NTNU
Norwegian University of
Science and Technology

Development of a Linear Tribometer

Mathis Dahl Fenre

Mechanical Engineering
Submission date: February 2016
Supervisor: Nuria Espallargas, IPM
Co-supervisor: Alex Klein-Paste, BAT
Felix Breitschädel, Olympiatoppen

Norwegian University of Science and Technology
Department of Engineering Design and Materials

Preface

This Master's thesis in Engineering Design and Tribology is carried out at the Department of Engineering Design and Materials (IPM) in collaboration with the Department of Civil Engineering and Transport (BAT). It is a part of the study program Engineering Design and Manufacturing at NTNU. It was carried out during the second half of the fall semester 2015 and the first half of the spring semester 2016. The project was first an assignment for "Olympiatoppen" (OLT), as a part of the research project "Ski 2018". Later, BAT and "Statens Vegvesen" got involved and included the project in the research center "Forskningssenter Vinterdrift". During the project there has been an ongoing communication with both OLT and BAT.

OLT came up with the idea of making a ski-tribometer, for measuring the exact friction on skis gliding on snow. A theoretical pre-masters project was carried out on the subject during the fall of 2014. In 2015, BAT and Statens Vegvesen started a large scale friction track project. The ski-tribometer project was then changed into a more general tribometer project where the goal was to measure friction on various materials gliding on snow and ice. Hence, minor changes to the title and content of the thesis has been applied since the project started in october. This project will be in the interest of not only OLT but also BAT and Statens Vegvesen.

Trondheim, 2016-02-28

Mathis Dahl Fenre

Mathis Dahl Fenre

Acknowledgments

I would like to thank my supervisor at IPM Nuria Espallargas for introducing me to the field of tribology and making it possible for me to combine my passion for winter and snow with a master thesis in mechanical engineering.

I would like to thank my co-supervisor Felix Breitschädel at Olympiatoppen/BAT for introducing me to the field of ski-technology and for his great support. Felix introduced me to the idea of a ski-tribometer when I started working on my pre-master project in september 2014, and he has been very helpful and enthusiastic about the tribometer project ever since.

Alex Klein-Paste introduced me to the snow lab at BAT, and gave me lots of good advice on how to accomplish the tribometer project. As my supervisor Nuria was in Switzerland during my master project, Alex suggested that he could be an official co-supervisor for me during the project. Alex has been my closest companion during the project and his hands-on mindset and willingness to execute plans really speeded up the project.

I would also like to give a huge thanks to everyone at the workshops at BAT and IPM, and especially Børge Holen and Carl-Magnus Midtbø. Børge and Carl-Magnus gave me great design advise and machined almost all the custom components for me. They were very helpful with all kinds of issues I stumbled upon during the building process.

I also appreciate the support I got from Katja-Pauliina Rekilä at BAT for sharing snow-lab specifications and making orders.

Finally, a big thanks to Statens Vegvesen and Olympiatoppen for financing the project.

M.D.F.

Summary and Conclusions

A mobile, linear tribometer for studying frictional characteristics on various materials gliding on snow and ice has been developed. The tribometer has the ability to adjust the normal force on the specimen to simulate realistic sports/transport conditions. Results from initial testing indicates that the tribometer can distinguish very small differences in friction forces. The friction of a set of rubber blocks sliding on ice has been tested, and the results indicates that increased rubber hardness leads to friction reduction, as expected from theory.

The tribometer is planned to run friction tests outdoors on snow and ice, and is also going to be used in the coming friction track at the BAT, to run experiments with more controlled environmental parameters.

Sammendrag

Et mobilt, lineært tribometer har blitt bygget for å undersøke friksjonskarakteristikk av forskjellige materialer som glir på snø og is. Tribometeret kan justere utøvet normalkraft på testprøvene for å simulere realistiske sport/transport forhold. Resultater fra initielle tester indikerer at tribometeret kan måle svært små forskjeller i friksjonskrefter. Glidefriksjon har blitt målt på et sett med gummiklosser med varierende hardhet som glir på is, og resultatene indikerer at hardere gummi gir lavere friksjon, noe som gjenspeiler teorien.

Tribometeret kan gjøre friksjonsmålinger utendørs på snø og is, og skal også brukes i friksjonsbanen i den nye snølaben på BAT, for å kjøre eksperimenter med mer kontrollerte miljøparametre.

Contents

Chapter 1

Introduction

1.1 Background & Motivation

Measuring friction is a difficult task in almost any discipline of engineering. Friction depends on many factors such as load, speed, materials in contact, temperature, environment, etc. However, friction is an important parameter to know in many engineering applications, but also in sports. Winter sports such as cross-country skiing or speed skating are very dependent on finding the optimal friction for achieving the best performance, while road vehicles depend on optimal friction to keep the wheels on the road.

Therefore, being able to measure friction between different materials and snow or ice would be a great step forward designing new materials and thus achieving full performance in winter sports. It would also be very useful for road safety research, as it can help designing new tire materials.

A tribometer is a device that can, among other physical contacting properties, measure friction forces. Different cases of friction require different types of tribometers, e.g. some are built to measure friction in bearings, others measures the rolling friction between an icy road and a tire.

Fenre (2014) concluded in a pre-master project that a new tribometer in Norway "can further improve knowledge and understanding about ski friction phenomena, and in time facilitate more top performances in winter sports such as cross-country skiing." In the report, different methods of measuring friction on snow and ice were compared and evaluated. People from the ski-racing business stated their opinions regarding existing field test methods. Existing laboratory test methods were also studied and evaluated. The report concluded that the research results that were most useful to outdoor ski racing were the ones obtained using ski specific parameters. Therefore, if a new ski tribometer is going to be built, it should be able to recreate the environment encountered in outdoor ski courses.

In the summer of 2015, the building of a new snow lab started at NTNU. With a controlled climate it can keep temperatures within $\pm 0,5°C$ between 0°C and -25°C, thus allowing experiments to be performed on stable snow and ice. A 9 meter test track, a railing system, a cable and a powerful electrical motor makes makes it possible to drag specimen across the snow or ice track. To measure the frictional forces between the snow/ice track and the materials that are dragged along it, a measuring device must be developed and built.

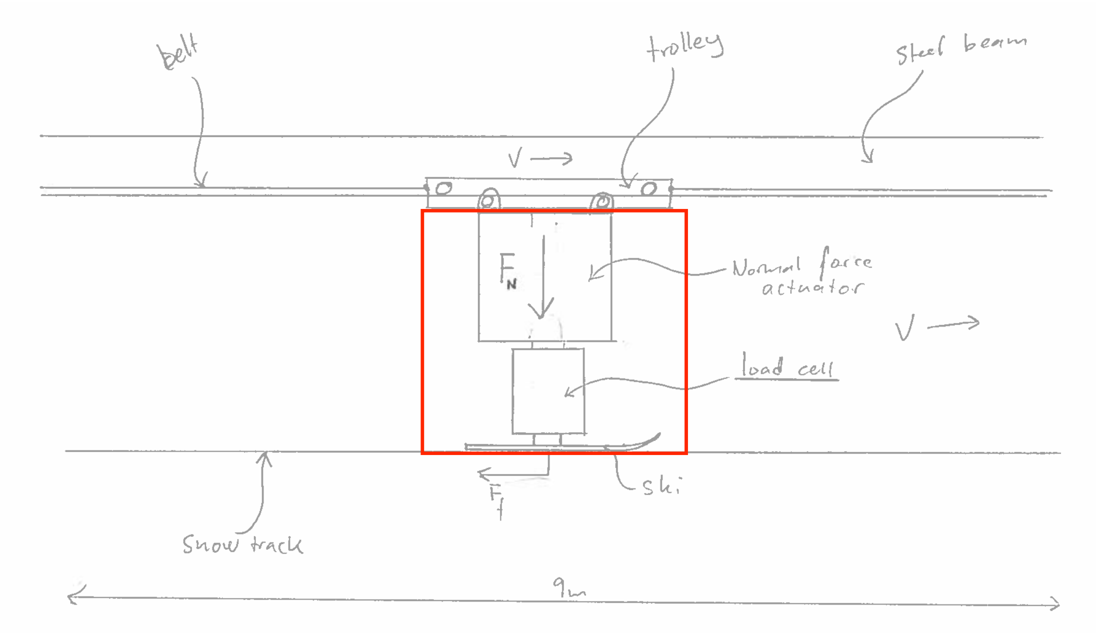


Figure 1.1: The red box indicates where the friction meter will be placed.

The purpose of the snow lab project was initially to measure traction of rotating wheels on winter conditions. Later, there was an agreement that in addition to measure rotating frictional forces, the lab also should have the functionality to measure sliding frictional forces, and that this could be an advantage of both winter sport- and traffic research. The snow lab has 3 different rooms. A control room, a snow production room and the experimental room where the actual snow/ice track is located. A 45 kW electrical motor, a belt and a trolley guided by two steel

(a) (b)

Figure 1.2: a) Snow lab control room b) Test track railings laying in the test room. Photos are shot on November 20th, 2015.

railings offers linear motion along the test track. The motor offers an estimated acceleration of $36 m/s^2$. With an acceleration phase and braking phase of 3 meters each, we are left with 2 meters of constant velocity. The estimated top testing velocity is estimated to be around 15 m/s. Early stage photos of the snow lab are shown in figure 1.2.

This thesis covers the development of the linear friction meter that is planned to be placed between the trolley and the test track (see figure 1.1).

1.2 Goal and Objectives

The goal of this project is to develop, construct and perform initial tests on a device that can measure frictional forces on materials sliding on snow or ice with realistic parameters. The normal force on the test specimen should be adjustable in order to recreate real sports/transport conditions. The tribometer should be able to perform friction measurements outside on snow and ice, and in laboratories, such as the new snow lab at BAT. The reach this goal, the following objectives will be completed:

1. Determine device requirements, based on real sports/transport conditions.
2. Evaluate different concepts and solutions to satisfy device requirements.
3. Create complete 3d models of the chosen concept.
4. Physically build a high velocity linear tribometer.
5. Perform initial tests on the tribometer for validation.

1.3 Thesis Outline

This master's thesis presents the development of the tribometer in this order:

1. Present theory of snow/ice tribology.
2. Determine device requirements.
3. Evaluation of different concepts and solutions to satisfy device requirements.
4. Present the final concept of the tribometer.
5. Perform initial tests on the tribometer for validation.
6. Discuss test results.
7. Discuss strengths and weaknesses of the design.
8. Draw general conclusions from the project.

Chapter 2

Tribology on Snow and Ice

Tribology can be described as *"the interaction between surfaces that are put together and slide one over another"* . More precise, tribology is known as the study of "Friction", "Lubrication" and "Wear". These three concepts are so closely related that they are almost impossible to study independently.

In the special case of tribology on snow and ice, the interaction between different materials and ice or snow is investigated. The theory part of this thesis is mostly based on literature from the research of skis sliding on snow or ice.

2.1 State of the Art

The nature of snow and ice, and the coefficient of friction between materials like wood, polymers or metals and snow or ice has been subject to numerous studies. It is more than 150 years ago that Faraday (1859) put two ice cubes in contact, and they instantly froze together. He concluded that the ice surface was covered by a thin water layer. Almost 100 years later, Bowden and Hughes (1939) looked at model scale sliders on ice and snow, and found that the low friction was due to frictional melting of the snow or ice surface. Bowden (1952), did further studies that supported the frictional heating theory. Later, this theory has been tested and supported by Ambach and Mayr (1981); Glenne (1987); Colbeck (1992, 1994); Lind and Sanders (1997) and Bäurle (2006).

Sturesson (2008) performed experiments on a spinning disk ski tribometer with small ski-sole specimen. Relations between the coefficient of friction, velocity, load and temperature were found. Fauve et al. (2006) found very good agreement when comparing results from ski friction field testing and laboratory ski friction testing with a spinning disk ski tribometer. Takeda et al. (2010) tested the effect different snow grain sizes and temperatures had on ski friction. Hasler et al. (2014) did experiments on a full scale linear ski tribometer where a dependency between different surface structures and the effect of racing wax was determined. Schindelwig et al. (2014) mounted temperature sensors in skis, and found a relation between ski pressure distribution and snow heating under a gliding ski, utilizing a full scale linear ski tribometer.

2.2 Sliding Friction on Snow and Ice

The kinematic friction coefficient (μ), defined as:

$$\mu = \frac{F_T}{F_N} \tag{2.1}$$

where F_T is the frictional force and F_N is the normal force, between most plastically deforming materials, can be assumed to be independent of normal force, velocity (v) and apparent area of contact (A_a). Results from many experiments though, like the ones performed by Bäurle (2006) show that the classical friction laws does not hold for materials sliding on ice or snow. Actually, when a material is sliding on ice or snow, the coefficient of friction is apparently very much dependent on the above parameters.

2.2.1 Frictional Heat and Lubricated Friction

Bäurle (2006) agrees with Bowden and Hughes (1939); Bowden (1952); Ambach and Mayr (1981); Glenne (1987); Colbeck (1992, 1994); Lind and Sanders (1997), and others, in that the low friction discovered when materials are sliding on ice or snow is due to a thin film of water between the surfaces, created by frictional heat. The amount of frictional heat generated can be expressed as:

$$P = \mu \cdot F_N \cdot v = F_T \cdot v \tag{2.2}$$

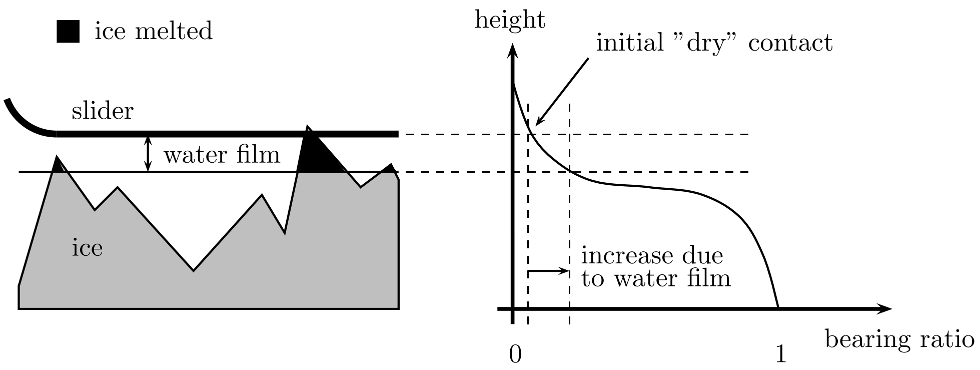


Figure 2.1: Relation between the water film thickness and the real contact area (A_c). Melting of ice corresponds to a slicing-off, and leads to the growth of existing contacts, and the formation of new contacts. (Adapted from Bäurle (2006))

Accordingly, the heat flux $\left(q''\right)$ through the slider with area A can be written as $q'' = P/A$.

At low velocities and cold temperatures, the frictional heat produced will melt little or no ice to create a lubricating water film, leading to high friction. At this point, we are close to the "dry friction" regime. Adhesive bonds will be created between the surfaces, and the frictional force can be explained as the force needed to shear adhesive bonds between the ski surface and the ice/snow surface:

$$F_T = \tau_c \cdot A_c \tag{2.3}$$

where τ_c is the shear strength of the adhesive bonds created between the surfaces. A_c is the real area of contact between the surfaces, meaning the sum of all the small contact areas where surface asperities meet. We see that a larger A_c leads to a higher frictional force. As suggested by Bowden (1952), A_c, is directly proportional to the applied load (F_N) and the hardness (H) of the softer material. Bäurle (2006), suggests that A_c increases with increased heat flux. As the frictional heat from the slider melts ice, causing a thicker water film, the slider slices off the asperities according to the water film thickness, leading to an increase in contact area (i.e. bearing ratio). This relation is illustrated in figure 2.1.

The high friction at low temperatures can also be described by adhesive ploughing. A hard ski sole material will deform the less hard snow or ice, and create friction.

On ice, real dry friction is very rare. Petrenko (1997) shows that ice has, even at very low temperatures, a thin liquid like film that lubricates the surface. The film has a thickness of only a few molecular layers.

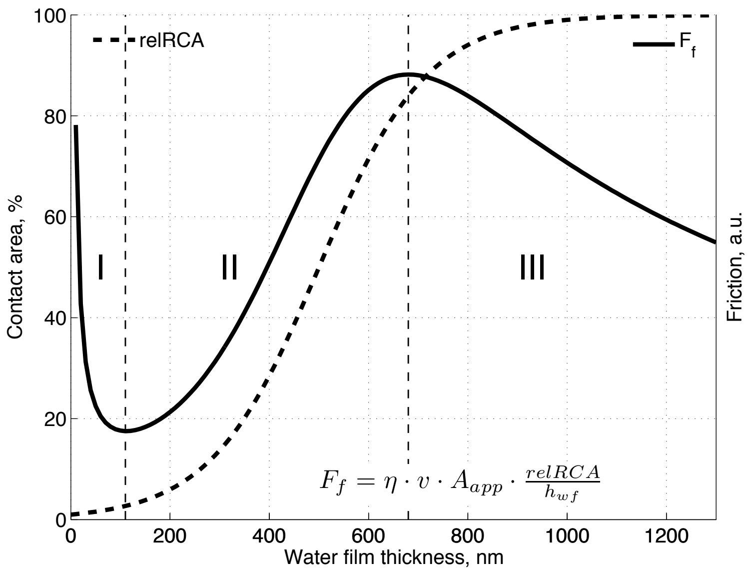


Figure 2.2: Contact area (dashed line, left axis) and friction (solid line, right axis) vs. water film thickness (Bäurle (2006)).

When the velocity or temperature rise, the surfaces will experience increased frictional heat. The friction force is no longer only dependent on the shearing of adhesive bonds or ploughing between the surfaces. A lubricating film is generated, leading to lower friction. Assuming τ_c is a constant, the frictional force can now be expressed as:

$$F_T = \frac{\eta \cdot v \cdot A_c}{h} \tag{2.4}$$

where η and h represents the kinematic viscosity of water at $0°C$ and the thickness of the lubricating water film, respectively. By introducing the relative real contact area, $relRCA = A_c/A_a$, we get:

$$F_T = \eta \cdot v \cdot A_a \frac{relRCA}{h} \tag{2.5}$$

A higher heat flux can lead to both increased h, which will lead to lower friction, and it can lead to a larger A_c, which leads to higher friction. The balance between them is dependent on the surface roughness of the slider. From Bäurle (2006), the relation between the friction coefficient and the water film thickness is described like this:

"I. Increase in film thickness leads to a sub-proportional growth of the real contact area; overall friction decreases. II. Increase in film thickness leads to an over-proportional growth of the real

contact area, overall friction increases. III. Real area of contact reaches 100%, other processes limit water-film thickness (pressing out, self-balanced film thickness: even thicker films lead to less heat available from shearing, in turn leading to thinner films and so on). Thicker films leading to again lower friction are therefore not expected." As illustrated in figure 2.2.

In other words, at low temperatures ($T \leq -10°C$), we have "dry friction, or boundary friction", or a badly lubricated system with high friction. At intermediate temperatures ($-10°C < T < -1°C$) we expect thicker water films and lower friction. This is also called the "mixed friction" regime. At temperatures close to the melting point ($T > -1°C$), we experience wet lubrication and high friction, due to largely increased contact area.

Remark: The model made by Bäurle (2006) is one of the most complete models made when it comes to ski friction. Trends seen in laboratory measurements though, are not always obeyed in real skiing. This is probably due to the experiments leading to this model was carried out on ice, rather than snow.

2.3 Skis and Snow

The modern cross-country racing ski is a result of many years of technological evolution. The advanced mechanical ski construction and the high-tech materials of the ski-sole both contribute to the low friction experienced when skis glide on snow.

2.3.1 Ski Base Materials

Ski-soles are usually made of a plastic material. Different varieties of ultra high molecular weight polyethylene (UHMWPE) is the material choice for competition cross-country ski-soles. UHMWPE is a suitable material for ski soles because of its low friction properties and good wear resistance. For different snow and weather conditions, different varieties of UHMWPE are chosen. In an earlier research project, Haaland (2013) tested 8 varieties of UHMWPE used in ski soles, and discovered different values of molecular weight and different additives in the tested materials. Some of the additives found includes carbon black and PTFE (teflon). The additives are added to the material to improve different properties, such as friction, hardness and wear resistance.

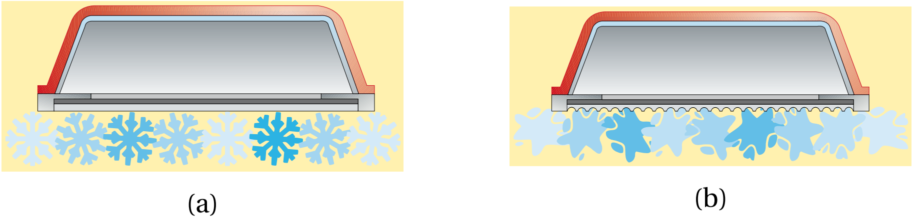

(a) (b)

Figure 2.3: a) Smooth surface structure for cold, crystalline snow. b) Coarse surface structure for old and wet snow (Figures adapted from TOKO (2014))

2.3.2 Surface Structure

For best gliding performance, different snow conditions requires different surface topography on the ski-sole. Smooth surface structures experience best glide on cold, fine-grained crystal structured snow (figure 2.3). A smooth surface ski-sole reduces snow contact area, and requires a thinner lubricating layer to stay in the mixed friction regime while sliding. However, if the temperature in the snow rises, the water film thickness will increase and may lead to higher friction. A coarser ski-base surface structure is then needed to take account for the increased thickness of the water film. The base structure of skis are usually applied with a stone grinding machine. The variety of patterns in base structures is huge, and research is continuously being done to best fit the ski-base surface pattern to different skiing conditions.

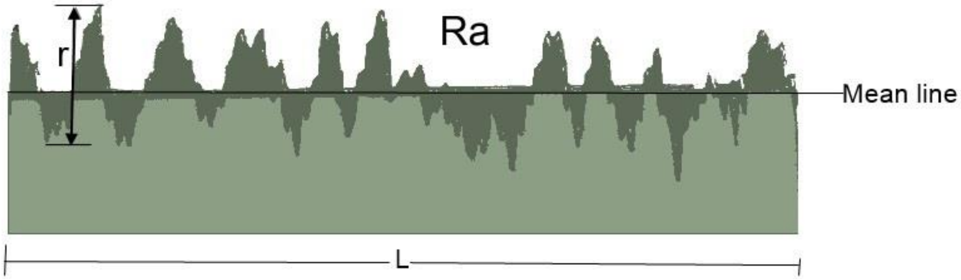


Figure 2.4: R_a is the average height of r over the length L (Alicona (2008))

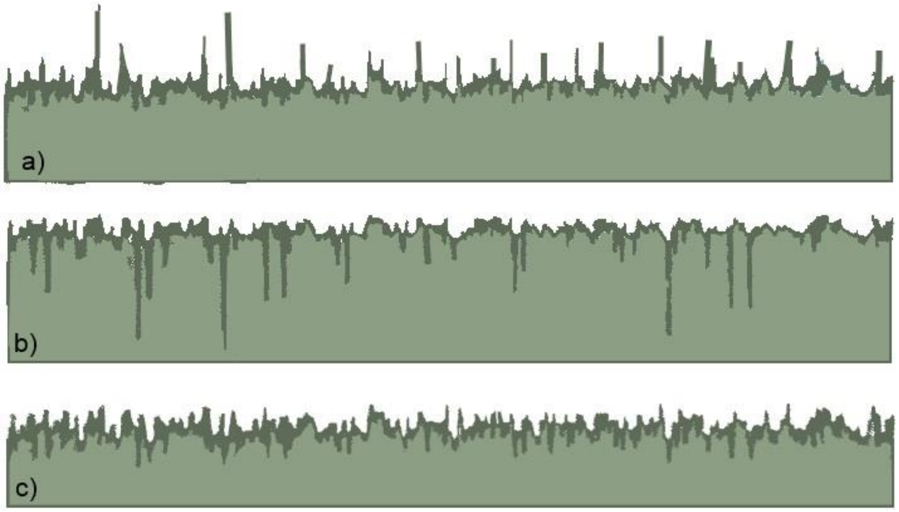


Figure 2.5: Seemingly different roughness profiles, all with the same value of R_a (Alicona (2008))

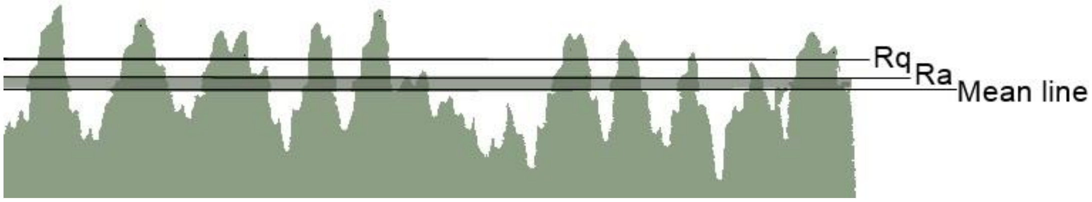


Figure 2.6: R_q takes the height of the peaks into account more than R_a (Alicona (2008))

2.3.3 Roughness

There are many methods to measure how smooth or coarse a surface is. The arithmetic mean roughness (R_a), is the most used parameter to measure ski-base roughness. (R_a) is the area between the roughness profile and the mean value, or the the integral of the roughness height (r) over the evaluated length (L) (See figures 2.4 and 2.5). The R_a does not take peaks and valleys of the roughness into account, it only gives an average roughness number. The mean square average roughness (R_q) takes the heights of peaks more into account (figure 2.6), while the mean spacing of profile irregularities of primary profile (Rsm) is a measurement of the spacing between the irregularities in the profile.

2.3.4 Wear

Cross-country skiing is an endurance sport, and it is crucial that the skis maintain good gliding properties as long as possible during a race. The friction coefficient between skis and snow tends to increase during races, especially when the snow is dirty.

Kuzmin and Tinnsten (2006) performed an experiment to examine the effect ski wax has on the development in gliding performance over several kilometers. The conclusion was that waxed skis lose their advantage over unwaxed skis after a critical distance. The critical distance is not constant, but is influenced by many parameters, such as dirt concentration, utilized racing wax, snow hardness and temperature. Kuzmin and Tinnsten's results shows that a fresh scraped UHMWPE ski sole is more dirt repellent than a ski sole treated with a "dirt repellent wax". They explain the results with the fact that a surface with a higher hardness is more dirt repellant than a surface with a lower hardness, and that the wax treatment leaves traces of ski wax, which undoubtedly has a lower hardness than the UHMWPE ski sole.

UHMWPE is a hard material because of its high molecular weight. Being a polymer, it is defined as a visco-elastic material and the hardness is time-dependent. Time-dependent hardness implies that the hardness increases rapidly if the load time is very short. As a result of extensive technological developments, the hardness of ski sole UHMWPE is now between 30 and 90 MPa, at room temperature, and can be expected to increase in lower temperatures.

Ice and snow hardness is highly variable, and depends on crystal structure, temperature,

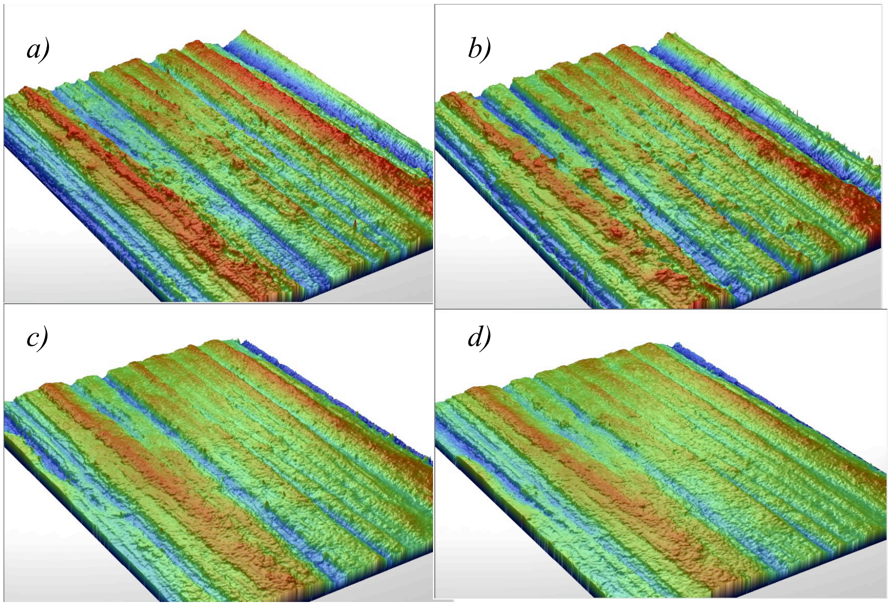


Figure 2.7: Ski base wear after a): Stone grinding, b): Wax preparation, c): Qualification race of Jarnforan, 43 km, -13°C, d): Vasaloppet 2007, 90 km. The comparison is made on the exact same area. Note the major difference after the Jarnforan race. (Adapted from Nilsson (2007))

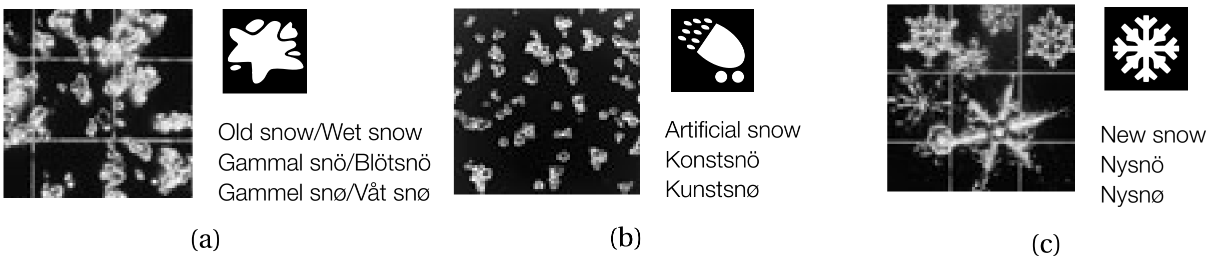
humidity and creep. Barnes et al. (1971) proposes that ice hardness behavior may be linked with the creep properties. Poirier et al. (2011) measured the hardness of ice in the Calgary Olympic Oval ice rink. An ice surface temperature between $-15°C$ and $0°C$ showed ice hardness between 40 and 15 MPa, respectively. Snow hardness is difficult to measure, but, due to lower density, it is likely somewhat lower than ice hardness.

Both wax wear and ski sole wear seems to affect the surface properties of skis. Figure 2.7 shows how a ski base is worn down after skiing 133 km. The roughness is clearly smoothed out.

2.3.5 Snow

Snow is a very complicated material, and its properties are affected by many parameters which are under constant change. Different snow properties requires different ski-sole roughness and gliding wax for optimal glide.

In recent years, the use of artificial snow for ski track making has increased. The main difference between artificial snow and natural snow is that the natural snow crystals freeze from the inside and grows bigger with time. Artificial snow grains are water droplets that freeze from the outside in. When the inner part freezes it expands, the snow grain may break, and leave



(a) (b) (c)

Figure 2.8: a), b) and c) illustrates different snow grains (adapted from TOKO (2014))

Table 2.1: Swix snow characterization table (adapted from Sætha and Lukertsenko (2014))

Artificial Snow	**Natural Snow**	**Grain Size**	**Snow Humidity**	**Track Hardness**	**Track Consistence**
A1 Falling new	FN Falling new	G0 0.0 - 0.2 mm. Ekstra fine	DS Dry	H1 Very soft	T1 Partly shiny
A2 New	NS New	G1 0.2 - 0.5 mm. Very fine	W1 Moist	H2 Soft	T2 Shiny
A3 Irreg. dir. new	IN Irreg. dir. new	G2 0.5 - 1.0 mm. Fine	W2 Wet	H3 Med. hard	
A4 Irreg. dir. Trans	IT Irreg. dir. transf.	G3 1.0 - 2.0 mm. Average	W3 Very wet	H4 Hard	D1 Partly dirty
A5 Transformed	TR Transformed	G4 2.0 - 4.0 mm. Coarse	W4 Slush	H5 Very Hard	D2 Dirty
		G5 >4.0 mm. Very coarse		H6 Ice	

sharp edges. Artificial snow also has higher density, higher hardness and larger contact area than natural snow. The difference between old and new natural snow and artificial snow grains is illustrated in figure 2.8.

SWIX has developed a snow characterization system that helps standardizing all the different kinds of snow (see table 2.1). Snow characterization is one of the most powerful tools when it comes to achieving optimal glide and traction in a ski race. An important factor in the snow characterization process is how the parameter values are obtained. To be able to use earlier experiences to achieve good results at later occasions, it is vital that the same parameter collecting procedures are followed every time; different procedures might lead to different results.

2.4 Friction of Rubber on Ice

The frictional behavior of rubber on ice surfaces has a great significance when studying skid behavior of vehicles in ice. Parameters such as normal pressure, speed and rubber hardness all play an important role to the frictional behavior. Investigations done by Venkatesh (1975); Conant et al. (1949) and Pfalzner (1950), indicates that the coefficient of friction decreases with increased normal force, but ceases to decrease at a certain point. It is suggested that the friction ceases to decrease because the real area of contact ceases to increase at a certain normal force. This has resemblance with the theory of Bäurle (2006) who suggests that the friction stabilizes when the relative real contact area reaches 100%. The investigations by Venkatesh (1975) further indicates that softer rubbers have greater coefficient of friction in a given load range, and that the coefficient of friction increases with speed up to around 0,8 m/s and then decrease. Experiments done with rubber tires skidding on ice by Nordström (2003), confirms that rubbers with high hardness obtain lower sliding friction than softer rubbers in the investigated range from 42 to 70 Shore (see results in figure 2.9).

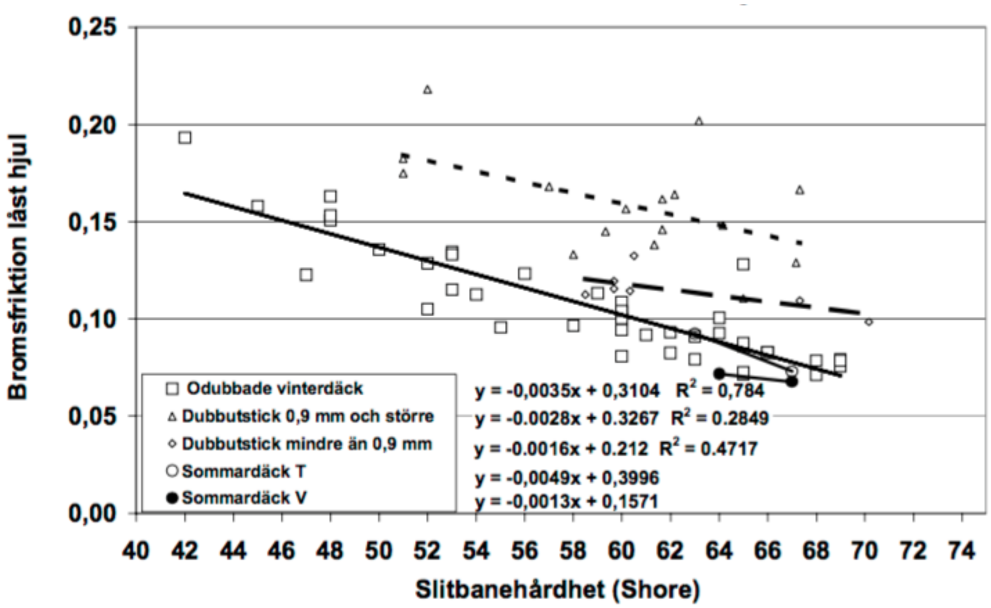


Figure 2.9: Decrease in friction with increased rubber hardness. Squares indicates winter tires without spikes. Friction indicated with the kinematic coefficient of friction. Adapted from Nordström (2003).

2.5 Piezoelectricity

In Britannica Academic Encyclopedia, piezoelectricity is defined as *"the appearance of positive charge on one side of certain nonconducting crystals and negative charge on the opposite side when the crystals are subjected to mechanical pressure."*In piezoelectric force sensors, crystal elements, such as quartz, creates the electrical output when a force is applied. The electrical charge is proportional to the applied force. The reverse reaction is also true. When the same crystal receives an electric current, their dimensions will change. The piezoelectric behavior is illustrated in figure 2.10. The principle of piezoelectricity is useful in force sensors. Piezoelectric sensor react very fast to load changes and are popular in dynamic force measurements. They are widely used in automated manufacturing processes. A piezoelectric force sensor could also be suitable for measuring friction forces between two surfaces sliding one over the other.

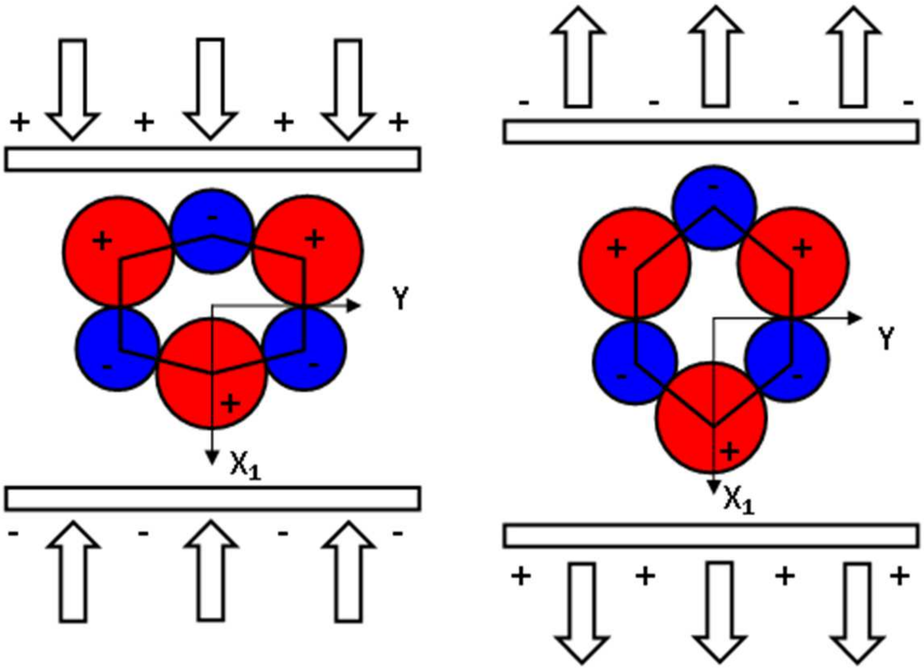


Figure 2.10: Compression and tension generating charge in a quartz crystal. Adapted from Erhart (2013).

Chapter 3

Product Development

3.1 Device Requirements

The goal of the device is to be able to measure the frictional forces of a material sliding on snow or ice with a controlled contact pressure and at a controlled velocity. In this section the requirements to achieve this goal are discussed and defined.

3.1.1 Normal Force

When defining the product requirements for the tribometer, the goal was to make the test conditions as similar to real skiing as possible while getting accurate enough measurements. Temperature, snow configuration and velocity was already defined by the laboratory. What the tribometer must control is the contact pressure (P_c) between test specimen (ski) and test track. The contact pressure is dependent on the normal force and the contact area. From Breitschädel (2014) we know that the contact area on competition skis at full body weight usually lay around 20% - 60% of the ski length, all depending on the stiffness and geometric form of the ski. A ski with a length of 200cm will therefore have a contact length of $40cm - 120cm$. The width of cross-country competition skis usually varies from 41 mm - 45 mm along the ski. The total contact area is then somwhere between:

$$400mm * 43mm = 17200mm^2 \tag{3.1}$$

and

$$1200mm * 43mm = 51600mm^2 \tag{3.2}$$

An average skier weighs $70kg$ or exerts $687N$ vertical force at sea level. The distributed pressure from the ski to the snow is therefore somewhere between:

$$687N/17200mm^2 = 0.04MPa \tag{3.3}$$

and

$$687N/51600mm^2 = 0.01MPa \tag{3.4}$$

To be able to obtain dependable measurements over the 2 meters of test track (at constant velocity), while keeping an even pressure below the ski, the test ski must be fairly short. A 100 mm long test ski sliding over 2 meters of test track at 15 m/s gives a window of 0.12 seconds to obtain measurements. The normal force needed to obtain between 0.01 MPa and 0.04 MPa on a 100 mm * 40 mm test ski is found by:

$$(0.01MPa \rightarrow 0.04MPa) * (100 * 40)mm^2 = 40N \rightarrow 160N \tag{3.5}$$

This is the force needed to reproduce the pressure created by a skier on a ski while skiing. The tribometer must therefore be able to produce at least this force. In addition, to facilitate research possibilities beyond the known parameters, the normal force requirement is set to minimum 1000 N.

3.1.2 Force Measurement Directions

In order to control the normal force, measure the force in the direction of motion and any potential sideways force, continuous measurements should be done in the vertical direction and in two horizontal directions.

3.1.3 Force Measurement Accuracy

Based on experiments done by Sturesson (2008) and Nachbauer et al. (2013) the expected frictional forces are expected to vary between below 0,1 N and below 200 N. The tribometer must therefore be able to measure friction forces up to 200 N with an accuracy of minimum 0,1 N. Based on calculations in section 3.1.1, the normal force will vary between below 40 N up to above 160 N. Normal forces must be measurable up to minimum 160 N with an accuracy of at minimum 1 N. If, at a later time, the test ski contact area should be larger, e.g. if testing is to be performed on real size skis, the normal force measuring range should go above 1000 N. As far as tire friction research is concerned a normal force measuring range above 1000 N is also adequate.

3.1.4 Force Measurement Principle

When it comes to measuring forces, two principles stands out as relevant in this case. Strain gauge and piezoelectric force measuring. Strain gauges can be very accurate and dependable, in all environments. They are often chosen in static measurements, as the measurements have little or no drift. Piezoelectric force sensors can also be very accurate in all environments, but the measurements tend to drift if the experiments are static over long periods of time. The piezoelectric principle though, implies that the sensors are very rigid, and work very good at dynamic measurements due to their fast response. Due to the short operational time, and dynamic nature of the planned friction measurement experiments in this project, a piezoelectric sensor should be chosen for force measurements.

3.1.5 Size and Weight Restrictions

The tribometer must fit inside the winter lab, and be possible to mount to the horizontally moving trolley. The vertical position of the railing in the lab is adjustable from approximately 500 mm to 1500mm above the track. The width of the test trolley is approximately 300mm and the spacing between the vertical supports is 450 mm. The length of the test track is 9 meter with a section of 2 meters in the middle where stable test measurements will be obtained. Test specimen should have a length of approximately 100 mm. When it comes to weight, the setup should

Table 3.1: A summary of the device requirements

#	**Requirement**	**Must**	**Should**
1	Exerted normal force	200 N	1000 N
2	Normal force measurement limit		1000 N
3	Normal force measurement accuracy	1 N	
4	Horizontal force measurement limit	100 N	200 N
5	Horizontal force measurement accuracy	0.1 N	0.01 N
6	Maximum height	750 mm	
7	Maximum length	1500 mm	
8	Maximum width	500 mm	
9	Maximum weight (without snow sledge)	30 kg	
10	Mobility	Mobile	
11	Rigidity	Stiff	

be as light as possible to keep inertial forces to a minimum. As per design criterion for the drive system in the snow lab the weight should not exceed 30 kg.

3.1.6 Mobility

Outdoor measurements in skiing or ice skating tracks are desired. Also, as the winter lab will not be ready before the due date of this master project, initial testing must be performed elsewhere. Hence, the tribometer should be mobile and flexible enough to perform outdoor initial testing. A stable snow sledge construction should be connected to the tribometer.

3.1.7 Rigidity

Due to very high accelerations in the friction track, up to $36 m/s^2$, the construction must be sufficiently rigid. This is also very important in order to keep the measurements as clean and noise free as possible.

3.1.8 Summary of Device Requirements

All the device requirements are summarized in table 3.1.

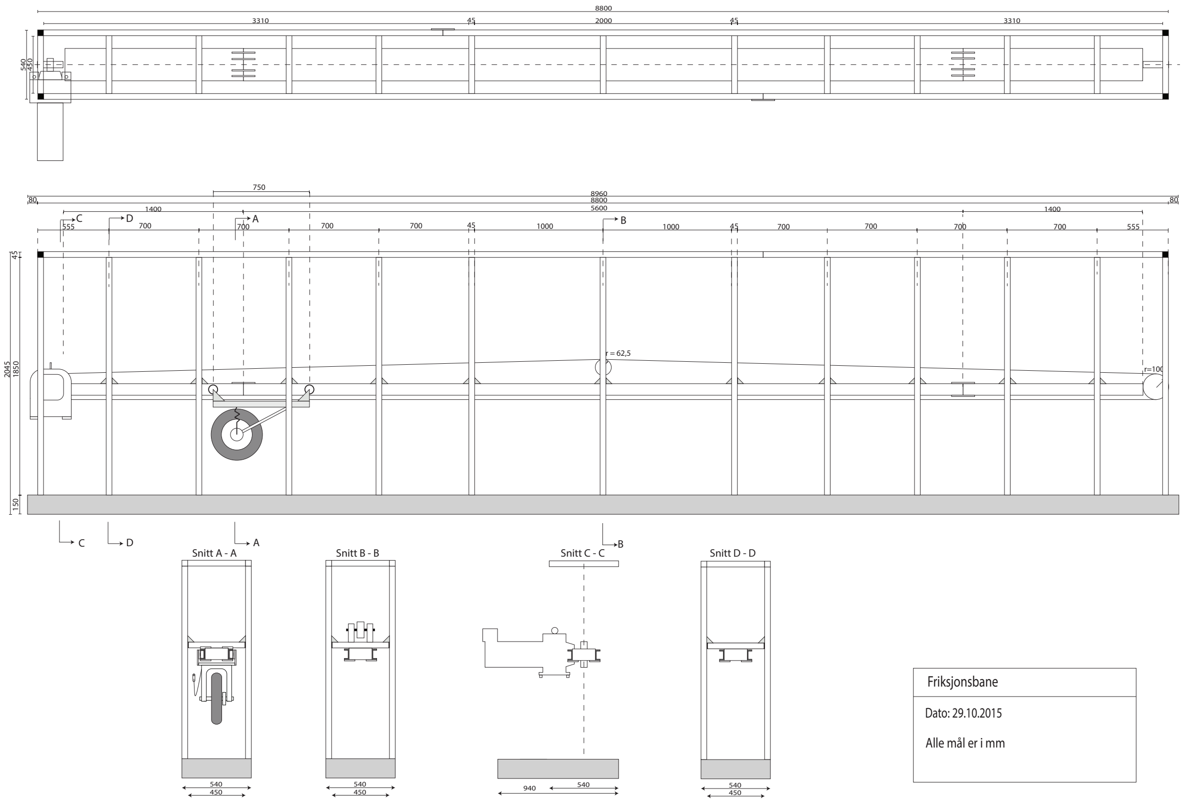


Figure 3.1: Early drawing of the winter test lab

3.2 Design Process

The design process was divided into four sections:

1. Defining/deciding major functions
2. Evaluate different solutions to the chosen functions
3. Detailed design of the different solutions
4. Design of the complete tribometer

3.2.1 Defining Functions

The functions needed to fulfill the requirements of the tribometer are:

1. Variable normal force exertion

2. Measuring of effective vertical and horizontal forces
3. Rigid frame construction
4. Snow sledge construction for outdoor testing
5. Transition between sensor and normal force actuator

3.2.2 Normal Force

The normal force function can be solved in many different ways. The evaluated solutions are: pneumatic cylinder, hydraulic cylinder, electrial actuator, measuring weights and manual actuator. Advantages and disadvantages of the different solutions are found in table 3.2. In order to adequately adjust the normal force, as well as adjust for uneven test surfaces, all of the solutions, except the pneumatic cylinder would need to be combined with a shock absorber. The compressible air in a pneumatic cylinder would act as a shock absorber it self. Figure 3.3 presents the different solutions graphically. In this project, the manual actuator was chosen. It gives the opportunity to a self locking, continuous adjustment of vertical force without the need of an external power source. The sensitivity can be chosen by the stiffness of the shock absorber spring and the pitch of the threads. The chosen solution is shown in figure 3.2. For the transition between the manual actuator and the shock absorber, some analysis was done to make sure the components would stand the load of 1000 N vertical force. To achieve an adequate thread depth, the inner component was designed to be cut out of a 10mm steel plate. The outer component was designed to be cut and bent out of a 5 mm steel plate. FEM analysis showed that a safety factor of at around 10 could be anticipated for the outer component, and an even larger safety factor was predicted for the inner part. Drawings of these parts are found in appendix B.17 and B.18.

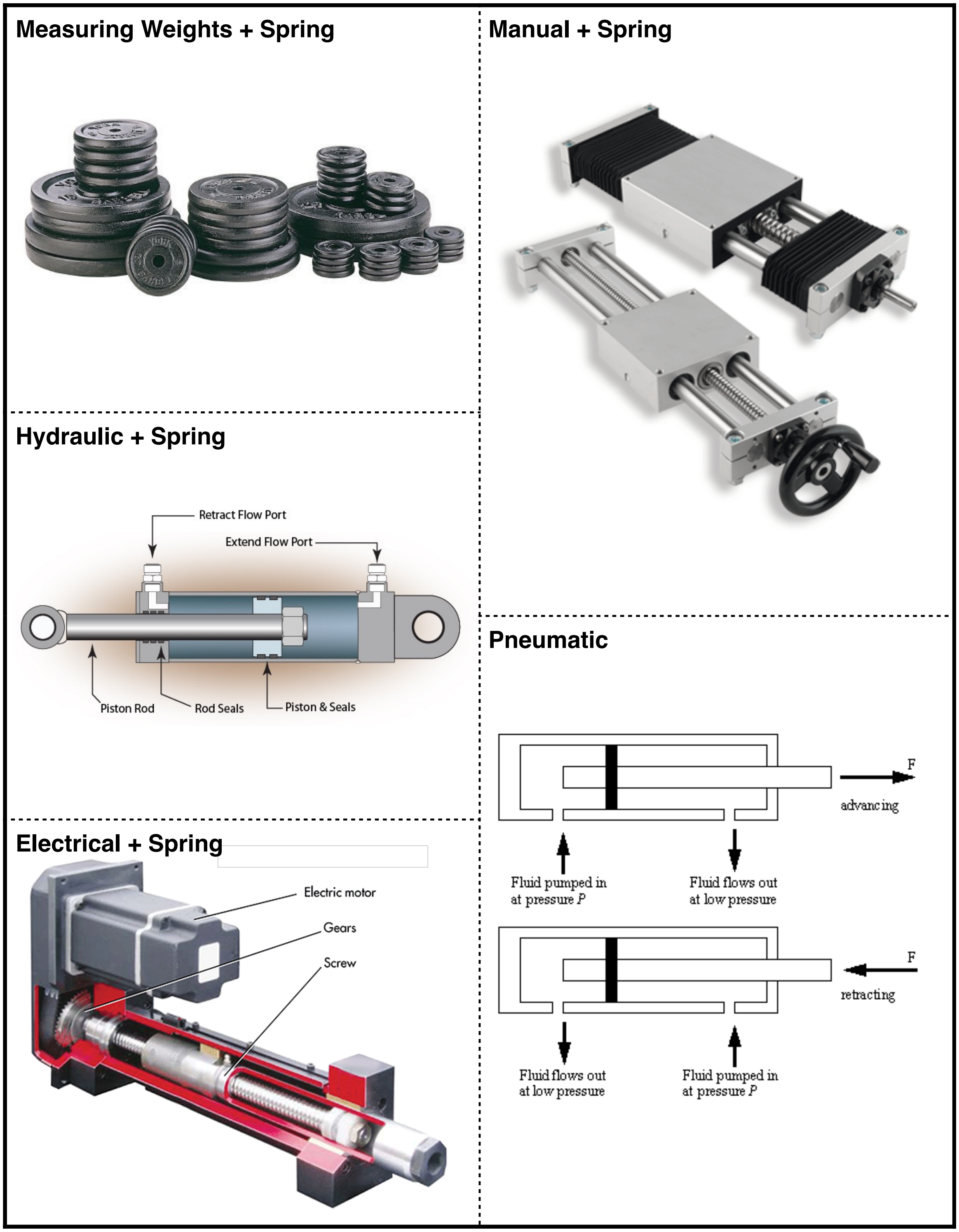
3.2.3 Measurements

Many considerations were made when deciding which measuring sensor that was best suited for this project. The measuring equipment must be very accurate, but also strong and durable.

Figure 3.2: Manual actuator combined with a shock absorber to exert normal force on the test ski.

Table 3.2: Advantages and disadvantages with the different normal force solutions.

Solution	Pros	Cons
Pneumatic cylinder	Clean Fast Provides damping Continous	Requires compressed air Low power to size ratio Pressure drop Noisy
Hydraulic cylinder	High power to size ratio Smooth Continous	Might spill oil Requires lots of equipment Heavy Noisy
Dead weights	Simple	Stepwise Heavy
Manual actuator	Self locking Continous Quiet	Requires man power
Electrical actuator	Self locking Continous Quiet	Requires power supply



Measuring Weights + Spring

Manual + Spring

Hydraulic + Spring

Pneumatic

Electrical + Spring

Figure 3.3: Different normal force solutions. Measuring weights and manual, hydraulic and electrical actuators would all be connected to a shock absorber. Illustrative pictures.

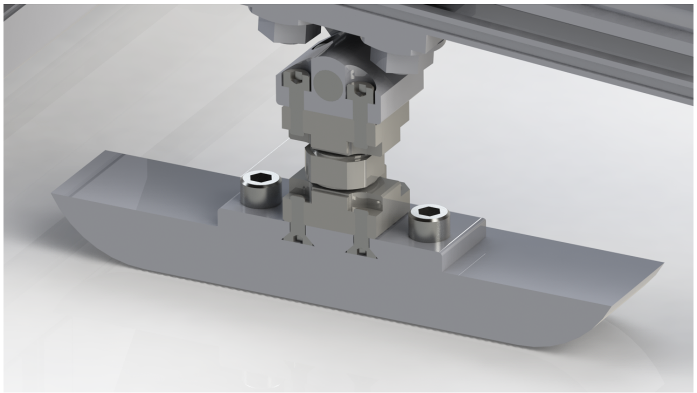


Figure 3.4: Section view of the strut profile-sensor-ski connection.

(a)

(b)

Figure 3.5: a) Kistler 9317c force sensor. Adapted from Kistler (2014) b) Kistler 5073a charge amplifier. Adapded from Kistler (2015)

The chosen sensor is a Kistler 9317c 3-component piezoelectric force sensor. The sensor offers very high sensitivity as well as a wide range, and is also strong and durable.

The sensor will be fixed on top of the test ski, and connected to the rest of the construction with a rotational degree of freedom about the horizontal axis normal to the direction of motion. This connection is shown in figure 3.4. In addition to the sensor, a small signal amplifier and a battery pack will be installed on the tribometer. The amplifier chosen is a Kistler 5073a 4-Channel Charge Amplifier, adjustable Range up to 1000000 pC. The amplifier converts the pC signals from the sensor to mV signals that can be read on a PC. It requires a power source of $\pm 20V$ and has an idle power consumption of approximately 250 mA. The sensor and amplifier are shown in figure 3.5.

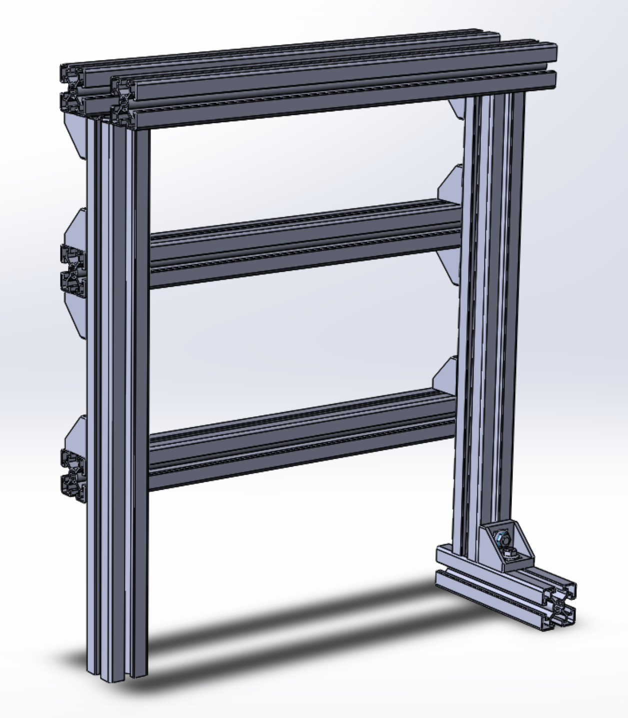


Figure 3.6: Model of the tribometer aluminium strut profile frame.

3.2.4 Rigid Frame Construction

The construction must be rigid to avoid vibrations. At the BAT winter-lab, aluminium strut profiles are used to build the tribometer construction. The same strut profiles will be used in the supporting frame construction of this tribometer. This will facilitate the installation of the tribometer in the winter-lab, as well as sharing of resources. The strut profiles are ordered from Bosch-Rexroth, who also offers various connector elements. A model of the frame is shown in 3.6.

3.2.5 Snow Sledge Construction for Outdoor Testing

For outdoor testing the tribometer must be stable while sliding in high velocities on snow and ice. Testing could be done by sliding the tribometer down a snow covered hill, or by pulling it at a controlled velocity with a pulling device. The tribometer should therefore be placed between two full size skis by a rigid connection. To avoid wobbling and high moments, there should be two connector points between each ski and the tribometer construction. The final snow sledge is shown is figure 3.7.

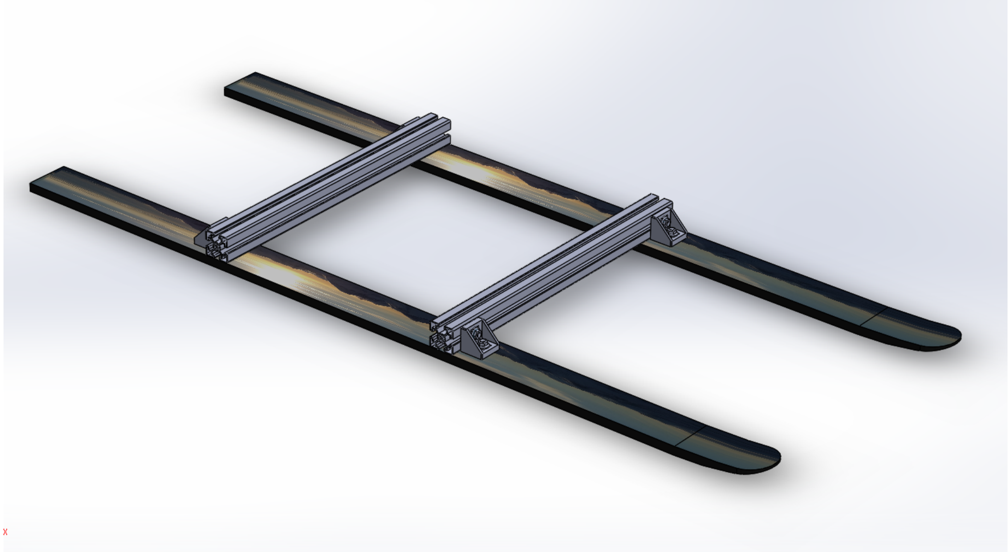


Figure 3.7: Snow sledge to be mounted below the tribometer.

3.2.6 Transition Between Sensor and Normal Force Actuator

Two concepts were considered for the transition between the sensor and the normal force actuator. One included two linear sliding bearings on each side of a strut. The other concept was a strut connected to a pivot point (both illustrated in figure 3.8). The pivot point solution was chosen because of its simplicity and adequate behavior. The thought problem of the sliding bearings solution was that the strut could possibly angle out of its horizontal position, transferring a large moment to the slide bearings and get stuck.

3.2.7 Final Concept

The final concept consists of a manual linear vertical actuator connected to a shock absorber for normal force exertion. The chosen manual actuator was a Rollco QME - 12 - 150 linear actuator. The QME unit will be self locked beyond 1000N and can travel 150 mm. The chosen shock absorber is a RockShox Vivid R2C bicycle shock absorber. It has a stiffness of 39,4 N/mm and a travel length of 89 mm. To obtain the required normal force, and still keep the sledge steady, two 10kg steel weight units are to be placed on top of the tribometer. The transition between the normal force actuator and the force sensor is by a pivoted strut profile. The measurements are performed by a Kistler 9317c piezoelectric force sensor and the signals are sent through a Kistler 5073a charge amplifier. Ski sole specimen will be fixed to a solid aluminium test ski with double

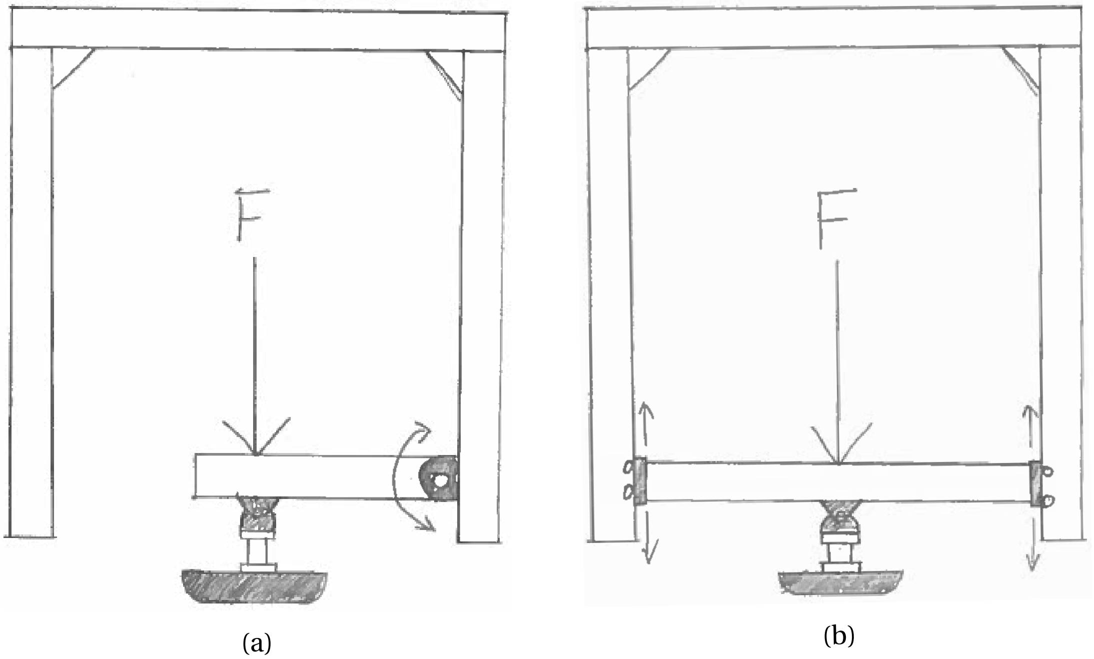


Figure 3.8: a) Pivot strut concept. b) Sliding strut concept.

sided tape. For testing friction properties between rubber and ice, a calibrated set of rubber blocks with different rubber hardness will be used. The blocks will be placed in a special holder, illustrated in figure 4.2. The tribometer has a rigid frame made from Bosch-Rexroth aluminium strut profiles and various connector elements. For outdoor testing, two skis are firmly mounted under the tribometer construction. The final design is shown in figure 3.10. When the new winter-lab at BAT is ready, the snow sledge can be dismounted from the tribometer, and the tribometer can be mounted to the trolley in the lab. With and without the snow sledge, the tribometer weighs in at 23 kg and 17 kg, respectively. See figure 3.9 for the part of the tribometer that is planned to be installed in the winter-lab.

3.3 Production Process

The design process and the production process was overlapping for the larger part of the project. As soon as the major design specifications were decided, major components were ordered. The aluminium strut profiles was first to arrive. They struts arrived in lengths of 5 meter, and were cut to design measures at BAT. The frame was built by adding connector brackets. The manual

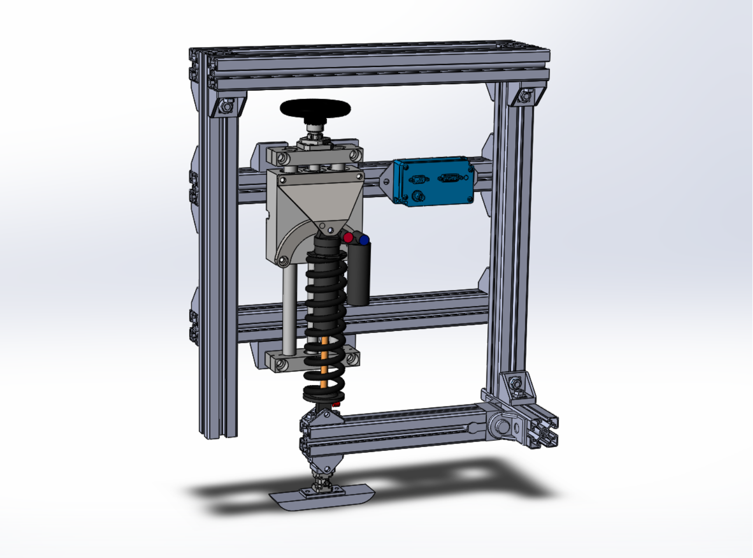


Figure 3.9: Lab version of the tribometer.

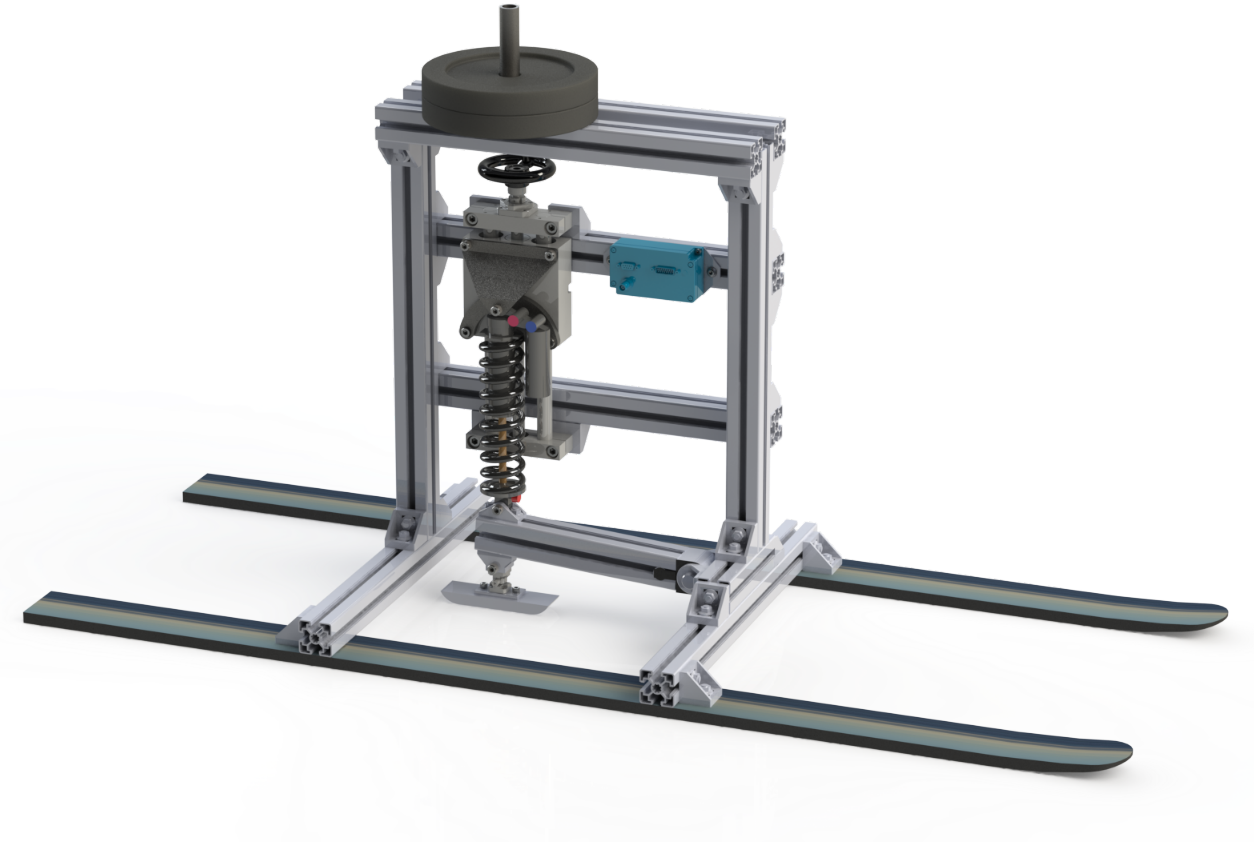


Figure 3.10: Final 3D render of the tribometer. For clearity, cables and battery pack are not visualized.

actuator was second to arrive. It was ordered from Rollco Norge AS, and arrived as an almost complete unit. In order to mount the adjustment wheel a hole was drilled in the center axle, and a pin was inserted to fix the wheel. The grooves in the aluminium profiles and the connector elements made it straightforward to install the manual actuator.

Before the pivot arm system was built, some design iterations had to be done (see figure 3.12 for different suggestions). The final design of the pivot arm was the simplest one, and it worked out very good.

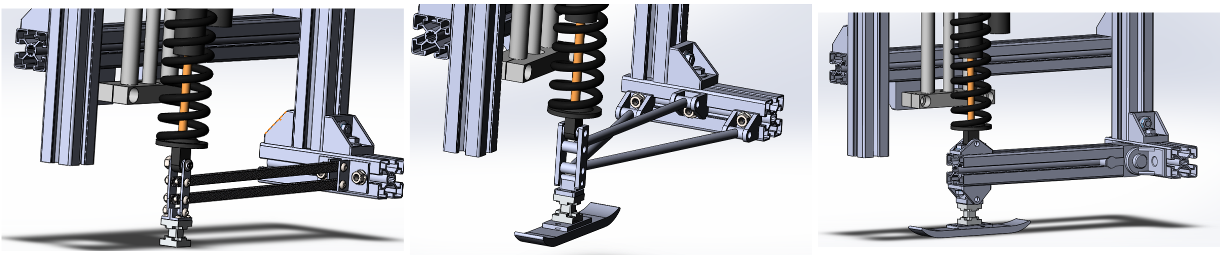
The snow sledge was also subjected to design alterations. The first design had the skis fixed to the tribometer at a single point on each ski. It turned out to be too wobbly. The design was the changed so that each ski was fixed to the tribometer at two points. The eary sled design is shown in figure 3.11a.

The charge amplifier requires an 18V - 30V external power source to be operated. According to the manual (Kistler (2012)), the power consumption is < 250 mA. Two 12V 1,5 Ah batteries connected in series was therefore mounted to the tribometer.

The transition between the actuator and the shock absorber turned out to be a constructional problem. It was not possible to construct the angled bracket (see figure 3.11b) at the IPM workshop, and the assignment was therefore "outsourced" to "Skanke Stål og Sveis" at Heimdal. They managed to produce a good component, and eventually the bracket was picked up at Heimdal, adjusted a little bit and mounted at the tribometer. Sensor, amplifier and computer rack was then mounted, and the tribometer was ready for testing. Testing was performed on february 17th (as seen in figure 3.13).

(a) (b)

Figure 3.11: a) Tribometer with an early sled design. b) Angled bracket for the transition between the manual actuator and the shock absorber.



(a) (b) (c)

Figure 3.12: Different versions of the pivot arm. a) Carbon strut pivot. b) A-frame pivot. c) Aluminium strut profile pivot.

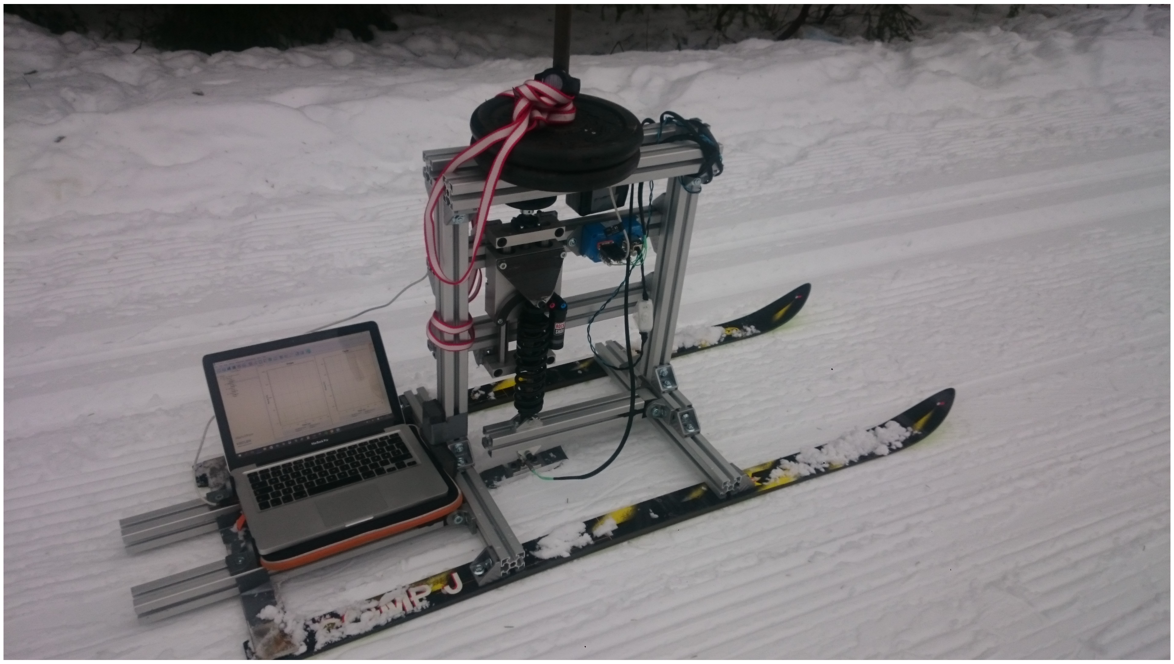


Figure 3.13: Tribometer during testing on snow.

Chapter 4

Testing

Initial testing was performed on wednesday february 17th, 2016. The location was Lohove, near Dragvoll, in Trondheim.

4.1 Goal

The goal of the initial testing is to evaluate the performance of the test apparatus while measuring friction between polyethylene and snow, and between rubber and ice.

4.2 Test plan

Two test procedures were planned for the initial testing:

1. With normal force varying between 40 N and 160 N, to test the friction between a polyethylene ski sole and a freshly groomed ski track. Test track should be a straight hill, ending in a straight flat. Adequate speeds should be obtained by letting the friction meter slide down the hill. Based on the theory in section 2.2.1, the friction force is expected to increase with increased normal force due to higher relative real contact area. If the relative real contact area increases above approximately 80%, the friction may be reduced.
2. With rubber hardness varying between 30.4 and 89.4 Shore and constant normal force at 100 N, to test the friction between blocks of rubber and an ice surface. The rubber

DUROMETER TEST BLOCK KIT

REX GAUGE TBK-A

TYPE	BLUE	RED	ORANGE	YELLOW	BROWN	BLACK	GRAY
A	30.4	42.7	50.0	63.2	72.7	79.7	89.4

SERIAL NO. 082911MM

TEMPERATURE 70°

HUMIDITY 45%

CALIBRATED

DATE DUE

The indicated readings are derived from an average of six reading taken with a Rex Durometer (**½"Diameter Foot**) calibrated per **ASTM D 2240**. For periodic verification of calibration accuracy, take an average of 3 readings in different spots on each test block. The results should be approximate to those shown above within **± 2 duro points** (Type M ± 4 duro points). Made in USA.

Result comparisons may vary between durometers with non-similar foot configurations.

Figure 4.1: Rex Gauge durometer test block kit. Used for friction testing on ice. The dimensions of the rubber blocks are 51mm x 51mm x 7mm.

blocks are calibrated by Rex Gauge Company, and works as a test kit. The kit is shown on figure 4.1. The test track should be a clean, even and flat ice surface. Adequate speeds should be obtained by manually pushing the friction meter along the ice surface. Based on the theory in section 2.4, the friction force is expected to decrease with increased rubber hardness.

4.3 Test Procedure

Date: *17.02.2016*

Location: *Lohove, Trondheim*

Air temperature: $3^{\circ}C$

Weather: *Partly clouded*

Right before the snow testing was initiated, the snow track was groomed. The friction meter was sent down a hill at a controlled speed (approximately 1 m/s) and a normal force of 40 N. The results from the first test showed a highly variable horizontal force, ranging from 0 N to above 300 N. The results did not look like a representable measurement, so another test was performed. The same results was obtained from the second test. When observing the behavior of the test ski during the test run it was clear that the small size of the test ski, combined with the soft snow surface, forced the ski to repeatedly dig into the snow, creating a sort of start-stop motion. When observing the polyethylene sole after a few test runs, snow had got stuck and accumulated on the sole, making sliding impossible. Circumstances taken into account, the decision was made to abort the snow testing procedure.

The friction meter was then moved to the ice to perform friction testing on the rubber blocks. The ice was covered in a thin water layer. The rubber blocks were placed in the aluminium holder made especially for this purpose (see figure 4.2). The ice was not perfectly even, but good enough for the friction meter to maintain a fairly even speed (with a little help from a pushing arm). The rubber blocks were each tested twice to get more representative samples. The uneven ice surface occasionally caused the rubber blocks to get stuck on the ice, leading the friction meter to a full stop. These stop motions was considered possibly harmful to the sensor, so the rubber testing ended after two test runs on each hardness. The measurements showed a variable horizontal force, but much more even than from the snow test. On average, the test time was 15,3 seconds. The trend shows a lower frictional force, and a lower coefficient of friction with higher rubber hardness.

After the successful rubber testing, it was decided to perform ski sole testing with variable normal force on the ice rather than on the snow. The procedure was the same as with the rubber

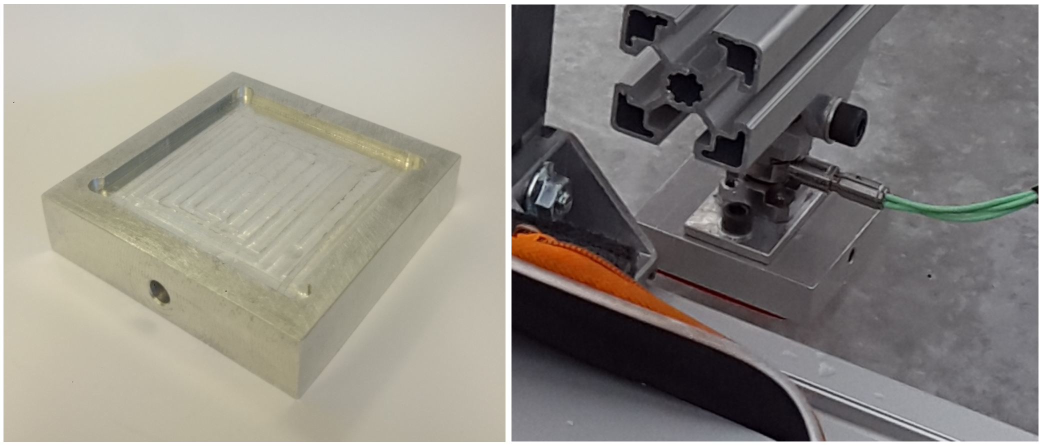


Figure 4.2: The aluminium holder for rubber blocks.

Figure 4.3: Friction meter in action on ice.

blocks. Ski sole tests were performed with normal force of 50 N and 100 N. Unfortunately, after only two test runs with the ski sole, the measurement apparatus stopped working properly. The testing session was therefore terminated (All functions are working properly after having the tribometer indoors over the night). The results from the testing are presented in the next section. The friction meter during testing on ice is shown in figure 4.3.

4.4 Results

The results are graphically presented in the figures 4.4, 4.5, 4.6 and B.16 in this section. The friction force and normal force test data is manually read from test graphs generated by the Kistler software ManuWare (See figure 4.4). Mean values from each run are calculated in Excel. The normal force was quite unstable, probably due to the uneven ice surface. The friction is therefore represented as the kinematic coefficient of friction (μ), which is defined in equation 2.1. The test motion was monitored with a GPS device mounted to the friction meter. The GPS file shows that all the rubber block tests were performed at a speed of approximately 1 m/s. The preliminary measurement apparatus has a measurement reading frequency of approximately 1,3 Hz.

4.5 Discussion

The results from the rubber testing are as expected from theory. The trend is showing a reduction in friction as the rubber hardness increases. The repeatability is not very good, indicating large uncertainties in these results. With more test samples, a more even ice surface, better speed control and better data acquisition tools, the repeatability is expected to be better and the trend to be even clearer. The results from the ski sole testing indicates that an increase in contact pressure reduces the frictional force of polyethylene sliding on ice. With only two samples, the uncertainty of these results are also very large. The results indicates that the set-up is working. With a few tweaks, the tribometer will be a useful tool for investigating frictional properties of different materials sliding on ice and snow.

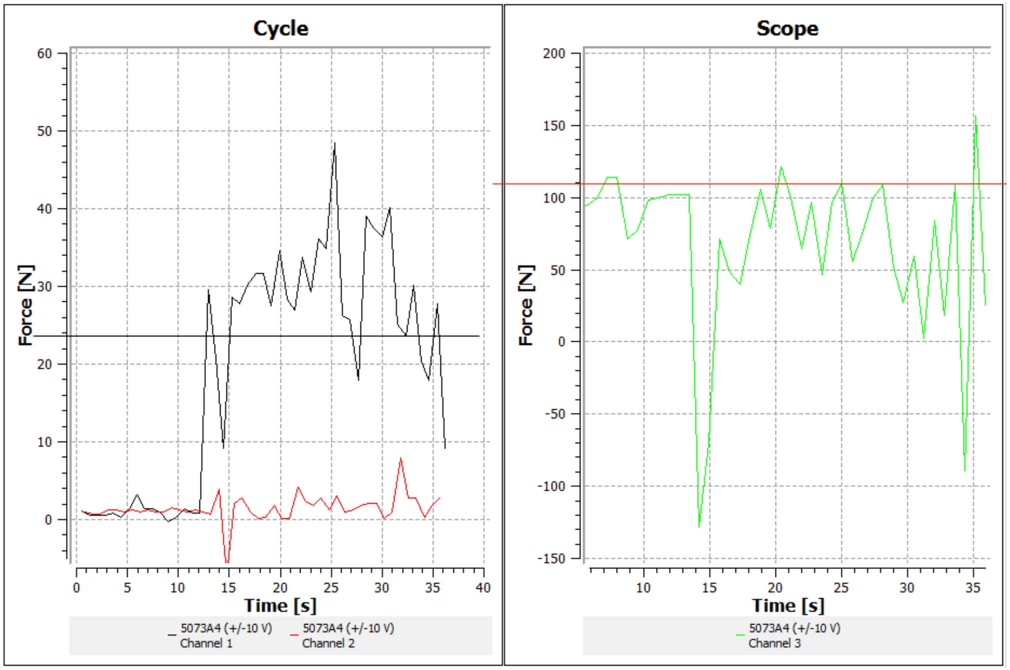


Figure 4.4: Example of test data generated by ManuWare. Channel 1 (black) shows the horizontal force in the gliding direction. Channel 2 (red) shows the horizontal force normal to the gliding direction. Channel 3 (green) shows the normal force. The horizontal lines are used to make readings of the graphs. A higher sample frequency and raw data extraction would greatly improve the quality of the results.

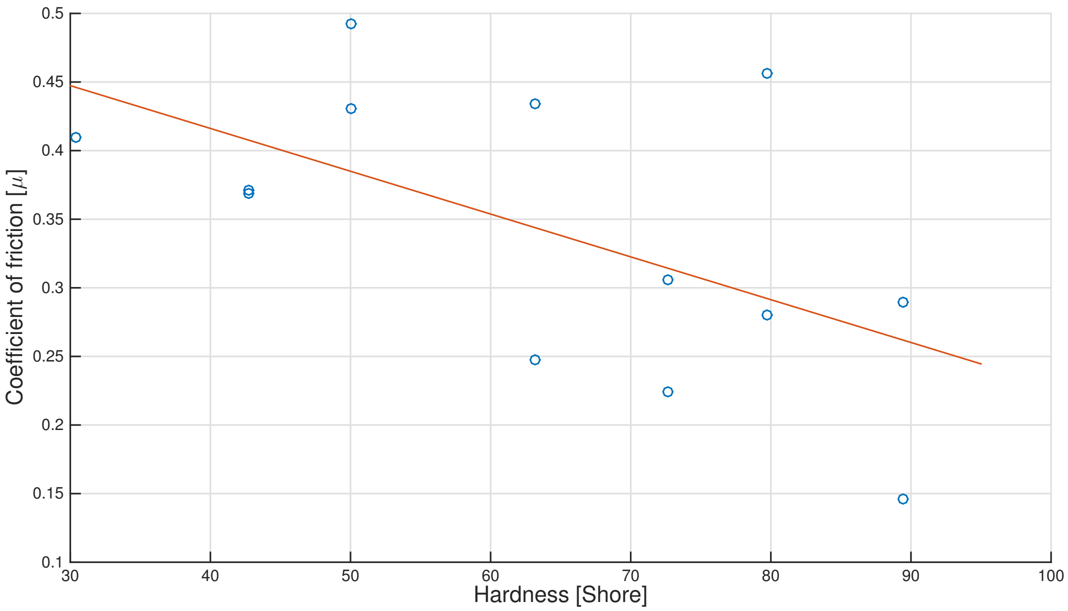


Figure 4.5: Test 1: Rubber on ice with an initial normal force of 100 N. The trend shows a decreased coefficient of friction with increased rubber hardness.

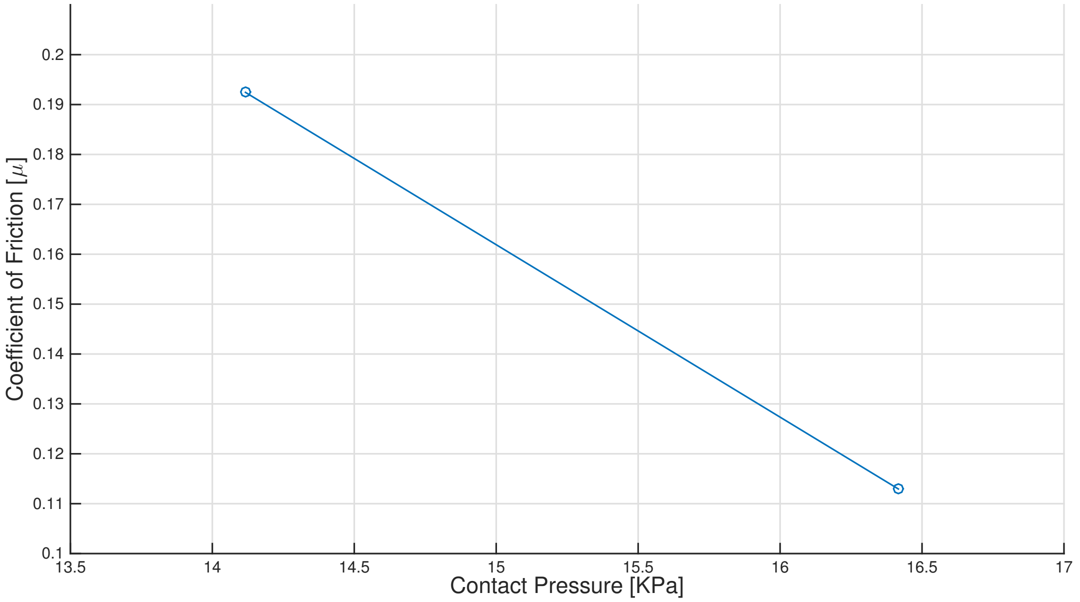


Figure 4.6: Test 2: Polyethylene on ice. Reduced coefficient of friction with increased contact pressure.

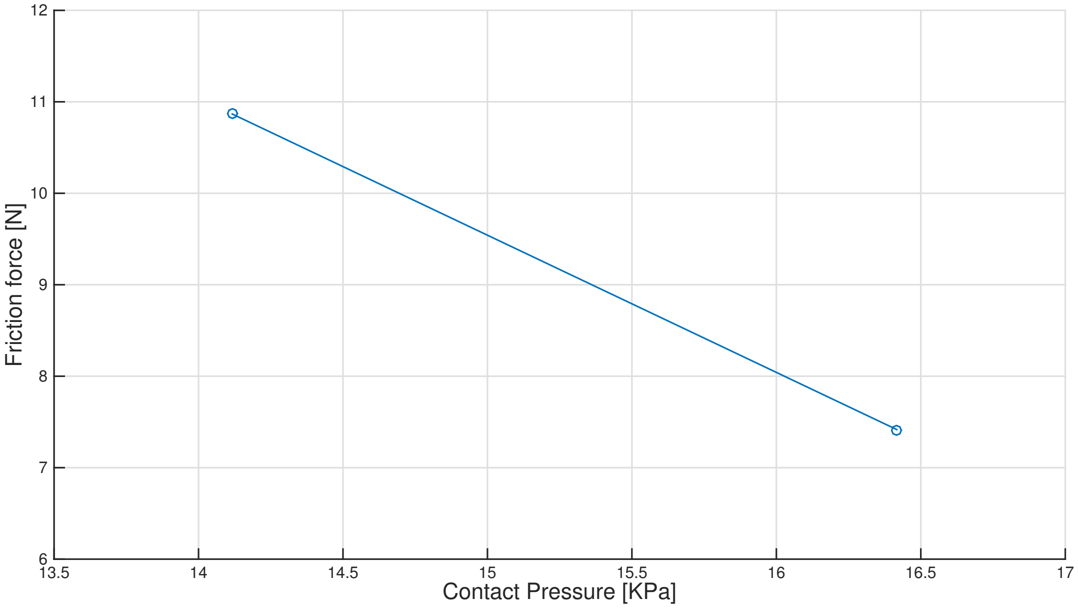


Figure 4.7: Test 2: Polyethylene on ice. Reduced friction force with increased contact pressure.

Chapter 5

Summary and Conclusions

5.1 Summary and Discussion

A versatile, mobile, tough and high accuracy linear tribometer have been designed, built and tested. Initial testing proves that the set-up is working, and that it is capable of measuring small differences in low frictional forces of materials sliding on ice. Testing was performed at low speeds (1 m/s), but if the test surface is even, there are no indications that higher test speeds will cause difficulties. For high speed testing on ice, ice blades should be considered instead of skis on the sledge.

During testing on snow, the ski seemed do dig into the snow, hence increasing the horizontal force because of heavy ploughing. A solution to this problem might be to increase the length and/or width of the test ski. The snow accumulation on the ski sole may be a result of dirt presence on the sole. A clean ski sole should not experience the amount of snow accumulation that was registered during the test procedure in this project. Finding the proper hill for snow testing is necessary in order to obtain useful measurements. The friction meter is mobile, but the weight could be considered reduced. Two people, or a sophisticated pulling device is needed to navigate the device through the ski tracks. The sample frequency should have been much higher than 1,3 Hz, but for the time being it is not possible to adjust this parameter with the used data logger software. This issue is probably possible to change with small computer actions.

The normal force during test runs was highly variable (see appendix B.1 for all test graphs). To get better measurements on uneven surfaces, a softer spring may be considered. To obtain a normal force of 100 N the spring only needs to be compressed about 2,5 mm. A travel length of 89 mm is available and could be put to use with a softer spring.

The functional stop at the end of the test procedure, and that all functions are working properly after a night indoors, might indicate that the tribometer has issues with operating in cold/moist environments for long periods (hours). One explanation could be that the battery voltage was reduced due to power consumption and cold temperatures. Another explanation could be that the the charge amplifier has operating issues at low temperatures (stated minimum operating temperature for Kistler 5073a charge amplifier is $0°C$, according to Kistler (2015)).

5.2 Conclusions

The tribometer has been developed, and initial testing proves that most functions are working according to requirements. With some adjustments and improvements, the tribometer will most likely be an effective tool for measuring low friction forces of all kinds of materials sliding on snow and ice surfaces. The tribometer can be utilized both outdoors, e.g. in ski tracks or ice rinks, or in laboratories such as the new snow lab at NTNU. The tribometer can be a useful tool in research to optimize friction in sports or research regarding tire friction and road safety on winter conditions.

5.3 Recommendations for Further Work

- Improve data logger software
- Improve test ski for snow testing
- Reduce weight to improve mobility
- Perform further testing to validate sensor performance

Appendix A

Acronyms

NTNU Norwegian University of Science and Technology

IPM Department of Engineering Design and Materials

BAT Department of Civil and Transport Engineering

GPS Global Positioning System

relRCA Relative Real Contact Area

UHMWPE Ultra High Molecular Weight Polyethene

PTFE Polytetrafluoroethylene

Appendix B

Additional Information

B.1 Graphs generated by ManuWare

Channel 1: Horizontal force along direction of motion, Channel 2: Horizontal force normal to direction of motion, Channel 3: Normal force.

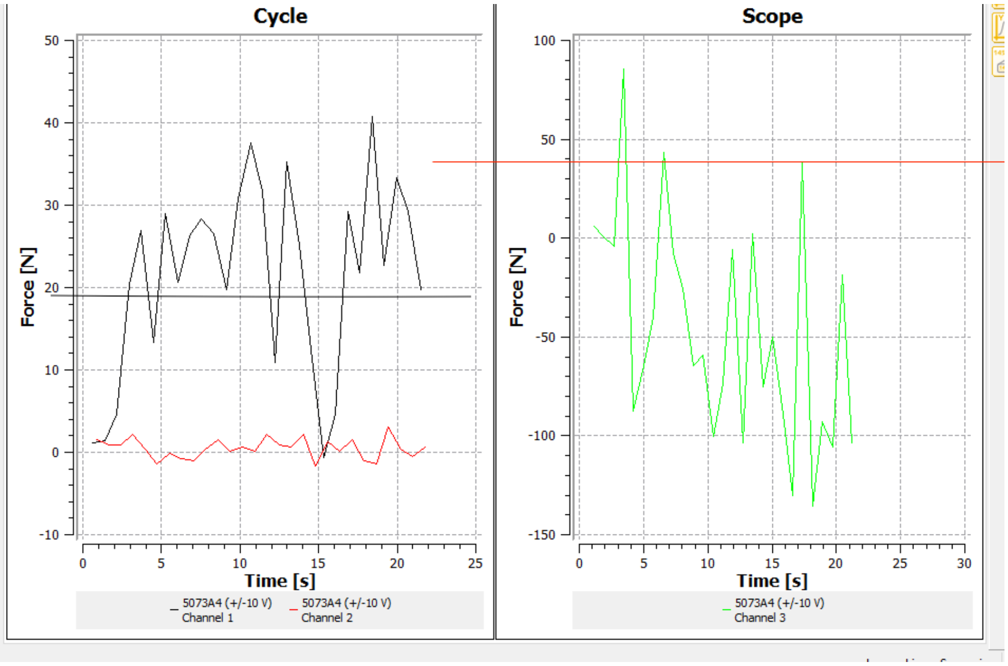


Figure B.1: Friction test with rubber on ice. Rubber hardness: 30,4 Shore.

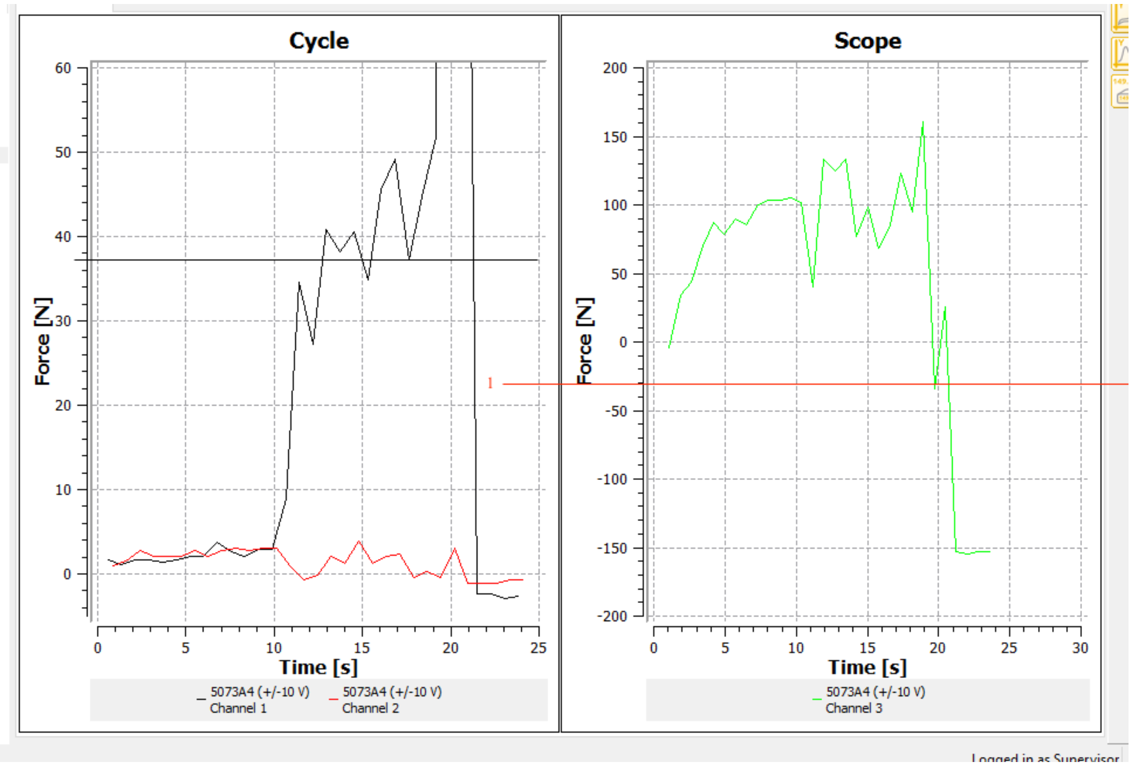


Figure B.2: Friction test with rubber on ice. Rubber hardness: 30,4 Shore.

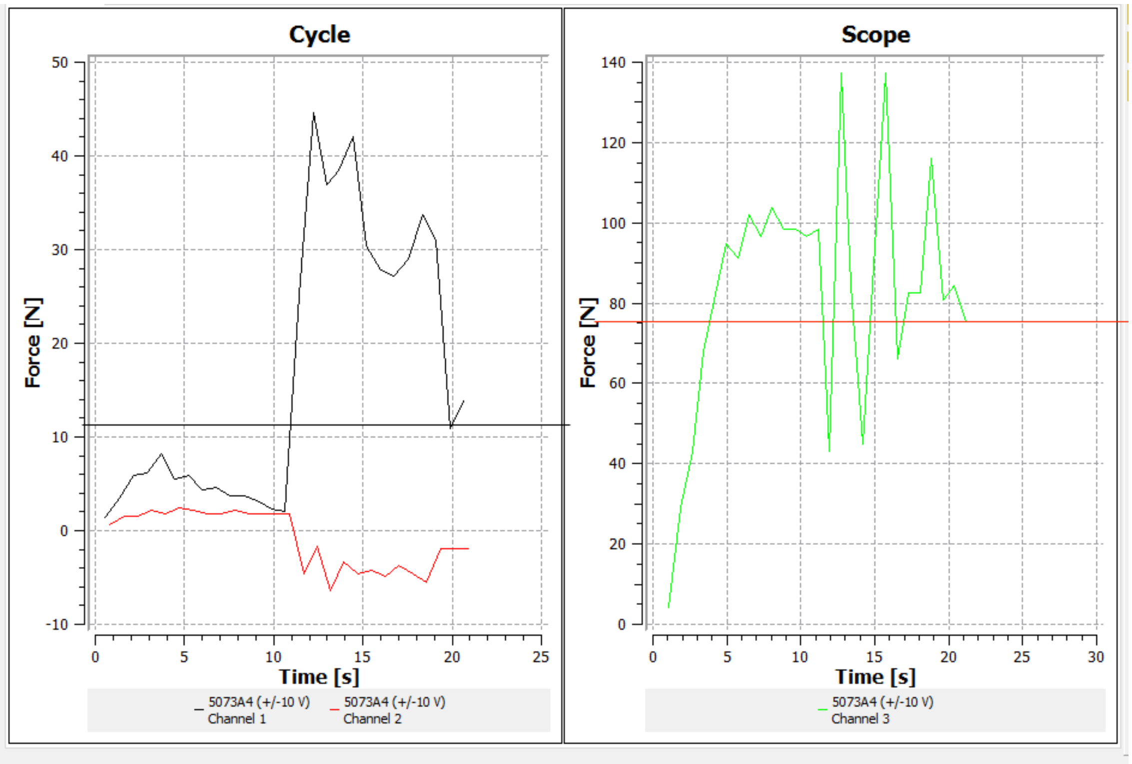


Figure B.3: Friction test with rubber on ice. Rubber hardness: 42,7 Shore.

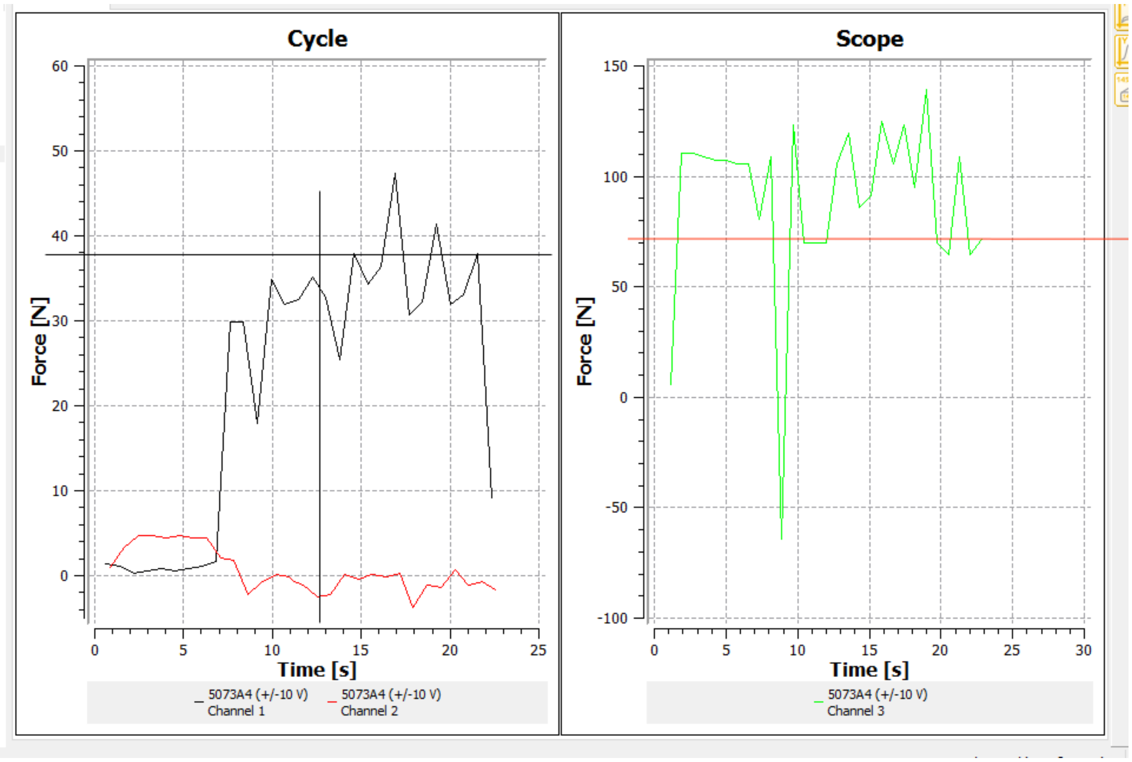


Figure B.4: Friction test with rubber on ice. Rubber hardness: 42,7 Shore.

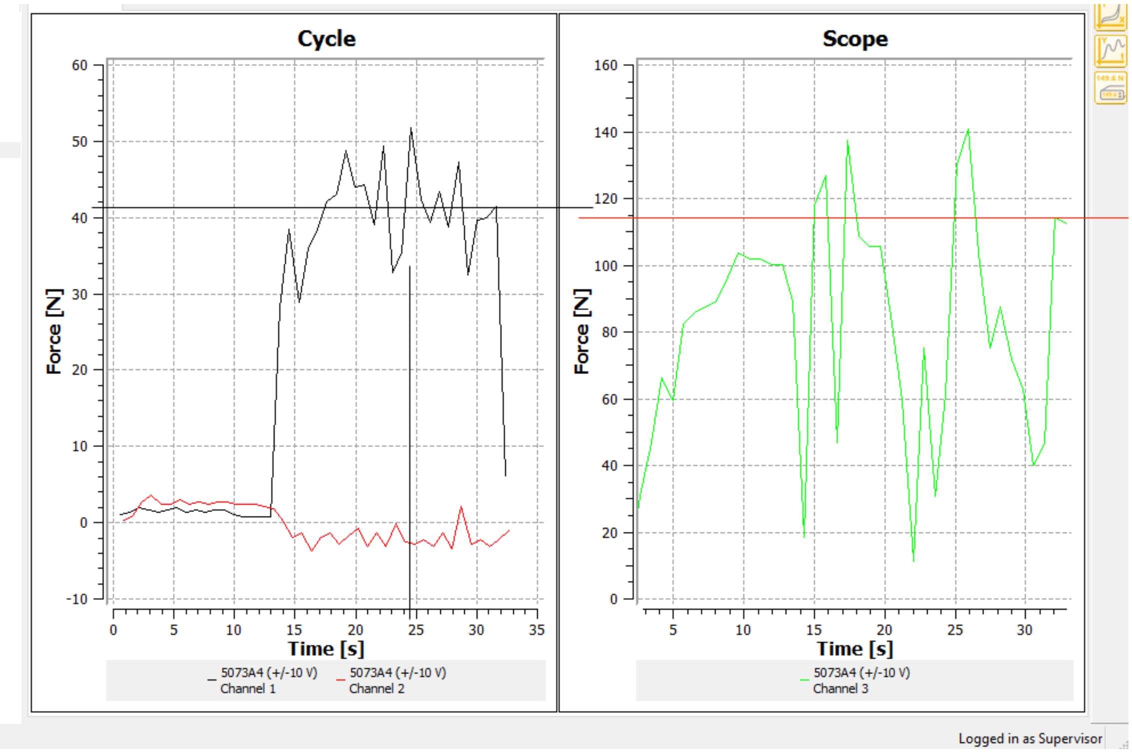


Figure B.5: Friction test with rubber on ice. Rubber hardness: 50,0 Shore.

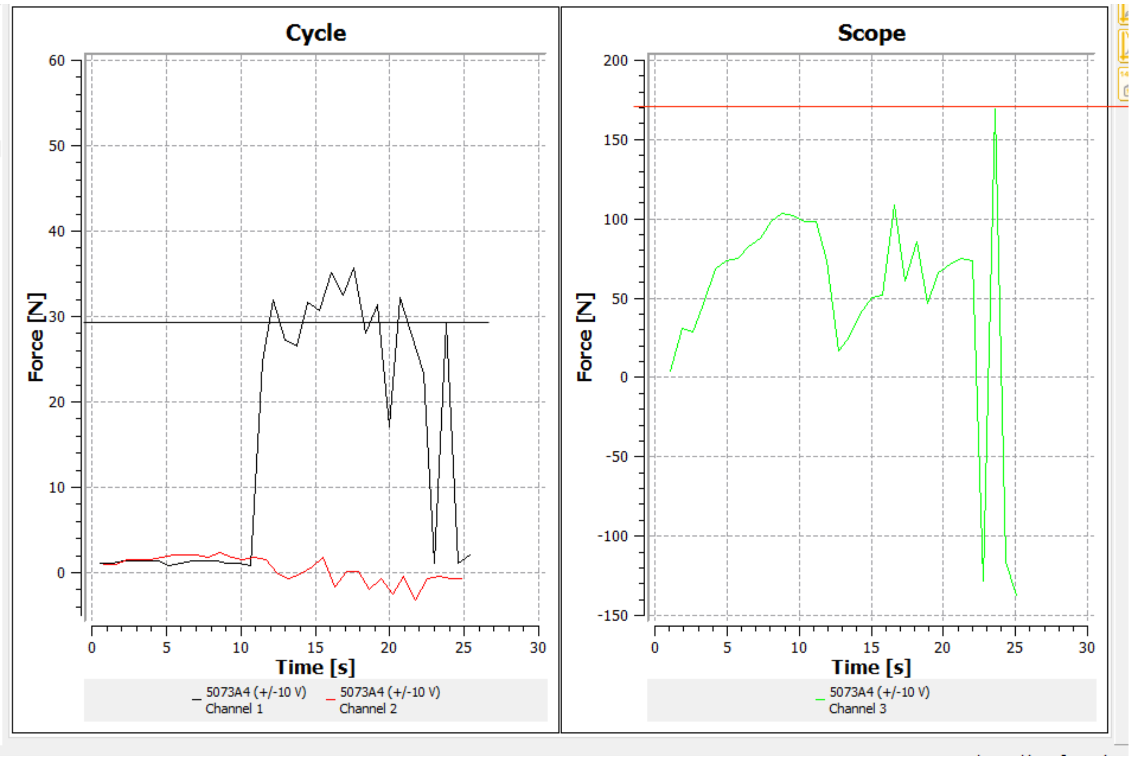


Figure B.6: Friction test with rubber on ice. Rubber hardness: 50,0 Shore.

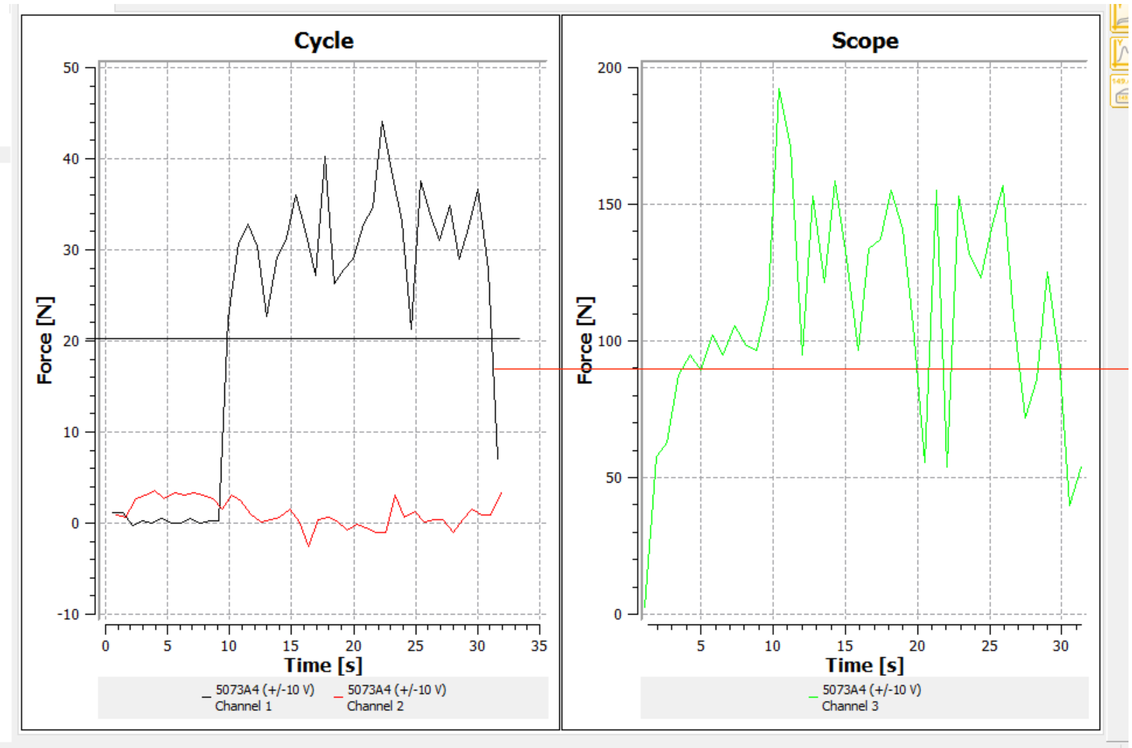


Figure B.7: Friction test with rubber on ice. Rubber hardness: 63,2 Shore.

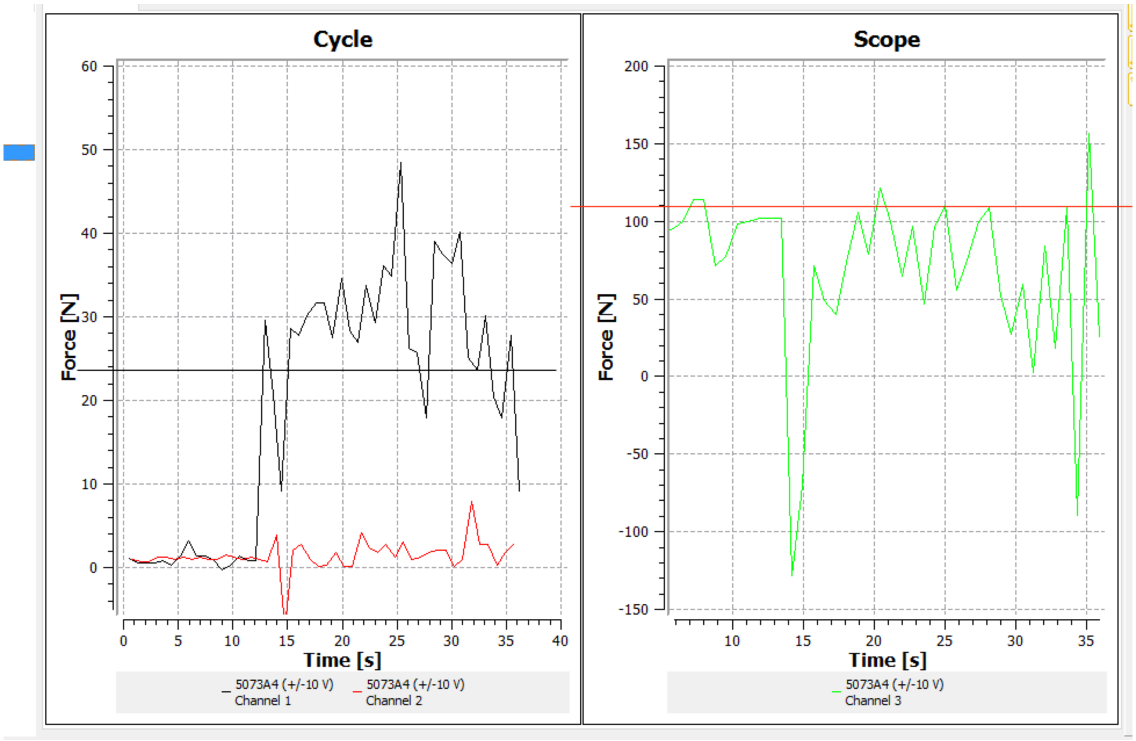


Figure B.8: Friction test with rubber on ice. Rubber hardness: 63,2 Shore.

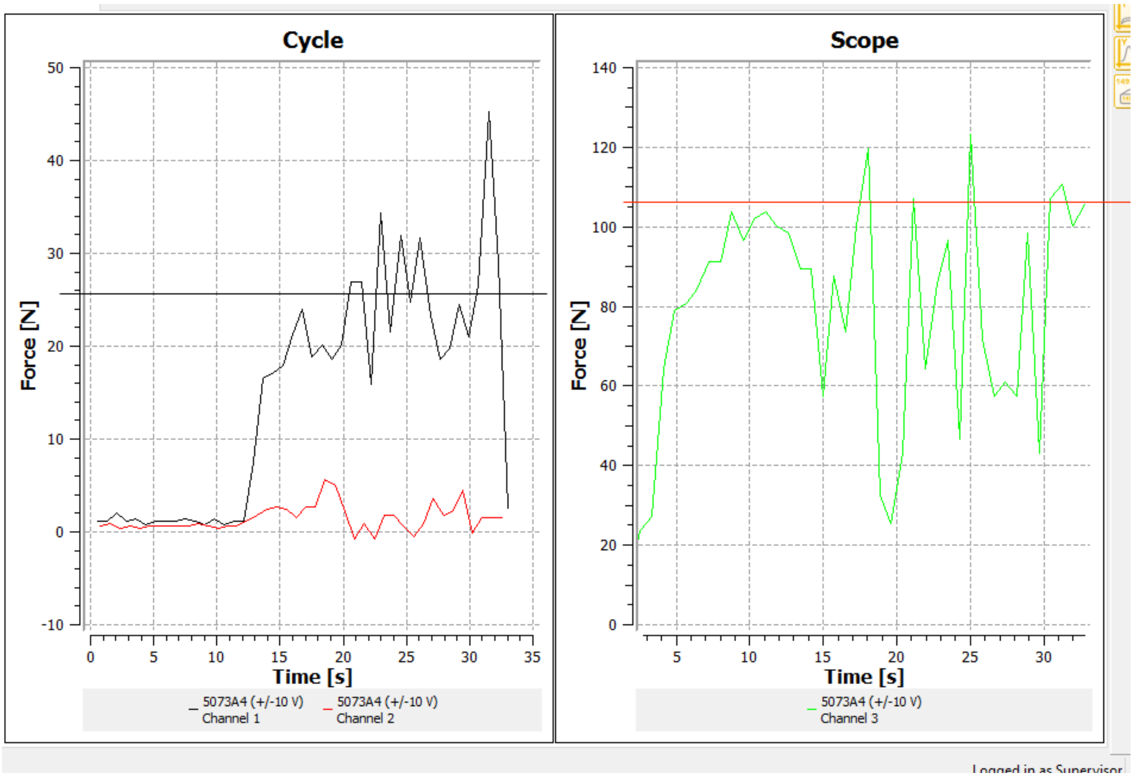


Figure B.9: Friction test with rubber on ice. Rubber hardness: 72,7 Shore.

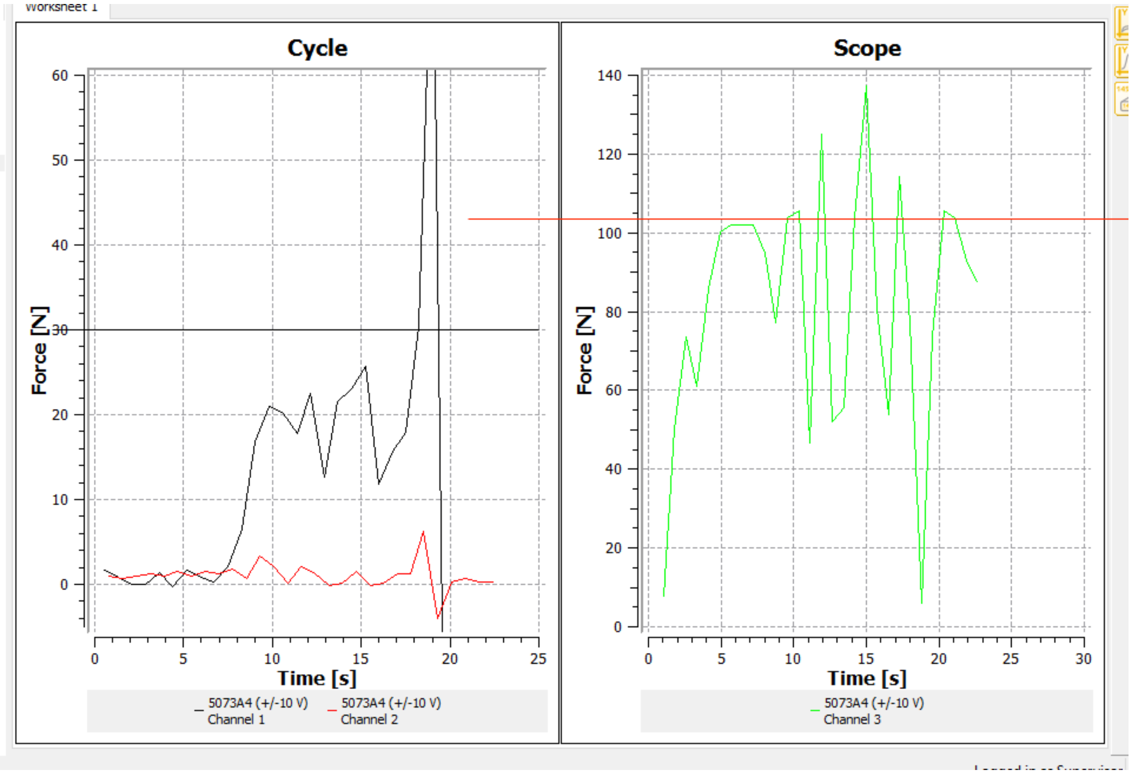


Figure B.10: Friction test with rubber on ice. Rubber hardness: 72,7 Shore.

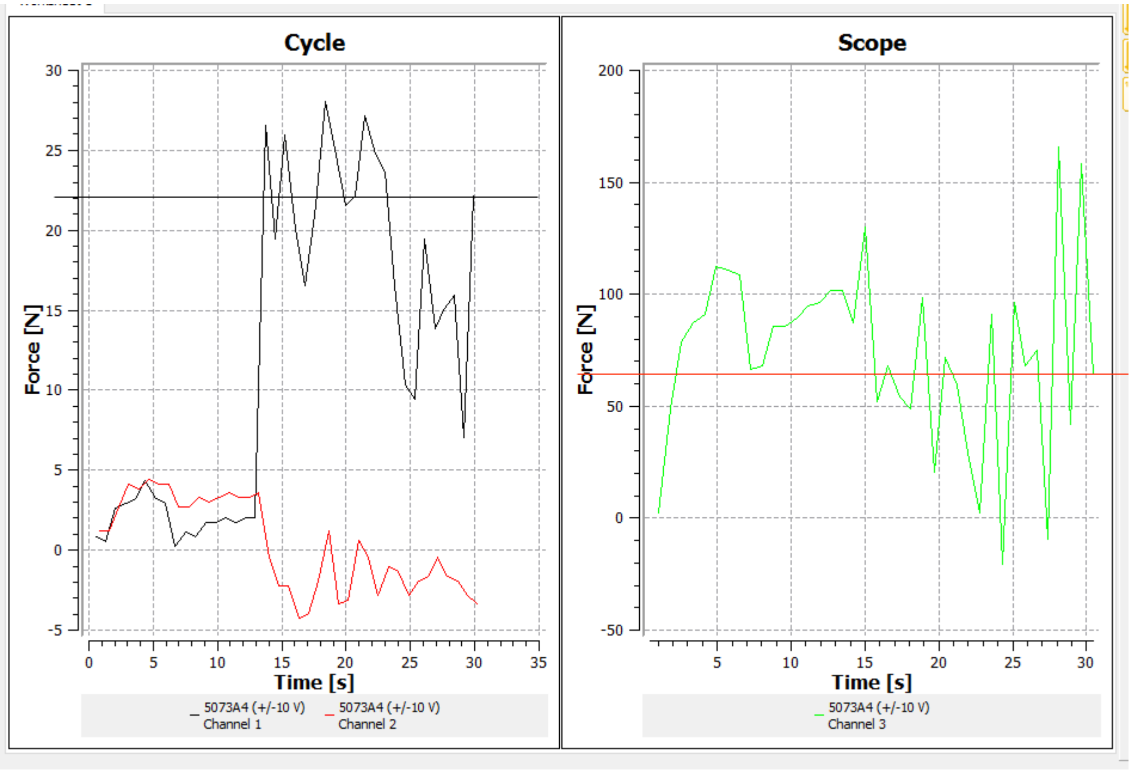


Figure B.11: Friction test with rubber on ice. Rubber hardness: 79,7 Shore.

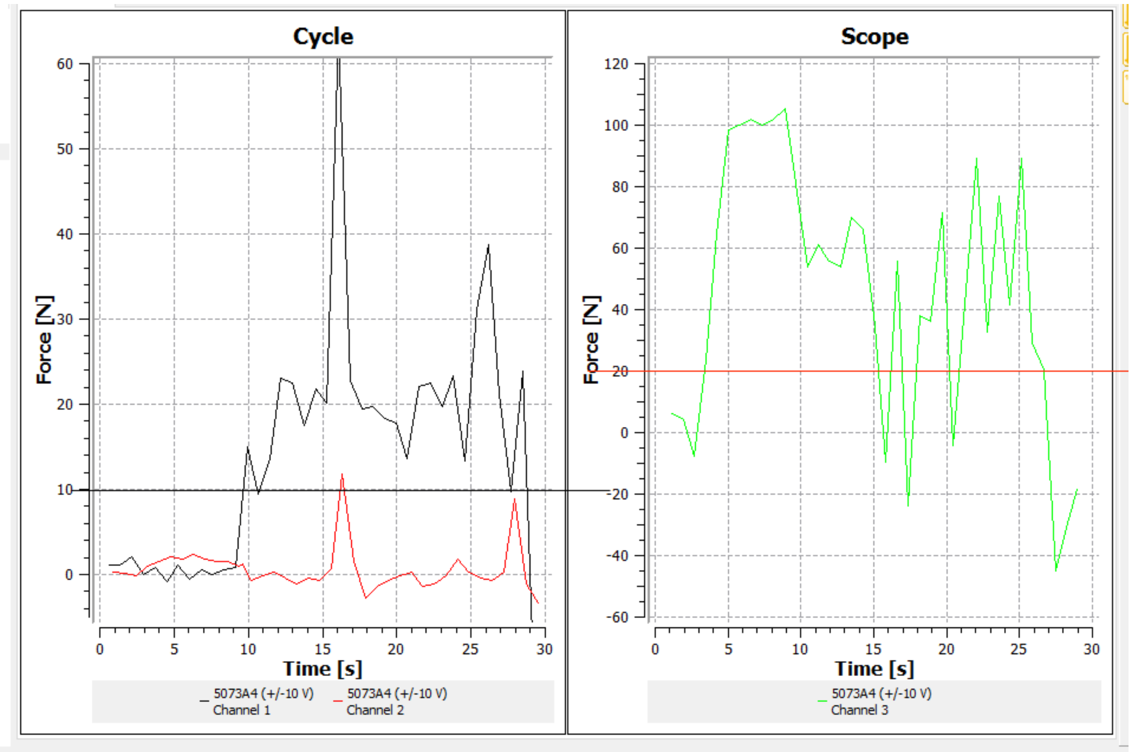


Figure B.12: Friction test with rubber on ice. Rubber hardness: 79,7 Shore.

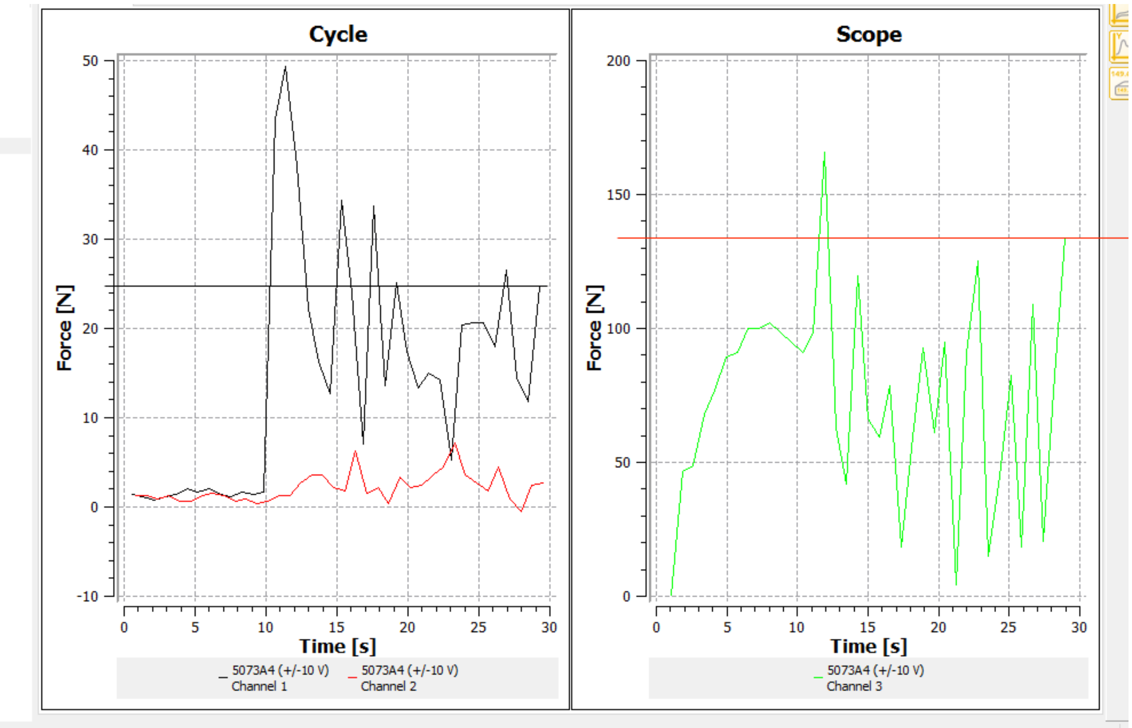


Figure B.13: Friction test with rubber on ice. Rubber hardness: 89,4 Shore.

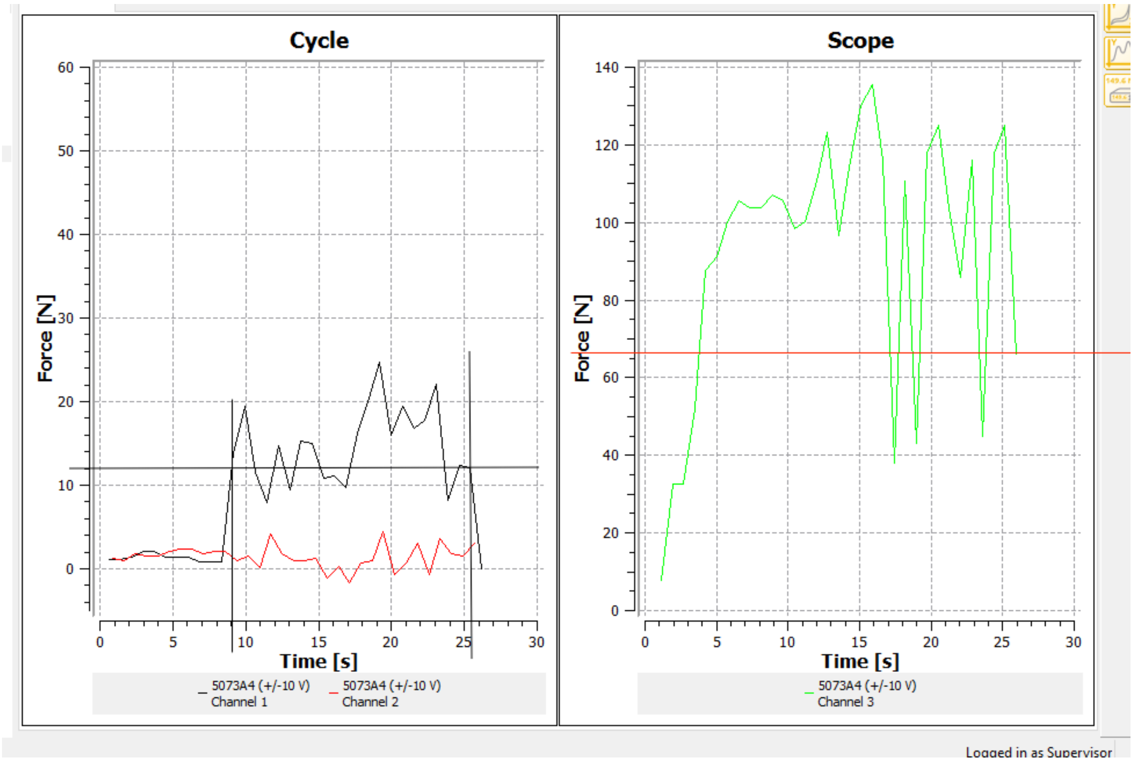


Figure B.14: Friction test with rubber on ice. Rubber hardness: 89,4 Shore.

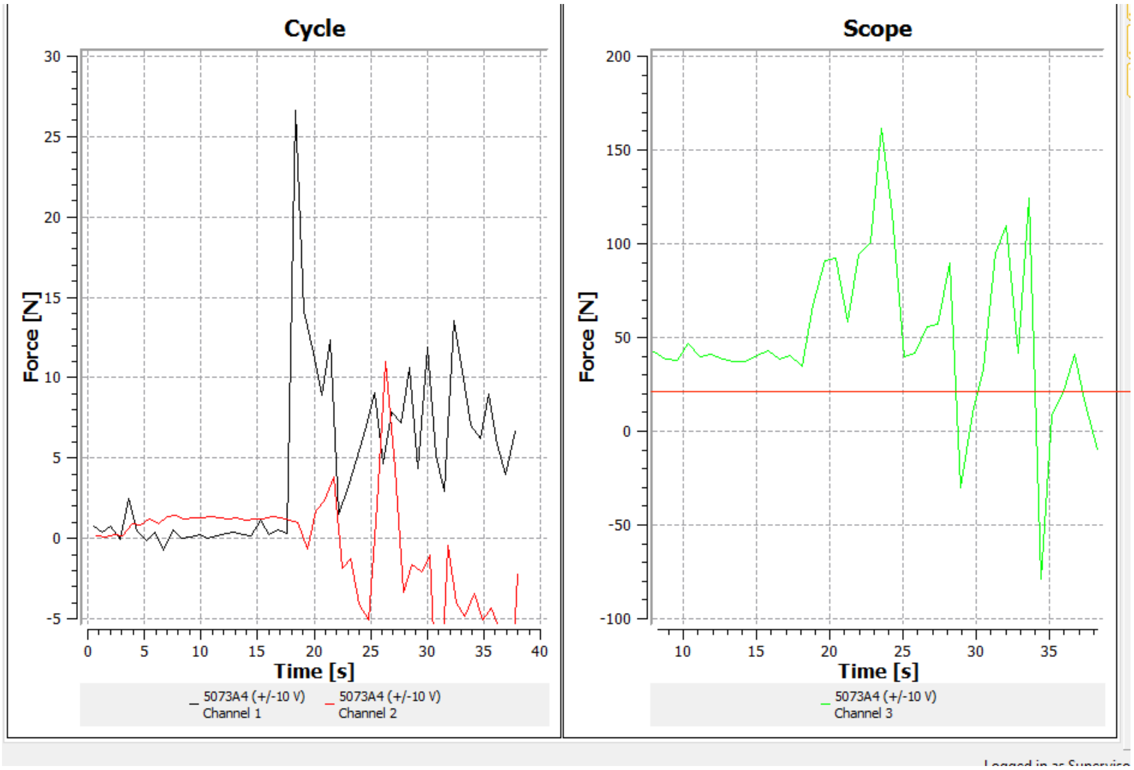


Figure B.15: Friction test with a polyethylene ski sole on ice. Initial normal force: 50 N (12,5 KPa contact pressure).

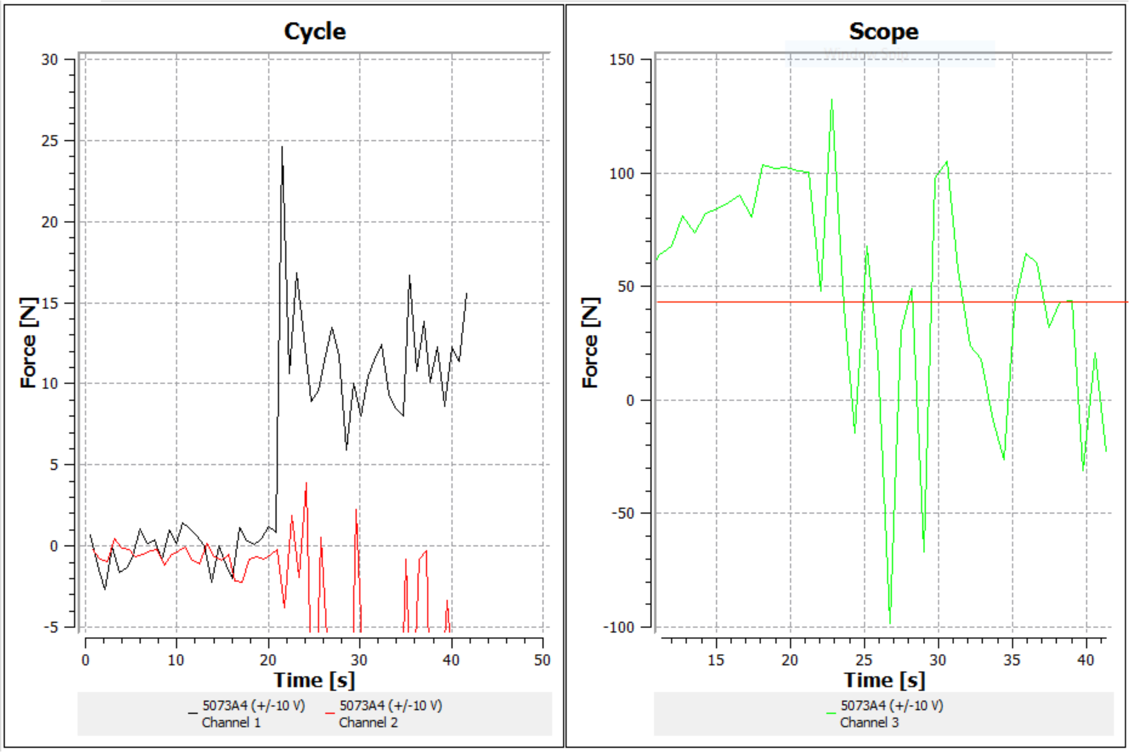


Figure B.16: Friction test with a polyethylene ski sole on ice. Initial normal force: 100 N (25 KPa contact pressure).

B.2 Selected Technical Drawings

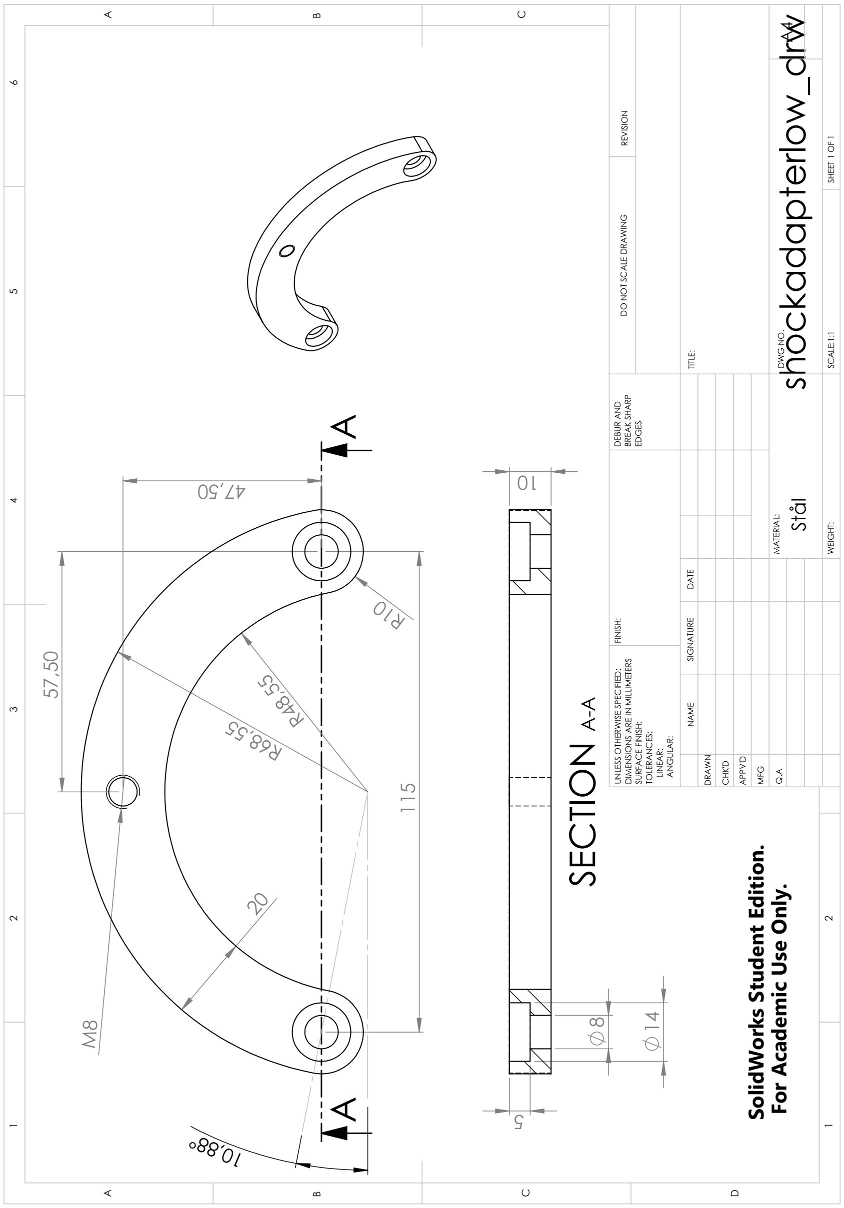


Figure B.17: Drawing of the inner part of the transition between the manual actuator and the shock absorber.

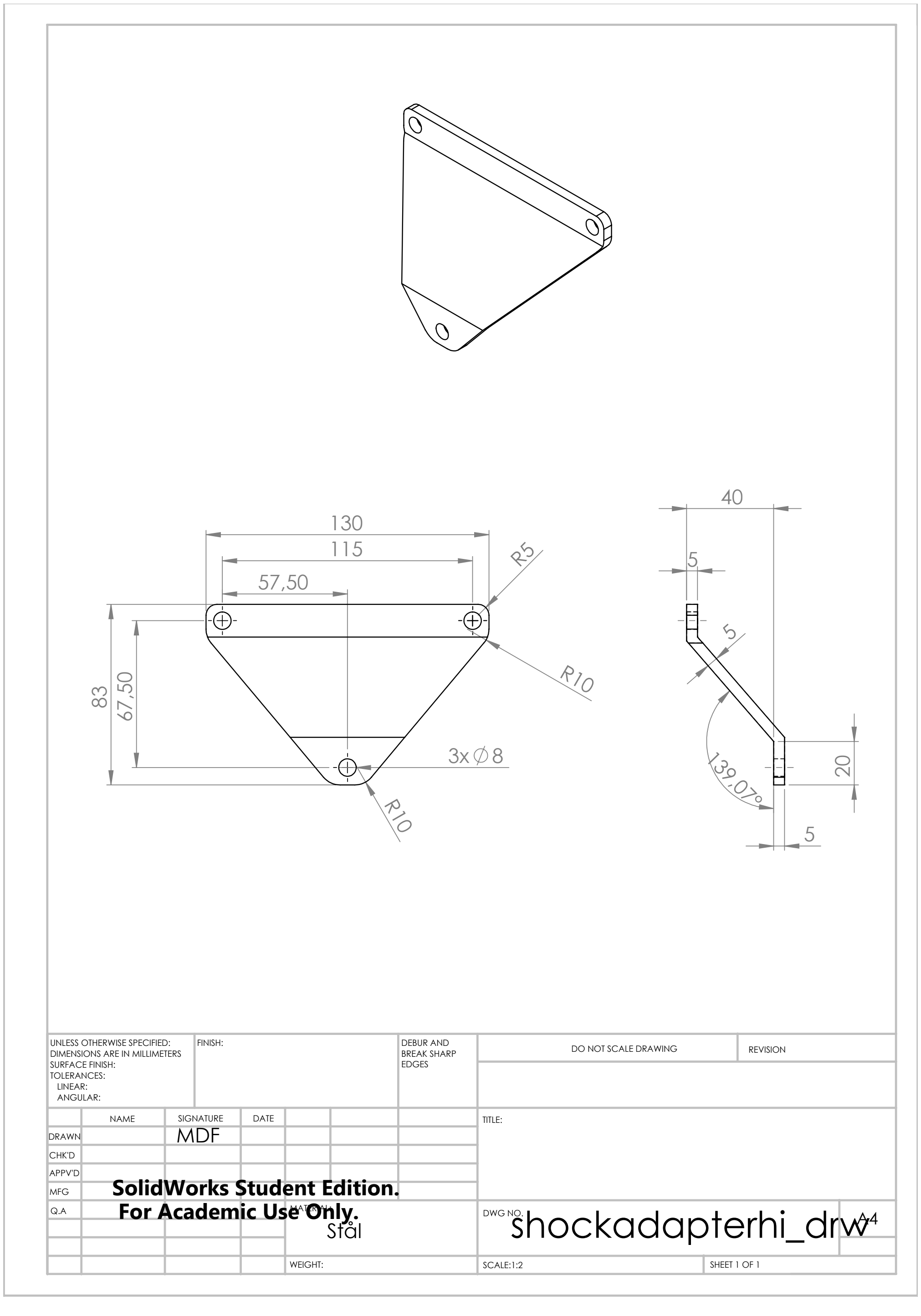


Figure B.18: Drawing of the outer part of the transition between the manual actuator and the shock absorber.

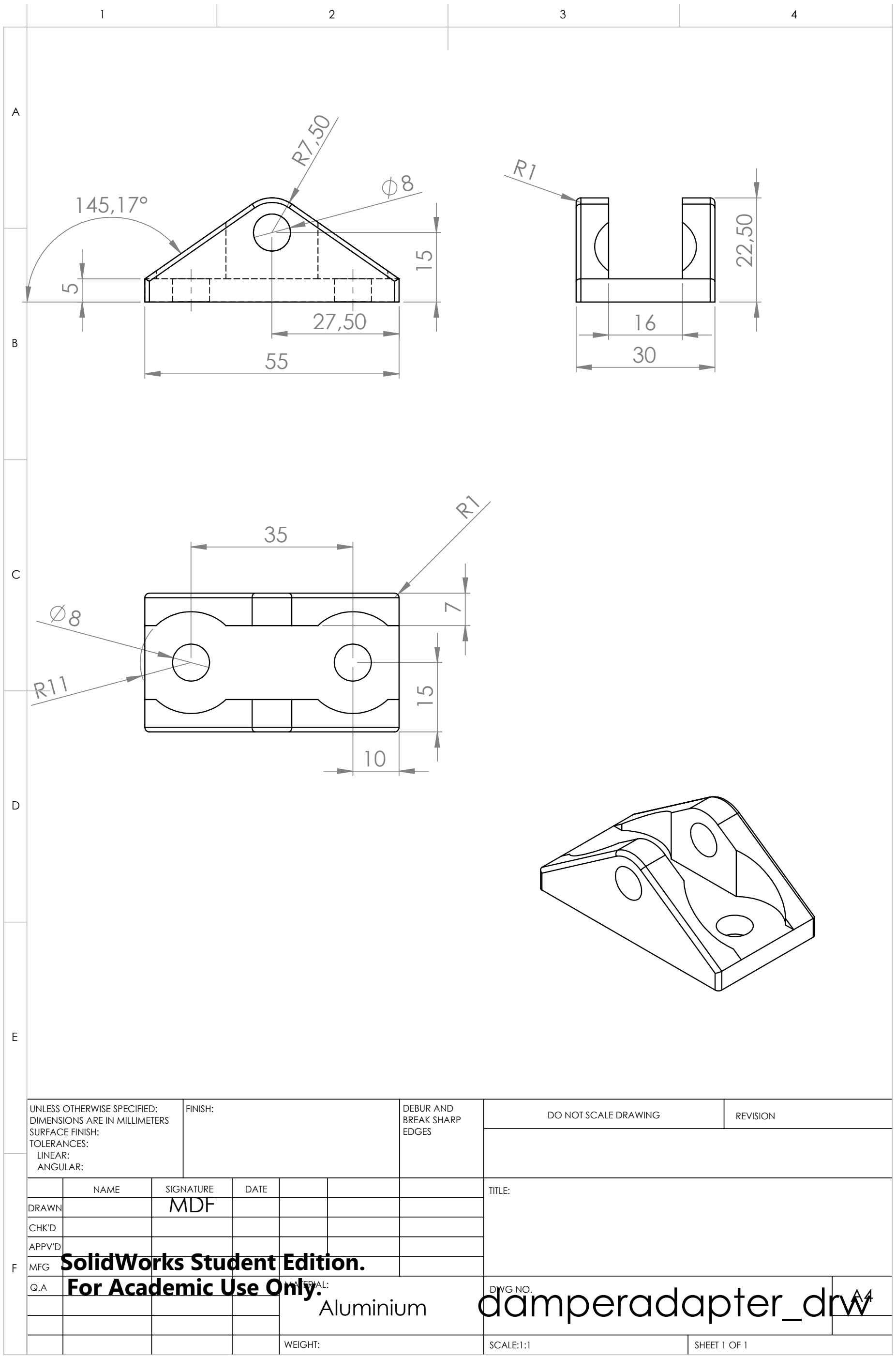
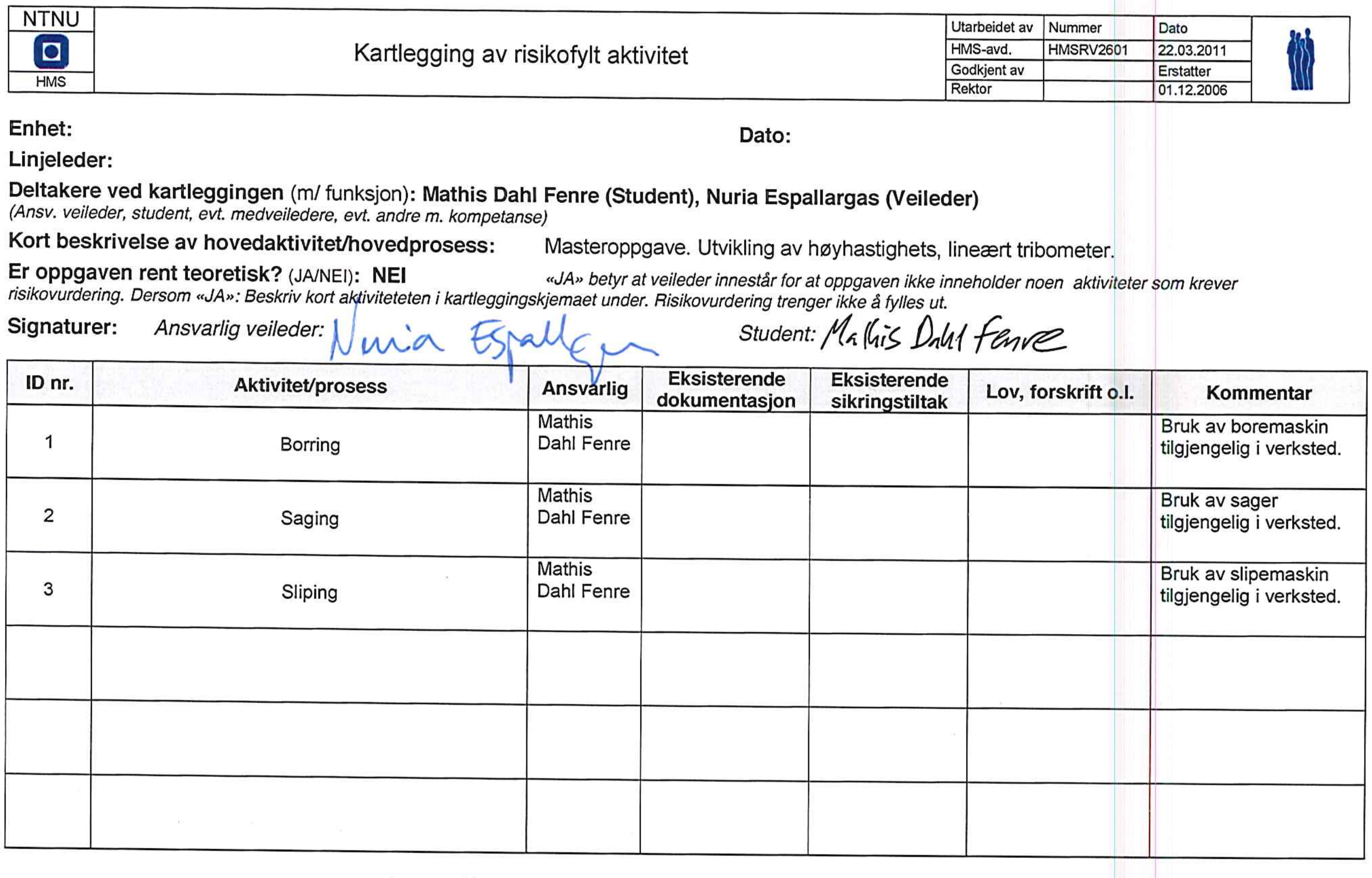


Figure B.19: Drawing of the adapter between the shock absorber and the pivot arm.

Appendix C

Risk Analysis



NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: **Dato:**

Linjeleder:

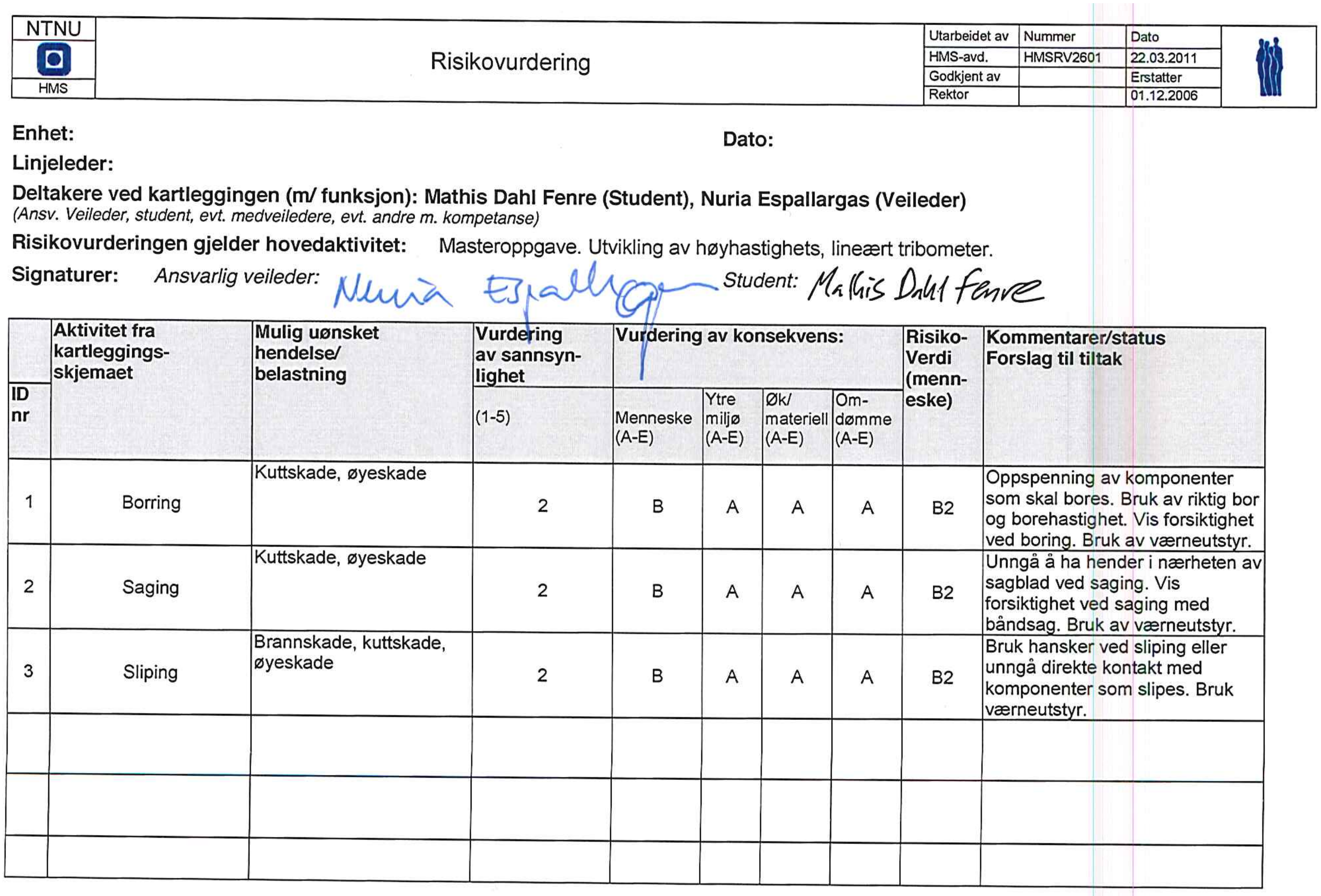
Deltakere ved kartleggingen (m/ funksjon)**: Mathis Dahl Fenre (Student), Nuria Espallargas (Veileder)**
(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave. Utvikling av høyhastighets, lineært tribometer.

Er oppgaven rent teoretisk? (JA/NEI)**: NEI** *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder:* Nuria Espallargas *Student:* Mathis Dahl Fenre

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Borring	Mathis Dahl Fenre				Bruk av boremaskin tilgjengelig i verksted.
2	Saging	Mathis Dahl Fenre				Bruk av sager tilgjengelig i verksted.
3	Sliping	Mathis Dahl Fenre				Bruk av slipemaskin tilgjengelig i verksted.



NTNU HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: **Dato:**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon): Mathis Dahl Fenre (Student), Nuria Espallargas (Veileder)
(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

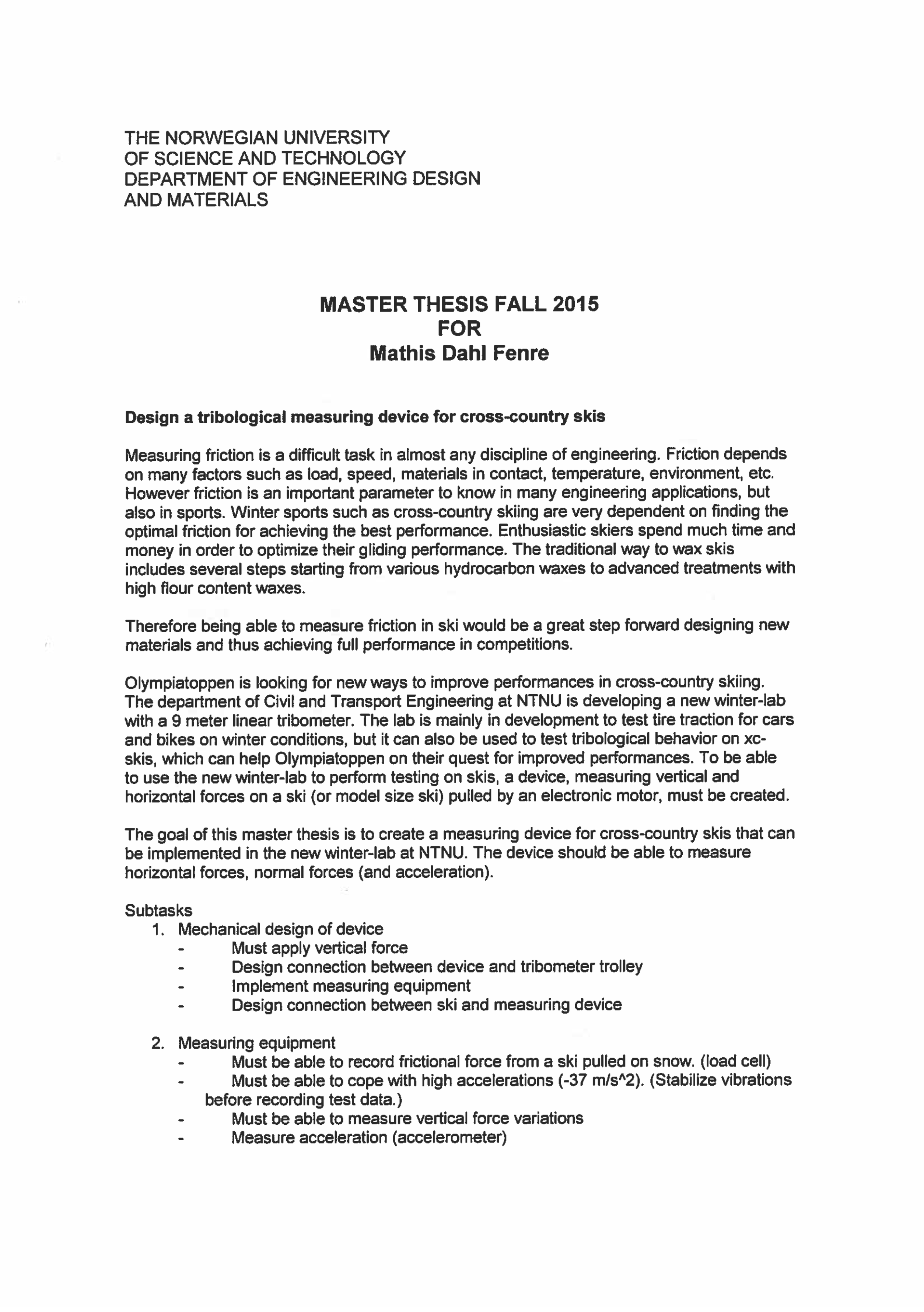
Risikovurderingen gjelder hovedaktivitet: Masteroppgave. Utvikling av høyhastighets, lineært tribometer.

Signaturer: *Ansvarlig veileder:* Nuria Espallargas *Student:* Mathis Dahl Fenre

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1	Borring	Kuttskade, øyeskade	2	B	A	A	A	B2	Oppspenning av komponenter som skal bores. Bruk av riktig bor og borehastighet. Vis forsiktighet ved boring. Bruk av værneutstyr.
2	Saging	Kuttskade, øyeskade	2	B	A	A	A	B2	Unngå å ha hender i nærheten av sagblad ved saging. Vis forsiktighet ved saging med båndsag. Bruk av værneutstyr.
3	Sliping	Brannskade, kuttskade, øyeskade	2	B	A	A	A	B2	Bruk hansker ved sliping eller unngå direkte kontakt med komponenter som slipes. Bruk værneutstyr.

Appendix D

Problem Text



THE NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER THESIS FALL 2015
FOR
Mathis Dahl Fenre

Design a tribological measuring device for cross-country skis

Measuring friction is a difficult task in almost any discipline of engineering. Friction depends on many factors such as load, speed, materials in contact, temperature, environment, etc. However friction is an important parameter to know in many engineering applications, but also in sports. Winter sports such as cross-country skiing are very dependent on finding the optimal friction for achieving the best performance. Enthusiastic skiers spend much time and money in order to optimize their gliding performance. The traditional way to wax skis includes several steps starting from various hydrocarbon waxes to advanced treatments with high flour content waxes.

Therefore being able to measure friction in ski would be a great step forward designing new materials and thus achieving full performance in competitions.

Olympiatoppen is looking for new ways to improve performances in cross-country skiing. The department of Civil and Transport Engineering at NTNU is developing a new winter-lab with a 9 meter linear tribometer. The lab is mainly in development to test tire traction for cars and bikes on winter conditions, but it can also be used to test tribological behavior on xc-skis, which can help Olympiatoppen on their quest for improved performances. To be able to use the new winter-lab to perform testing on skis, a device, measuring vertical and horizontal forces on a ski (or model size ski) pulled by an electronic motor, must be created.

The goal of this master thesis is to create a measuring device for cross-country skis that can be implemented in the new winter-lab at NTNU. The device should be able to measure horizontal forces, normal forces (and acceleration).

Subtasks

1. Mechanical design of device
    - Must apply vertical force
    - Design connection between device and tribometer trolley
    - Implement measuring equipment
    - Design connection between ski and measuring device

2. Measuring equipment
    - Must be able to record frictional force from a ski pulled on snow. (load cell)
    - Must be able to cope with high accelerations (-37 m/s^2). (Stabilize vibrations before recording test data.)
    - Must be able to measure vertical force variations
    - Measure acceleration (accelerometer)

3. Data transfer/electronics
   - Measured data must be recorder, filtered and transferred to computer.
   - Electricity to power vertical force, measuring equipment and data transfer equipment.

4. Model ski design
   - Model ski must be designed to achieve desired pressure distribution

5. Building a physical device
   - Order parts and book workshop hours
   - Build

6. Test measuring device
   - The winter-lab will probably not be ready for testing in time
   - Test device (outside) with high acceleration to evaluate performance

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (http://www.ntnu.no/ipm/masteroppgave). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.

Co-supervisor of this work is: Assoc. Prof. Alex Klein-Paste and Dr. Felix Breitschadel.

Nuria Espallargas

Torgeir Welo
Head of Division

Nuria Espallargas
Professor/Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Bibliography

Alicona (2008). Ifm manual. *Infinite Focus*, 28.11.2008.

Ambach, W. and Mayr, B. (1981). Ski gliding and water film. *Cold Regions Science and Technology*, 5:59–65.

Barnes, P., Tabor, D., and Walker, J. C. F. (1971). The friction and creep of polycrystalline ice. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 324(1557):127–155.

Bäurle, L. (2006). *Sliding Friction of Polyethylene on Snow and Ice*. PhD thesis, Swiss Federal Institute of Technology Zurich.

Bowden, F. (1952). A discussion on friction: Introduction to the discussion: The mechanism of friction. *Proceedings of the Royal Society of London, Series A (Mathematical and Physical Sciences)*, 212:440 – 449.

Bowden, F. and Hughes, T. (1939). Mechanism of sliding on ice and snow. *Proceedings of the Royal Society of London, Series A (Mathematical and Physical Sciences)*, 172:280 – 297.

Breitschädel, F. (2014). *Technical aspects to improve performance in cross-country skiing*. PhD thesis, NTNU.

Colbeck, S. (1992). A review of the processes that control snow friction. *CRREL monograph*, 92.

Colbeck, S. (1994). The friction of snow skis. *Journal of Sport Sciences*, 12:285–295.

Conant, F. S., Dum, J. L., and Cox, C. M. (1949). Frictional properties of tread-type compounds on ice. *Industrial & Engineering Chemistry*, 41(1):120–126.

Erhart, J. (2013). Piezoelectricity and ferroelectricity phenomena and properties. Lecture.

Faraday, M. (1859). On regelation, and the conservation of force. *Philos. Mag.*, 17:162–169.

Fauve, M., Bäurle, L., and Rhyner, H. (2006). Laboratory device for measuring the friction between ski-base materials and ice or snow. Technical report, WSL, Institute for Snow and Avalanche Research (SLF).

Fenre, M. D. (2014). Ski tribometer. Pre-Masters Thesis, NTNU.

Glenne, B. (1987). Sliding friction and boundary lubrication of snow. *Journal of Tribology*, 109:614–617.

Haaland, N. H. (2013). Nano ski waxes, effects and benefits. Master's thesis, NTNU.

Hasler, M., Schindelwig, K., Knoflach, C., Reichl, W., and Nachbauer, W. (2014). Kinetic friction of boardercross-snowboards. *Procedia Engineering*, 72:310–314.

Kistler (2012). *ICAM – Industrial Charge Amplifier for Manufacturing Applications Type 5073A...* Kistler Group, Eulachstrasse 22 8408 Winterthur Switzerland.

Kistler (2014). *3-Component Force Link - 25x25x30 mm up to 2 kN – Type 9317C.* Kistler Group, Eulachstrasse 22, 8408 Winterthur, Switzerland.

Kistler (2015). *Kistler 5073a... Industrial Charge Amplifier for Applications in Manufacturing.* Kistler Group, Eulachstrasse 22, 8408 Winterthur, Switzerland.

Kuzmin, L. and Tinnsten, M. (2006). *Investigation of the Most Essential Factors Influencing Ski Glide.* PhD thesis, Luleå University of Technology.

Lind, D. and Sanders, S. (1997). *The Physics of Skiing: Skiing at the Triple Point.* American Institute of Physics.

Nachbauer, W., Hasler, M., Mayr, B., and Schindelwig, K. (2013). A novel tribometer for snow friction measurements. Friction measurements under ski specific conditions.

Nilsson, D. (2007). Ytkarakterisering av skidbelag i olika stadier av inkörning. Master's thesis, Luleå Universitet.

Nordström, O. (2003). Nya och begagnade vinter- däcks isfriktion på skrovlig is. Note 34, Swedish National Road Administration and Norwegian Public Roads Administration.

Petrenko, V. (1997). Study of the surface of ice, ice/solid and ice/liquid interfaces with scanning force microscopy. *J. Phys. Chem. B (USA)*, 101:6276 – 81.

Pfalzner, P. M. (1950). On the friction of various synthetic and natural rubbers on ice. *Canadian Journal of Research*, 28f(12):468–489.

Poirier, L., Lozowski, E. P., and Thompson, R. I. (2011). Ice hardness in winter sports. *Cold Regions Science and Technology*, 67:129–134.

Sætha, M. and Lukertsenko, M. (2014). *WAX TEST INFO #1, Beitostølen, 19.11.2014.* SWIX Sport.

Schindelwig, K., Hasler, M., Van Putten, J., Rohm, S., and Nachbauer, W. (2014). Temperature below a gliding cross country ski. *Procedia Engineering*, 72:380–385.

Sturesson, P. (2008). Friction characteristics between sk base and ice -fundamental lab scale tests and practical implications. Master's thesis, Uppsala Universitet.

Takeda, M., Nikki, K., Nishizuka, T., and Abe, O. (2010). Friction of the short model ski at low velocity. *J. Phys., Conf. Ser. (UK)*, 258.

TOKO (2014). *Toko Wax and Tuning Manual.* TOKO-SWIX SPORT AG.

Venkatesh, S. (1975). Laboratory studies of the friction of rubber on ice. *Tribology International*, 8(2):51 – 55.