapter 1

Introduction

Ice skating has been practiced by mankind for thousands of years. Not just as a sport, but also as a way to travel. In other words, ice skating is a part of our way of life. It is know that tsar Peter the Great from Russia traveled to Holland in the 17th century to learn how to build boats that could sail on ice. For such an old phenomenon it is surprising to find out that the mechanism behind the skating is not fully understood. There are theories that suggest that a thin water layer lubricates the ice and the skate so the friction is very low and you can easily glide on the ice. However, thorough experimental verification of the thickness of the water layer has not yet been conducted.
The research to find the mechanism started three years ago by Jorinde van de Vis [1] and continued by Martijn Zuiddam [2] and Tom van der Reep[3]. Their results shown that it is possible to measure the dielectric response a medium (water or ice) between the skate and the ice while a skate passes over it. This bachelor thesis will describe a further attempt to unravel the mystery and mainly focus on the improved set-up. Chapter 2 describes the Theory and chapter 3 the Set-up and the improvements. Chapter 4 contains the newly required data and results. Chapter 5 and 6 present the Discussion & Conclusion,respectively. And, last but not least Chapter 7 Outlook for a future students.

Chapter 2

Theory

The theory for the origin of the thin lubricating water layer is described by Jorinde van de Vis [1], Martijn Zuiddam [2] and Tom van der Reep [3]. In this Chapter only a brief impression of the theory is given.
The idea to find the water layer under a skate is based on a capacitance measurement. The dielectric constants of ice, water and gas are different. Water has a relative dielectric constant of 87 (dimensionless) , gas of 1 and the dielectric constant of ice is frequency dependent.

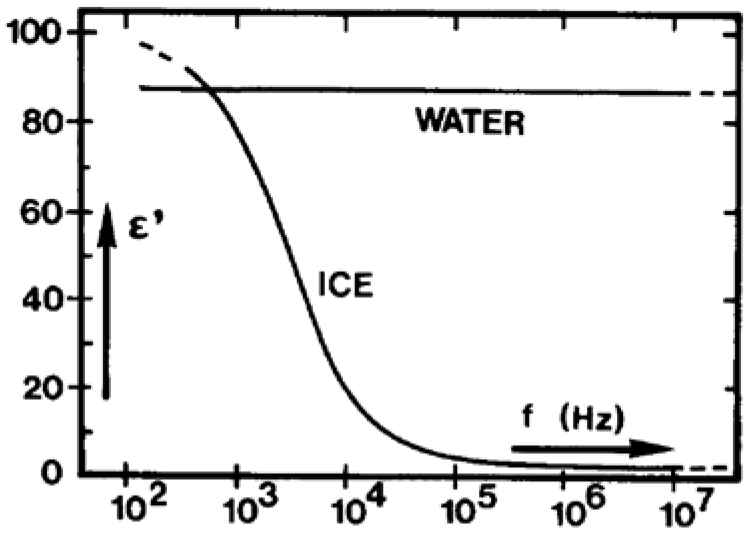

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Figure 2.1: *[4] The dielectric constant of ice and water as an function of the frequency. The dielectric constant of ice is not frequency dependent in the frequency range of our capacitance measurements, the one of ice is.*

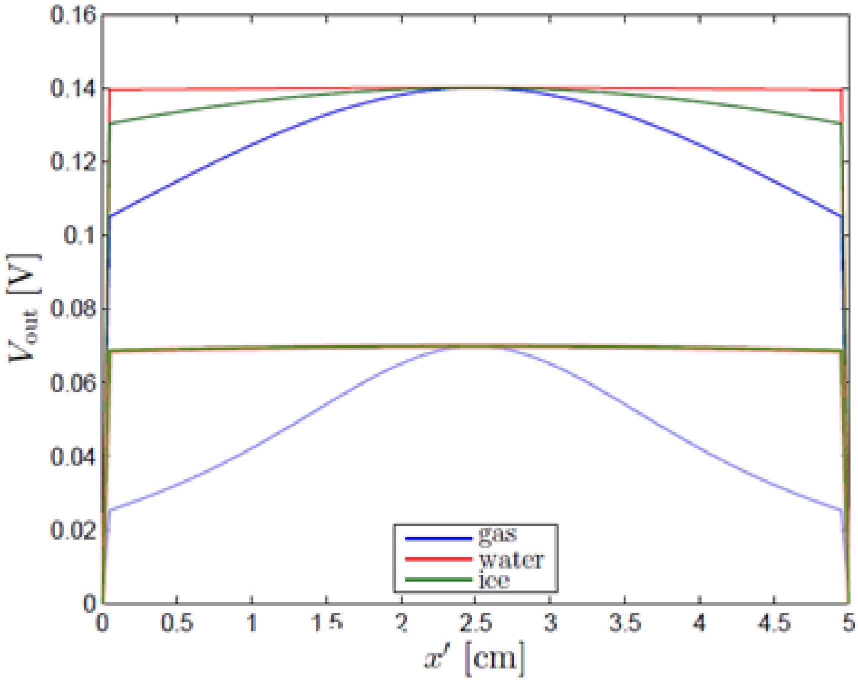

Figure 2.2: *[3] Prediction of the output voltage as a function of the medium between the skate and the electrode. The gap between the round skate and the ice is filled with ice, water or gas. The upper three lines are at $f = 1MHz$ ($V_{in} = 2$ V) and the lower lines are at $f = 11$ kHz ($V_{in} = 10$ V). The relative position of the skate with respect to the electrode is x'.*

An ice skating blade is curved with an radius in the order of 10 meter. The relative difference between the middle and the tip of the skate is very small, but is filled with a medium. This medium is either water, ice, gas ore a composition of these substances. By looking at the relative dielectric constant at two different frequencies it is possible to determine were the medium consists of. An important remark to make is that because of the large radius, the skate is approximated as a flat plate. Under the ice an electrode is placed to complete the capacitor.

Comparing this simulation (fig 2.2) with the measured data can indicate which medium is between the skate and the ice. The signal of ice and water at 11 kHz are the same, the signal of 11 MHz shows a difference. So by measuring the two signals and comparing them the medium can be distinguished.

Chapter 3

set-up

In this chapter the set-up and the methods used to determine the thickness of layers in the medium will be described and discussed. Several improvements to the set-up have been made and will be explained part by part. On the next page are pictures of the old and the new set-up. The parts are discussed from bottom to top. Notice the box surrounding the experiment. The box is filled with nitrogen gas to lower the humidity. If the humidity is too high, the entire set-up can freeze and that will influence the experiment and the results.

3.1 Thermoelectric cooler

The first part of the set-up is a thermoelectric cooler (TE Technology CP-121). This device is based on the Peltier effect. It is designed to make a large temperature gradient between the two sides of the device. By controlling the current sent to the thermoelectric cooler, it is possible to regulate the temperature of the cold side. Even though it is possible to have a range of different temperatures for the ice, the experiments were carried out at an ice temperature of -13° Celsius. For the temperature determination a Fluke's 651 IR-thermometer with emissivity set to high is used, but this thermometer is not very precise. It is recommended to use a better thermometer in the future, e.g. to glue a thermocouple or resistor onto the printed circuit board. This part of the set-up has not been changed in comparison wit the old one.

Figure 3.1: *The old set-up. The box surrounding the experiment is to prevent water vapor in the air to enter the set-up and contaminate it with ice.*

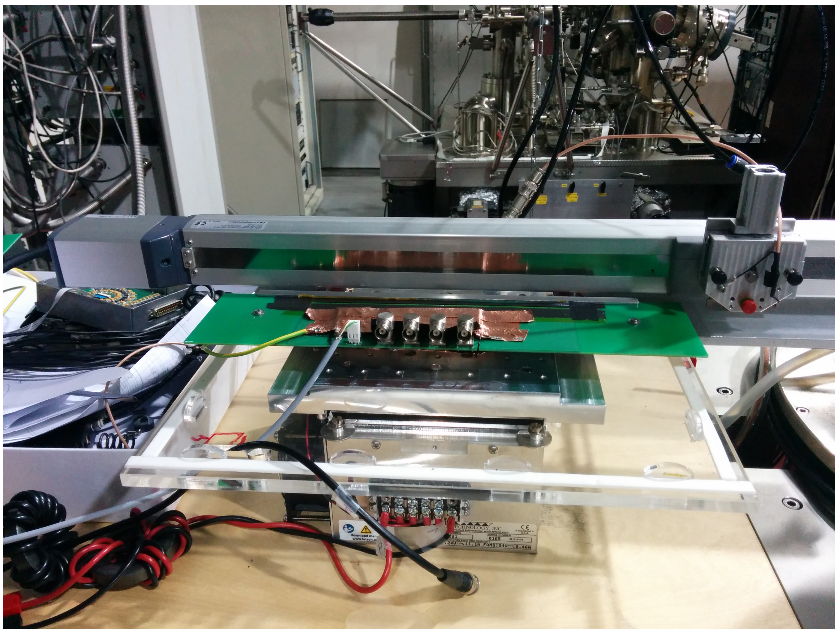

Figure 3.2: *The improved set-up has IV-converters integrated on the printed circuit board with the electrodes as well as a motorized skate with pneumatic vertical load.*

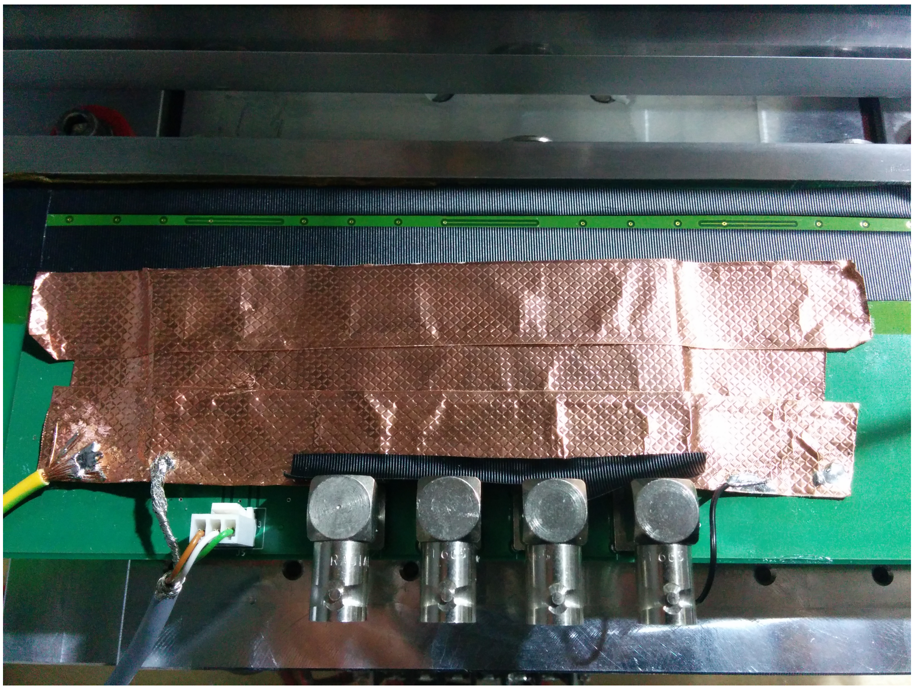

Figure 3.3: *The printed circuit board.*

3.2 Printed Circuit Board (PCB)

This is the part of the set-up where the ice is created and the measurement is performed.This part is improved. On the PCB is a track of 16 electrodes, in figure 3.3 they are visible between the black tape. There are 13 round electrodes of 1.13 mm^2 and three long, ellipse shaped electrodes of 25.2 mm^2. The ellipse electrodes are more sensitive because they may pick up more signal, so they are used to determine if there is any amount of water. The round electrodes detect less signal but with a better spatial resolution and they are used to determine the thickness of the medium between the ice and the skate. The electrodes are grouped in four to an IV-converter, in the figure the IV-converters are underneath the copper tape.In the old set-up the IV converter where not on the PCB, but next to it connected with a flat cable. The copper tape is used as a shielding for any ambient noise and to protect the IV-converters from ice forming. Because the electrodes are grouped only one of the electrodes is connected to the IV-converter with a so called jumper. In one run of the experiment it is possible to measure with maximal four differently grouped electrodes. The jumpers were not ready in time to use in our experiment and we do not know what will happen if multiple electrodes are connected to one IV converter.

The electrodes underneath the ice are protected by a thin tape of kapton. The kapton tape is 25.4 μm and protects the electrodes from the razor sharp skate when the ice is gotten to thin and the skate cuts trough it. The disadvantage of kapton is its hydrophobic behavior. The kapton was replaced by a natural mineral called Mica, which occurs in very thin sheets. The big advantage of mica is its hydrophilic behavior, but unfortunately it is also very porous and the water oozed out before it could freeze. In the future it might be possible to chemically modify the kapton tape to make it hydrophilic.

To make an ice track, water is put between the two black tape strips. Using a syringe, water is injected between the tape and due to the capillary effect, the water will uniformly distribute and form an ice layer when the thermoelectric cooler is on. The ice layer is approximately 200 μm thick. During the experiment ice is shaved off, which limited the amount of times the skate could run over the ice. After about 250 passages the ice was too thin and new ice needed to be created before the experiment could be continued.

3.3 Electrical circuit

Although a new printed circuit board with integrated IV-converters is now used, the electric circuit did not substantially change. It still looks like the one from Van der Reep's report [3] (figure 3.4).

The main difference is the removal of the flat cable. By removing this weak link the capacitance went down in C_C causing less noise and a better signal transfer. The circuit shown here does not differ on other places from the circuit used in the current set-up.

3.4 Electrical Motor and skate holder

The next part of the set-up is the electrical motor. It is a RCP4-SA5C-I-42P ROBO Cylinder type with a spindel (fig 3.5).In the previous experiments the skate was moved by hand or using springs. The skate was placed in a holder with two gliders. Because of the manual movement it was very hard to keep a constant velocity and repeat this velocity. In the new set-up the motor can be programmed to run at a very precise velocity , with a

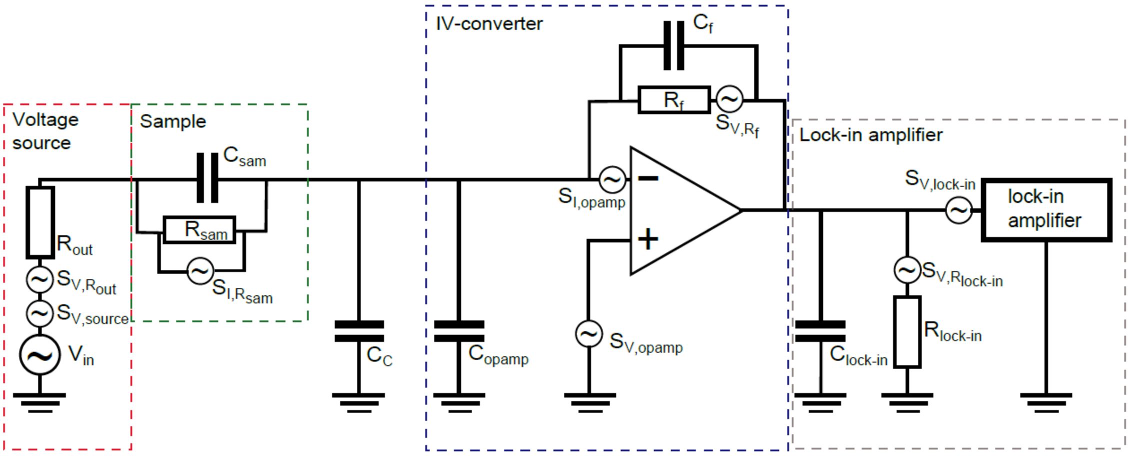

Figure 3.4: *[3]The electrical circuit of the set-up.*

maximal speed of 1440 mm/s (± 1 mm/s). The maximal acceleration and deceleration is 9.81 m/s^2 ($\bar{1}$g). The motor slide is longer than the PCB so the maximum velocity of 1440 mm/s was not reached, but 800 mm/s was possible.As shown in figure 3.6 the speed is very constant.

The skate was attached to the motor trough a skate holder. At the bottom of the skate holder the skate is visible (fig 3.5). The skate used is cut out of a regular long track speed skate. The skate has an radius of 22 meter and is 5 centimeters long by 0.11 cm wide.The tip and end of the skate are, due to the round shape of the skate, 10 μm higher than the center. The edges on the skate has been rounded with an radius of 0.1 centimeter to prevent excessive heating. The cable connected to the skates transfers the voltage to the skate. To cool down the skate, a small water layer is created on the cooling element near the ice track where skate is placed. The skate is electrically isolated from the motor using a plastic holder.

A small air piston pushes the skate down to simulate the weight of a skater. Using the contact surface of the skate the force on the skate is calculated. The factor between the skate in the experiment and a regular skate is 1 bar of pressure given by the piston equals 1kg at a regular skate. To simulate a normal person of 80 kg the pressure should be 80 bar. Unfortunately, the piston is not able to reach such high pressures, so for the experiments 2 bar to 5 bar is used. If the pressure is higher, the ice will crack and the data will be very difficult to interpret.
With the new skate holder, it is possible to adjust the angle of the skate. In a normal skate stroke, the skate is places at an angle on the ice to improve grip. In the experiments conducted the skate is placed vertically on the ice

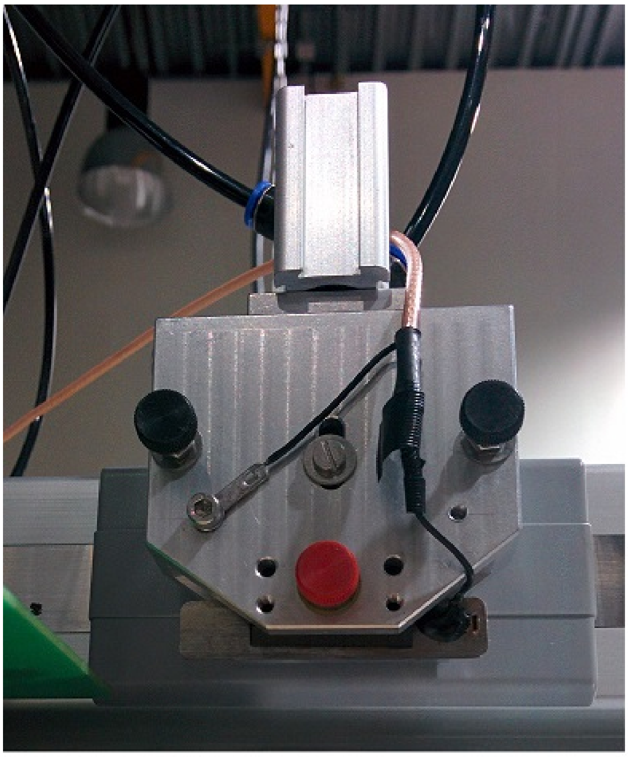

Figure 3.5: *The skate holder attached to the motor.*

but in the future it is possible to simulate different phases of a skate stroke.

3.5 Lock-in amplifier

The last part of the set-up is the Lock-in amplifier. The lock-in creates two signals, a 1 MHz (2 V) signal and a 11kHz (10 V) signal. After the signals are transmitted to the skate and the current is measured by the IV-converters on the PCB, these signals are send to the Lock-in and saved with a rate of 28.8Ksample/s resp. 7.2Ksample/s. This means that the 1MHz signal has four times more data points than the 11kHz signal. Because of the improved PCB and the integrated IV-converters the noise has gone down with a factor two. The signal has been improved by a factor snelheid.jpg

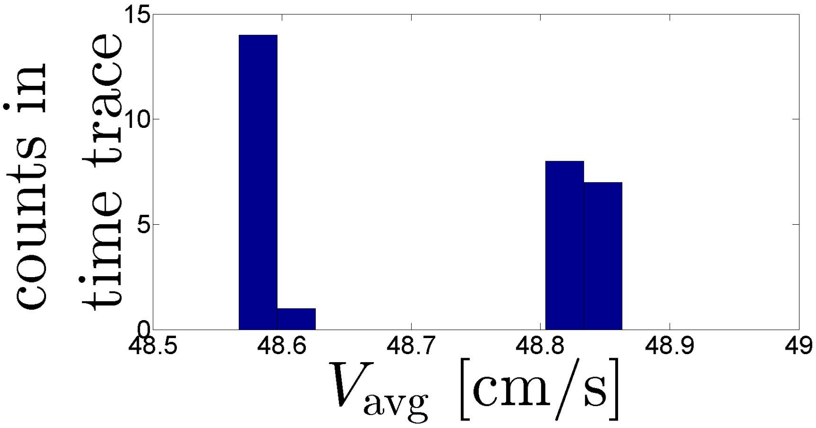

Figure 3.6: *Speed distribution of a typical experiment.There are 15 runs to the left and 15 to the right. The speed in the two directions are slightly different, but are still very reproducible.*

three. Although the absence of an flat cable was expected to reduce the noise level and improve the signal, this factor of 6 was not expected and is not understood.

Chapter 4

Results

The experiments were performed by moving the skate over the ice with embedded electrodes. Several velocities have been used with a ice temperature of -13 ° Celsius. Also the pressure varied from 2 bar to 5 bar to compare if this has a big effect on the results. A typical measurement is shown in figures 4.1 and 4.2. During all the experiments the ice layer thickness was approximately 200 μm, but no careful measurement on the ice thickness is performed during the experiments. The data shown in this chapter was not all obtained using the same ice layer due to the fact that the measurements were conduct on different days. The humidity during the experiments was low, so there was no ice forming except on the ice track.
For a better understanding of the figures the next relation is important:

$$V \propto C \propto \frac{\epsilon_r}{d_W} \tag{4.1}$$

Where V is the output voltage of the IV-converters, C is the capacitance of the skate moving over the electrode, ϵ_r the relative dielectric constant of the medium between the skate and the ice and d_W is the distance between the skate and the ice.

4.1 Measurement of 500mm/s

The first thing that stands out are the difference in shape of the curves. The two colors are not symmetric in time. In the 1MHz graphic (figure 4.1) the blue line has a shoulder like part between t=0.005s and t=0.04s where the

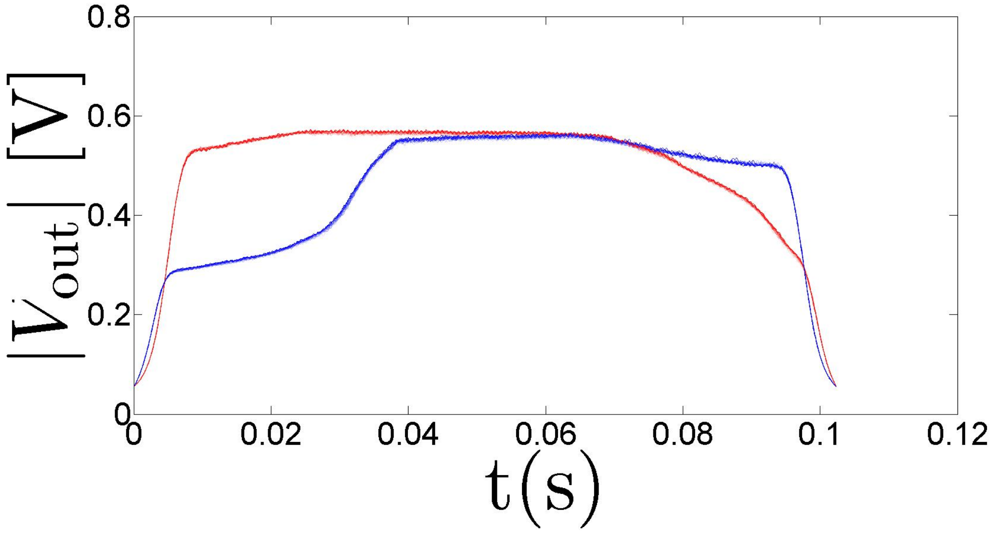

Figure 4.1: *A 1 MHz measurement conduct with a velocity of 50 cm/s, P= 2 bar and a start voltage of 2 V. The blue lines indicate that the skate moved from right to left, the red lines are vice versa. The brightness of the lines indicate the number of the line in which it is measured.*

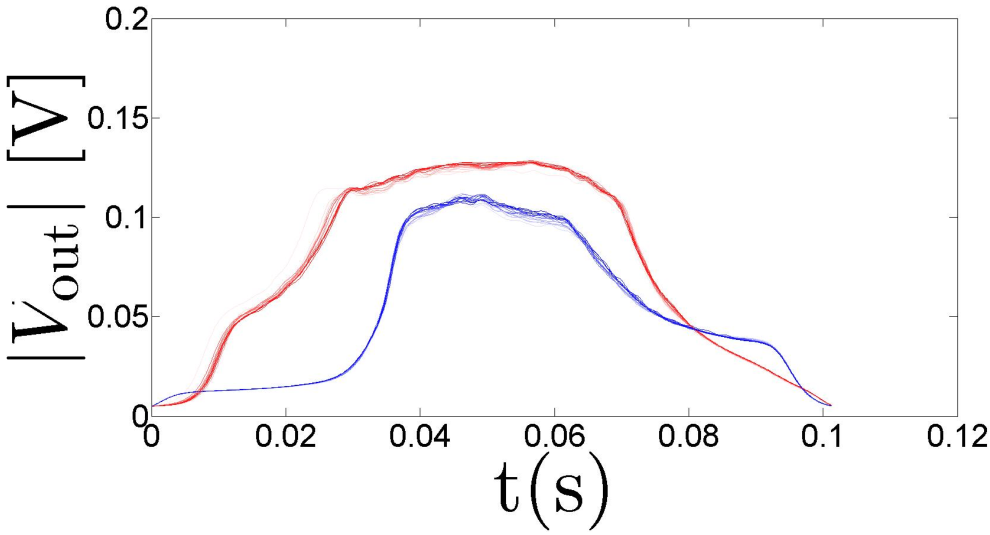

Figure 4.2: *The 11 kHz signal belonging to the figure above. Again, blue is from right to left and red vice versa. The brightness of the colors indicate which line number it is.*

red line is constant at a higher level.To have a nearly constant line, $\frac{\epsilon_r}{d_W}$ needs to be constant. The skate is round so the distance d_W decreases towards the middle of the skate. This indicates that ϵ_r also decrease, so the medium between the skate and the electrode changes from ice or water to gas. The lines almost perfectly overlap in the region between t=0.04 and t=0.075. After the overlapping part the red line drops with a tinny bump whereas the blue line slowly descend to a point where it rapidly drops. The red and the blue line come back to nearly overlapping again and the skate moves to far from the electrode to detect any signal. Because they are not symmetric in time, there is an indication that the effects on the skate are not similar. Apparently the symmetry in the 1MHz measurement is broken.

In the 11kHz graphic (figure 4.2) other features appear. The output signal is lower then in the 1 MHz graphic, which is expected from the simulation shown in Chapter 2. In this graphic the red and blue line, which indicate the direction in which the skate is moving, hardly touch. The blue line is in the center, the point were the skate should be closest to the electrode, lower than the red line. In the middle of the skate the transmission of the signal should be at its highest, because the distance between the skate and the electrode is at a minimum. From equation 4.1 it is clear that when the distance between the skate and the ice, d_W, decreases, the signal V increases causing a top in the graphic. Clearly, the tops do not have the same height which can indicate that the distance between the skate and the electrode is not the same if the skate is moving in an opposite direction. Also the shape of the blue line at 11 kHz shows a different form with the blue line at 1 MHz. The blue line started almost straight between t= 0 and t=0.03s but then rapidly goes up.After the maximum a shoulder occurs before the measurement is done. The red line is again not similar to the blue line. The 11 kHz signal starts slower than the 1 MHz signal and has a tiny bump at t= 0.01s. At t=0.03s the line nearly reached its maximum and only slowly increas. After t=0.075 the red line fast decrease until the skate is no longer near the electrode.

4.2 Fourier transform

From both figure 4.2 and figure 4.1 a tiny wobble on the signal can been seen. When the full data set from the measurement is taken and the tops

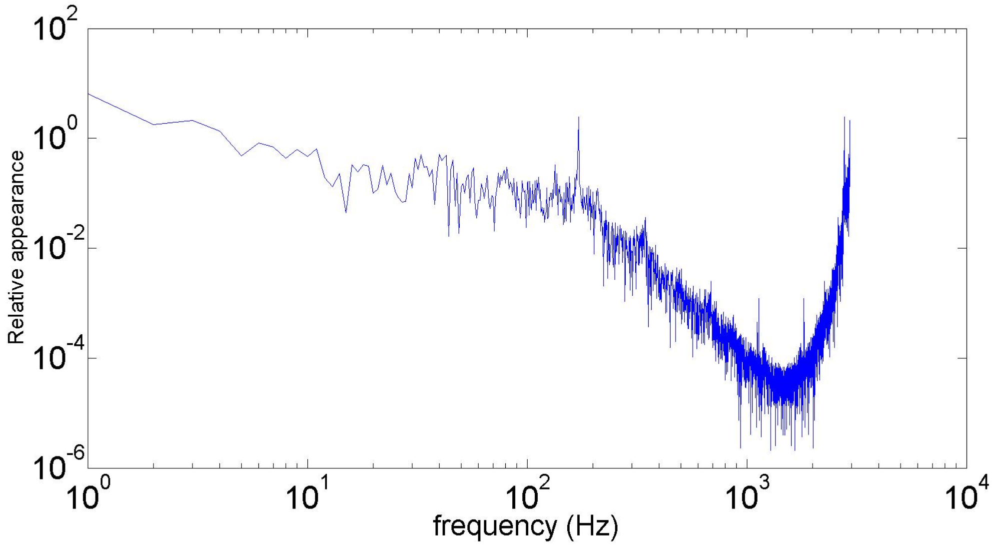

Figure 4.3: *Logarithmic plot of the Fourier transformation of the low frequencies of the lock-in amplifier output [8].*

are extracted only the low frequencies remain. The Fourier transformation spectrum of these frequencies are shown in figure 4.3. In this spectrum a few things stand out. There is a local minimum near 1500 Hz and then a peak towards 11kHz. In this region the line is very wide. This can indicate that the 11 kHZ signal created by the Lock-in is not precisely 11kHz.When this spectrum was compared with data from Van der Reep [3] it showed that there is more noise at low frequencies in the new set-up. This does not mean that the data is more corrupted because this is not the frequencies at which the experiment is performed. To make the 11 kHz signal peak more narrow a different signal generator can be used.

In figure 4.3 also a peak can be seen at 110 Hz. This peak is caused by the electrical motor, which has an frequency of 108 Hz when moving with 500mm/s. In this spectrum no 50 Hz or higher peaks can be identified, which means that there is very few noise coming from the electrical network. The skate is apparently nicely electrical isolated.

Chapter 5

Discussion

5.1 Front of the skate

The data seen in the previous chapter show some interesting results. First the shoulder of the blue signal in the 1 MHz figure (figure 4.1). As stated before, the only way to have a nearly constant signal is when ϵ_r decreases at almost the same rate as d_W decreases. The decreasing of d_W is caused by the round shape of the skate which leaves the explanation of the decreasing ϵ_r. The only way for ϵ_r to decrease is if the medium between the skate and the electrode has a lower relative dielectric constant in comparison with the first part of the skate. The 11 kHz signal shows that the signal is low near the shoulder. This is an indication that there was water between the ice and skate but that the water changed to a different medium with a lower dielectric constant as shown in figure 5.1.

The thin water layer stick to the skate with a small pocket between the water and the skate. In the figure the radius of the skate is exaggerated, in reality the edges of the skate are only 10μm higher than the center of the skate as stated in chapter three. The water layer stick to the skate by capillary force and this force prevents the water from leaving the skate. This does not explain the high signal coming from the red line, when the skate is moving in the other direction. Clearly there is no pocket in front of the skate in this direction. Further on in this chapter will be more about this signal.

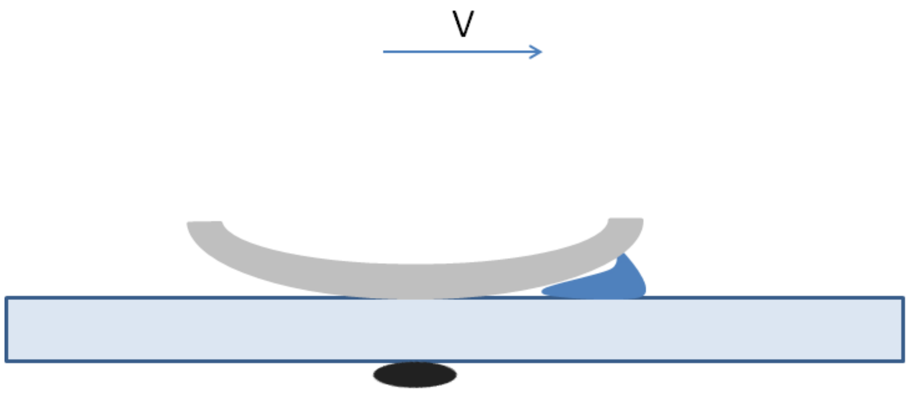

Figure 5.1: *Schematic impression of the thin lubricating water layer formed while skating. In front of the skate is a small layer with a pocket between the skate and the ice. The black oval shaped part is the electrode with an ice layer on top of it.*

5.2 Back of the skate

The blue and red lines from figure 4.1 show that when the electrode passes the center of the skate and is at the back of the skate the signal is different from the signal when the electrode is at the front of the skate. The blue line stays high suggesting a water or ice layer sticked to the back of the skate. The 11 kHz signal shows that the signal is to high to be gas until the end of the skate reaches the electrode. In figure 5.2 this is illustrated.

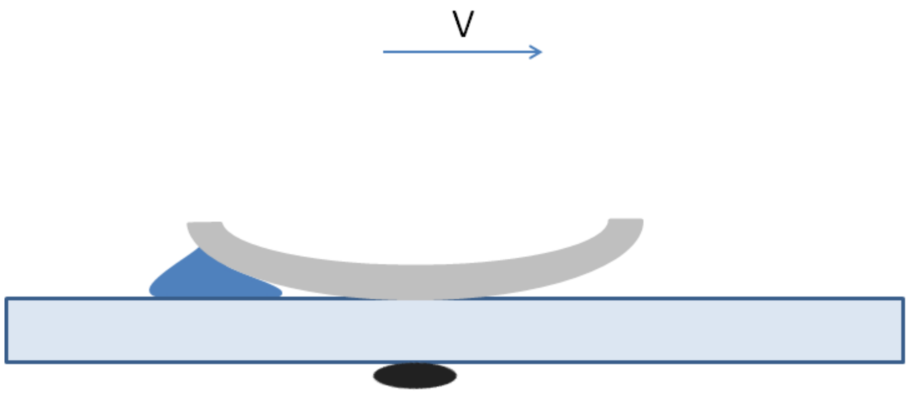

Figure 5.2: *A schematic impression of the thin lubricating layer formed while skating at the back of the skate. The layer sticks to the back of the skate and is dragged along with it.*

5.3 Layer thickness

To determine the thickness of the medium between the skate we make use of geometry. Due to the round shape of the skate the formula for calculating the layer looks like this:

$$d_W = r - \sqrt{r^2 - x^2} \tag{5.1}$$

Where d_W is the thickness of the medium, r is the radius of the skate and x is the part of the peaks from the signal that suggests water or ice.To determine the height of the medium it is very important to make sure the length of the skate and the width of the signal corresponds. If the signal is only a bit off there will be a big difference in the water layer because you take the relative size of the flat part of the peak, for example 25 % and convert that to the length of the skate, 1.25 centimeter in this example. So it is vital to know the length of the skate for the determination of the thickness of the lubricating layer.

If the length of the skate is taken to be 5 centimeters the water layer can be calculated using equation 5.1. It turns out the layer is between 3.5 and 5 μ thick. This is in agreement with earlier results which suggested that there is a water layer in the order of 10 μm.

5.4 Symmetry

As stated in the previous chapter, the signals are not symmetrical. This can be an indication for an asymmetrical shaped skate. This does not automatically indicate the skate not to be round shaped but oval or even worse, it also can indicate that the skate is not perpendicular to the ice. In figure 5.3 this illustrated.

The angle α is probably very small. But even a small angle can have an effect on the calculation of the thickness of the medium between the skate and the ice. If $\alpha = 1^\circ$ this results in a drop of the end of the skate of 1.5 μmeter, 15% of the total hight! In the experiment it is very important to fixed the skate to prevent the skate from tilting even slightly. The tilted skate however can explain why the signal is not the same as the direction of the movement is changed. The skate will be closer to the electrode at one point but further away when the skate moves back. If there is not a big layer in front of the skate but the skate is closer to the ice this can explain the red line in figure 4.1 which starts high. it also explains the red signal

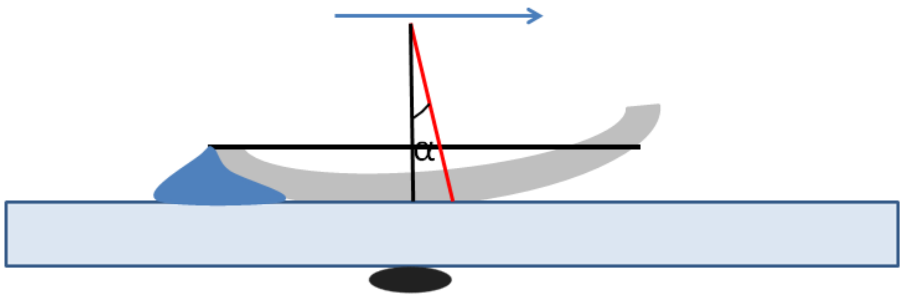

Figure 5.3: The skate slightly tilted at an angle α. The black line parallel to the ice indicates the height of the lowest point of the skate. The red line is the line perpendicular to the ice and is in the middle of the skate. The other black line is the new line perpendicular to the skate in the point the skate is closest to the electrode.

going down, because the end of the skate is higher, meaning further away from the electrode. To determine if the skate is tilted more research needs to be done.

Chapter 6

Conclusions

The conclusion of this experiment is that there are signs suggesting a thin water layer surrounding the skate while moving, e.g. the fact that the peaks in the capacitance have a flat part.The thickness of the lubricating layer is measured to be between 3.5 and 5 μm. The layer also can be partially made up by ice shavings, near the center of the skate it is hard to distinguish the signal of ice from water.

The improved set-up works properly. The motor gives a constant well defined speed and due to the new printed circuit board the signal has increased and the noise went down. Due to the higher signal to noise ratio and the better controlled velocity the experiment can be performed with higher accuracy when compared to the old set-up.

Last but not least is the possibility of asymmetry in the experiment due to the tilting of the skate. This deficiency is not yet understood but can be very important in the future to fully understand the experiment.

We have possibly measured the presence of a water layer between the skate and the ice. The gap between the curved skate and the ice is very thin. This raises the question whether or not the capillary force due to the negative curvature of the liquid air interface causes a sufficient force on the water layer to pull it forward such that a water film might advance in front of the skate. This is especially relevant for our experiment because our skate moves back and forth.

Chapter 7

Outlook

Even though the set-up has been revised things still can be improved.
The skate can be equipped with a small cooler and thermometer to control the temperature of the skate more properly. There are small coolers called micro Peltier coolers [5] and they are small enough to be placed on the skate. If a thermometer also is installed on the skate it may become possible to measure the friction of the skate on the ice. When you know with which amount the skate heats up during a run and the velocity is known, it may be possible to determine a change in the friction coefficient from a change of temperature.
I would also be nice to integrate a force sensor on the skate. We have investigated the feasibility of using strain gauges or a laser fiber interferometer (not reported here) to measure the shape changes of a modified skate. We could not find a commercially available force sensor that might be placed in between the skate and the skate holder that is mounted on the motor, but it is worth looking for one.
With the new printed circuit board it is also possible to measure multiple electrodes in one run. The lock-in amplifier can handle two signal at once and since there are four IV-converters it should be possible to measure four electrodes in one run when two such lock-in amplifiers are used.
Using the four electrodes a variety of experiments can be done. During an 'interval experiment' one might vary the speed of the skate over multiple electrodes in a single run. Multiple signals from different electrodes with different speeds in a single run can then be compared.
In the results, a remark about the roundness of the skate has been made. By a measurement at the LIS it turns out that the skate in not as round as we thought it was.There is a difference of the rounding of the skate of 30μm, which is huge when compared to the relative difference of 10 μm.

For the next experiments it is advised to determine the shape of the skate more accurately so the models can be adjust to the new skate.

Appendix A

Table 1. Useful parameters of solid and liquid ice [7]

property	value	unit
Heat of melting	334	kiloJoule/ kg
Heat capacitance of ice	1960	Joule/kg/K
Heat capacitance of water	4220	Joule/kg/K
Young's modulus of ice	10	GPa
Young's modulus of the PCB	24	GPa
Yield stress of ice	$14.8 - 0.6\ \frac{T_{ice}}{[^\circ C]}$	MPa
relative dielectric constant of ice at 1 MHz	3	-
relative dielectric constant of liquid water at 1 MHz	87.9	-
relative dielectric constant of water vapor at 1 MHz	1	-
Viscosity of water at 0° C	1.794	mNs/m^2
vapor pressure of liquid water at 0 ° C	611	Pa
vapor pressure of solid ice at -24 ° C	213	MPa
Surface tension of liquid water	75	mN/m

References

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