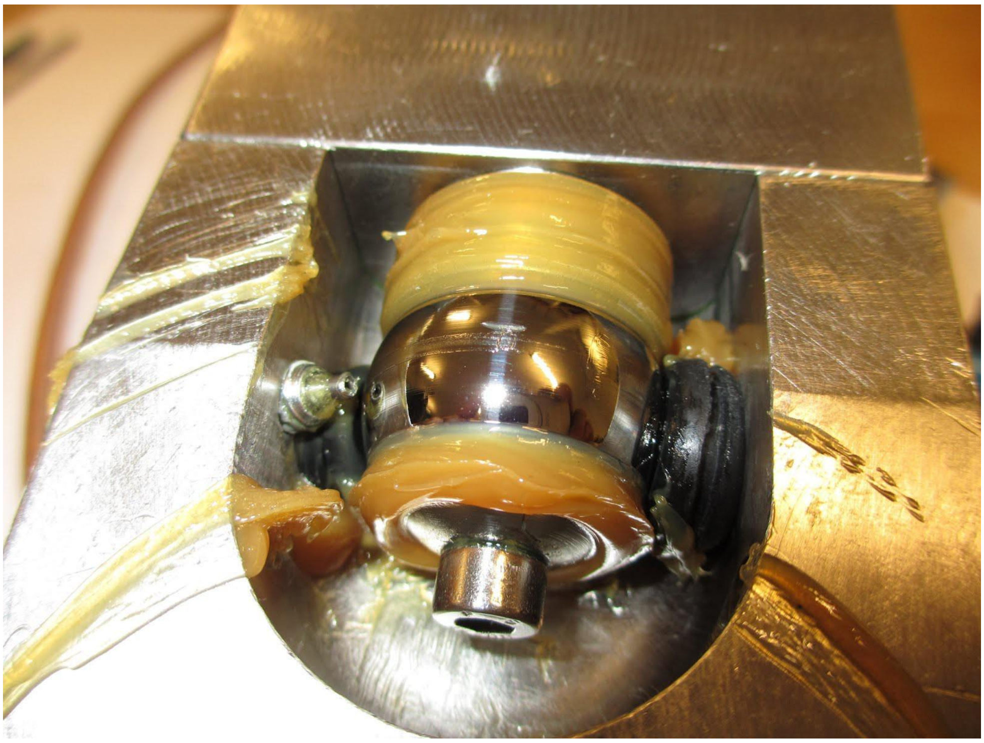
MASTER'S THESIS

Ball-on-disc Machine

Control and Measurement for a Study on Starved Grease-lubricated Contact



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Master thesis

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Control and measurement for a study on starved grease-lubricated contact.

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Abstract

The focus of this thesis was to make a preliminary study on lubricant-starved elastohydrodynamically lubricated contacts (henceforth referred to as EHL contacts), such as those found in ball bearings or gear contacts in transmissions. If fully successful, the study would give some information about one specific question: at what point is the inbound film thickness so thin that it will affect the film thickness inside the contact? To answer this, equipment is needed to simulate an EHL contact, measure the contacts film thickness, and measure and control the inbound film thickness. In aid of this, an old "Ball-on-Disc" machine from a previous PhD project at the university was to be updated with better control and measurement equipment. This machine was also intended to be used in future research project, thus increasing the demands on the upgrades needing to be made. Furthermore, equipment intended to measure both the contact film thickness and the inbound film thickness, as well as controlling the inbound lubricant, was needed to be located or manufactured.

The most common method of measuring EHL film thickness is probably the optical method, using spectrometry to profile the contact in 3 dimensions. This method is, however, both expensive and complicated. Furthermore, it can not be used in steel-steel contacts. This project instead investigated a combination of resistive and capacitive measurements of the contact (henceforth RC measurement) to quantify the film thickness between surfaces.

Controlling the inbound lubricant film was achieved by applying an excessive amount of lubricant, then scraping it off. The scraper would only let a certain lubricant film thickness pass through and enter the ball on disc contact. The scraper would also be connected to an RC measurement equipment in order to quantify the amount of lubricant being let through.

The last part of the project was to build a program in LabVIEW. The function of the program was to control, present and record much of the machine's capabilities. Effort was put in giving the program a user friendly interface for future use.

In the end, the study did not produce enough usable data to say much about starved lubricating conditions. It did however show encouraging results about the methods being used. The lubricant/grease scraper that was designed showed some success both in controlling the inbound lubricant film thickness and also in making this measurable. The RC method had already been proven as a useful way of measuring the film thickness in EHL contacts, but could now be shown usable in measuring the inbound film thickness as well. Furthermore, it was proven possible to measure two quantities simultaneously in close proximity without causing false correlation.

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- Appendix 1 - RC measurement instruction manual, 6 pages.
- Appendix 2 - Ball-on-disc machine instruction manual, 12 pages.

1 Background

This project served to restore and expand the capabilities of an existing ball on disc machine at Luleå university of technology (hereby also referred to as LTU). This machine had been in storage since about 2004. Before that it had been used for measurements of tribological systems, mainly on the film thickness in a ball on disc contact. The technique used was mainly optical, using interferometry/spectroscopy. Some research with RC measurement was also done and used for an example in the work presented at Nordtrib 2006[1].

The project was also intended to make an initial study on starved lubrication conditions, hopefully finding a way of performing live measurements. Live and on-line measurements of bearing conditions could provide immense reductions in cost of maintenance. Often, bearings are either run until they break or periodically replaced. Both of these situations are likely to cause expensive stops in production. Periodic replacement of bearings likely replace bearings that are fully functional. Besides gaining the ability to predict failures more precisely, the particular field studied in this thesis may even help extend bearing life. If lubricant starvation can be reliably detected and identified during use, the conditions of the bearing can be adapted accordingly.

Even more possibilities opens up if more data about the state of machines become available over time, such as planning and optimizing an entire production process in coordination with its maintenance. All these possibilities make it both relevant and important to do research and development in the field of tribology and condition monitoring. Renovating, adapting and expanding the abilities of the ball on disc machine and its surrounding equipment could therefore be an important step for future research.

1 Larsson and Lord, Film-forming capability in rough surface EHL investigated using contact resistance

2 Method

In this part the methods used are presented along with some brief statements about the initial conditions of the project along with some of the goals the project.

2.1 Hardware

2.1.1 Ball on disc

A ball on disc machine is an equipment commonly used for studying EHL contacts. In its most basic form, it consists of a ball (1) and a disc (2) which are pressed together while in relative motion, as seen in Figure 1. The machine used in this thesis has the ball-disc contact (3) underneath the disc. It permits a wide range of running conditions to be simulated.

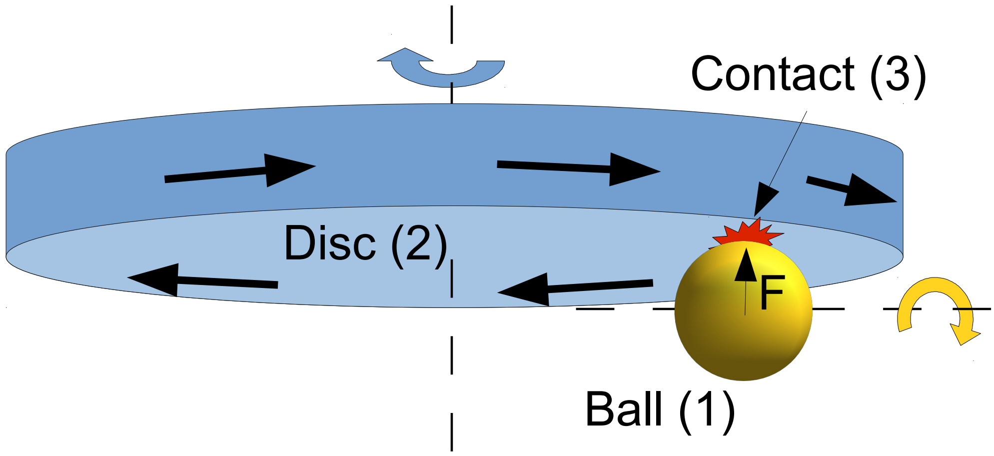


Figure 1: Basic ball on disc schematic

2.1.2 Machine body

The machine's body is already well documented in a PhD thesis by John Lord[2]. As a result, this report focuses on the changes done and the new features added to the ball on disc machine.

Since the machine had been in storage for some time it was important to look it over for damages, missing parts and/or other defects. The machine was also inspected for attributes that could be improved or changed for the new additions. Some of the things of particular interest were the ball bearings, electrical properties and equipment layout.

2.1.3 Interference suppression

In both measurement and control, interference is important to consider. This was especially true with the physical layout of this hardware, where control and measurement equipment was placed in

2 Lord, Thin lubricating films in elastohydrodynamic contacts : experimental techniques and applications

the same box as the motor controllers, which contained power electronics. For this reason, proper shielding was given a high priority. All cable shields were connected to ground and the main box was thoroughly grounded. There was also a shielding wall separating control and measurement equipment from the power electronics. Measurements were done to confirm a low impedance to ground in all connectors and shields. In addition to proper shielding, some equipment was fitted with twisted pair cables and/or used differential signaling. Finally, digital control and/or communication was used where possible.

2.2 Data acquisition

2.2.1 Software

Certain criteria for the software were used to aid in selecting a optimal programming environment. The first criteria was that it should be a software familiar to the staff at Luleå university of technology. Another desired feature was that the program should be easy to learn since none of the people involved had much experience with programming. If the program already had some sort of data acquisition equipment incorporated then it would also be a plus. Another important aspect was that the software should not be too expensive to procure and/or utilize.

2.2.2 Equipment and its properties

The sample rate and the number of channels needed was unknown since the exact nature of future measurements were unknown at the time of this project. This made determining the resolution and sample rate needed somewhat speculative, but generally; the higher the sample rate and resolution the data acquisition device could handle the better. There were however other aspects about the data acquisition that also were of importance. To secure the machine from being dependent on a specific computers hardware a criteria was added that the new data acquisition equipment should be as independent from the computer as possible. Preferably, the new solution should only require a USB compatible hardware interface. Other aspects were also important, such as the price of the device as well as user friendliness.

2.2.3 Interface layout

An end user should preferably not have to go into the code to run or use the standard commands of a program. Such programs exclude anyone lacking programming experience and are likely be time more consuming and unfriendly to work with. Therefore it was decided that a graphic interface was to be implemented to assist future users with standard commands. The interface should contain controls for all basic settings the user would need to run tests with the machine, as well as presenting some of the data collected.

This required a good interface layout. Some objectives for the design of the interface was chosen. The design was to be made as simple and structured as practically possible, so that the user intuitively would know which parts of the program were related to the corresponding parts or functions of the machine. This was to be done both graphically and with text. A vivid colour scheme was also to be applied to help to separate different parts of the program.

Some basic functions had to be on the interface, such as controlling the sampling, controlling the motor speeds, length of test, where the data should be stored as well as some graphic representation of the data. However, presenting all functions would likely had lead to a confusing program to work with. These functions were mainly deeper functions that was not required in the day to day use of the machine e.g. functions like those including changing, adding or subtracting channels and/or methods of measurement, adapting how data is stored, digital filters and/or making other operations on the signals.

2.2.4 Measurement areas

- Temperature. Temperature was a critical measurement since it affects most physical data, especially in a tribological sense. Temperature measurements were also important for the basic safety for the users of the machine if more extreme conditions were to be tested. Some lubricants could also catch fire with obvious danger resulting, making lubricant temperature measurement critical.
- Force and torque. The machine was already equipped with gauges for measuring the force applied to the contact and the torque experienced by the machine. These two measurement devices were reused since both loads are highly relevant to a bearing. The applied force was important since it was one of the main factors affecting ball bearings and the torque was used to calculate friction.
- Lubricant film thickness. The film thickness was measured using RC measurement, this is described further in chapter 2.4 Contact film thickness measurement.

2.3 Control

To achieve useful measurements, certain features needed to be user defined. These features included:

- Motors (ball speed and disc speed).

- Disc contact radius (enables reusing discs in multiple tracks).
- Contact force.

Control of the contact force was done pneumatically (1) (Refer to Figure 2 for numbered illustrations). Equipment to do this was already in the design of the rig so all that was needed was to measure the piston (2) diameter and calibrate the pressure feedback sensor. To ensure that friction in the piston would not interfere with results, a seal-less piston was used. This means that some air continuously leak from the piston (3), which counteracts friction. Furthermore, the ball spindle joint was made of a flexible blade (4), this was to avoid both the friction and the hysteresis applied by a hinge. The disc holder was mounted to the rig on such a blade (5) for the same reasons, with the motor (6) mounted on the disc holder itself to prevent motor torque interfering with friction force measurements (7).

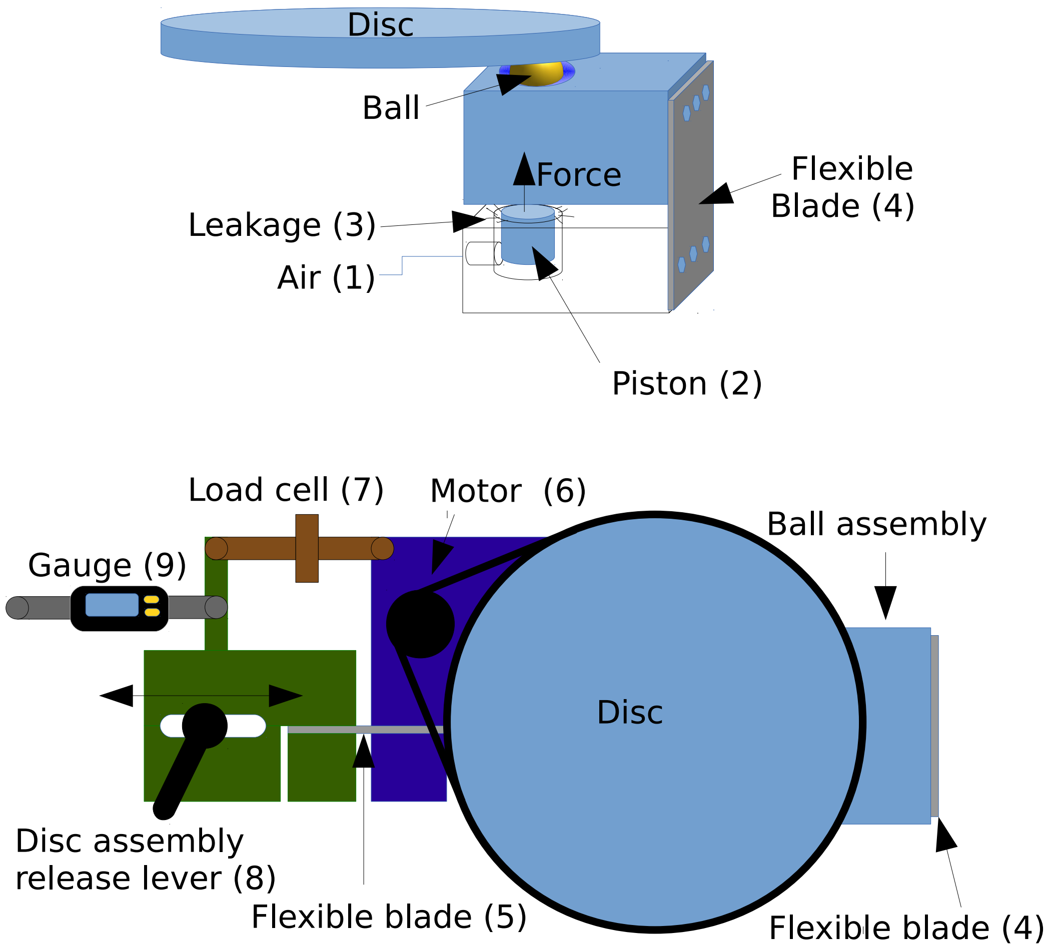


Figure 2: Schematic of ball and disc assemblies

The disc contact radius was made adjustable by releasing a lever (8) and moving the disc assembly using a crank. The position could then be verified by a digital absolute value gauge (9), whose value was fed to the control and acquisition software to compensate for friction force results and slide/roll ratio.

2.3.1 Motor control methods

With some of the old hardware missing, control of the motors had to be reimplemented.

Original control type:

Based on analysis of what equipment was left on the rig, the motors had clearly been controlled via analogue voltage. This was simple to implement and had some advantages, among other:

- Very fast response to changes.
- Motors can be controlled individually and simultaneously.

However, the motor control was less proficient at delivering precisely the torque and speed requested. A regulator was therefore necessary, and the behavior of this regulator may affect responsiveness and stability. It could also prove sensitive to interference and noise.

An alternative:

An interesting control type mentioned in the motor controller instruction manual is “Electronic gearing”. In this mode, the motor controller can read an encoder signal and track it, enabling highly synchronous control. This would be useful in studying the effects of slide/roll ratios with great precision. However, it turned out that one of the motor controllers were of an older version and did not support this feature. Thus this control type was abandoned.

Chosen control type:

The implemented control type used direct serial communication. The motor controllers supported a proprietary protocol called LUSTBUS, implemented using RS485. RS485 is a serial communication interface, similar to the more common RS232 in its use of start bits, stop bits, and parity checks. However, RS485 uses differential signalling through twisted-pair cables to help reject interference.

Using this control type required very little hardware acquisition. An RS485-RS232 cable capable of connecting a single motor controller to a computer was used. For preliminary testing, an older laptop with RS232 was used since most newer computers lack the RS232 port. Once functionality was confirmed, a USB-RS232 converter was acquired and used with the stationary computer assigned to the ball-on-disc machine. The RS485-RS232 adapter was then modified to communicate with both controllers. The modification was not entirely trivial since this cable was not designed to work in a network. When networking, all units should be opto-isolated from each other to prevent interference and even damage to the hardware. The motor controllers had RS485 drivers that could be isolated if connected to an external power supply, but the available RS485-RS232 cable was designed to draw power from a non-isolated supply within the motor controller itself. To get around this problem, the second connector that was soldered in place took power from the first motor controller to power the RS485 driver of the second controller. This way, only one of the controllers were isolated. However, since this did isolate the controllers from each other, the required conditions were met. Please note that this was probably not applicable to more than two controllers since the power supply might be insufficient. The second connector was attached by a shielded cable with twisted pairs, and the shield was soldered to ground inside the original connector.

The document from LT-i drives (formerly LUST, the motor controller manufacturer) describing the LUSTBUS protocol had a few unfortunate misprints. Some of the example templates had considerable errors in them, leading to much confusion. Unfortunately, control through the serial interface offers essentially infinite user privileges, meaning that a faulty command could have changed any parameter and potentially damaged the device.

To give a quick understanding of the communication protocol: The protocol uses “enquire” and “select” telegrams, depending on whether you want to read or write to a parameter. Parameters and values are sent using the ASCII representation of their values, to not interfere with commands, which are sent as command characters. For an example, to send the value 12, one would not send the binary representation of 12, but instead send the character “1” followed by the character “2”. As a general description, to set a parameter one has to send a select telegram in the form of “select->device address->parameter=value->checksum”. The controller will respond with “address->acknowledge” or “address->parameter=value” if properly received. The checksum is simply the bitwise XOR of some of the bytes in the message. For certain applications, one can also use broadcast telegrams, which are read and applied by all devices on the network without them responding with a confirmation. This was used to start/stop both motors.

2.3.2 Motor control Interface

The following motor controls and functions were considered critical for the graphical interface:

- Start/stop control of both and/or each of the motors.
- Speed control of both and/or each of the motors.
- Connection port selector.
- Error readout capability.
- Feedback of some kind.
- Proper disconnect and shut down buttons.

This interface was to be implemented in the chosen software, where buttons were to be added for simple controls, sliders for speed and slide/roll ratio, and a serial port readout window for feedback.

2.4 Contact film thickness measurement

Measuring the contact film thickness is a rather difficult task since the film thickness often is extremely thin (typically in the micrometer or nanometer range). Nevertheless there were a few methods of achieving measurements. Two methods were considered for this thesis.

2.4.1 Optical measurement

The typical way of doing measurements in this application was by some type of optical measurement, usually using interferometry (monochromatic light) or spectrometry (white light). These methods have the same basic layout in a ball on disc setup, using a disc made out of a transparent material such as glass or sapphire. The ball is pressed against the disc on one side and a microscope and a light source is directed at the contact from the other side. Some light will be reflected by the glass-lubricant interface and some will be reflected by the ball-lubricant interface. This causes an interference pattern (example in Figure 3) which can be evaluated by advanced image analysis software.

These methods can profile the contact in three dimensions and in high detail. One limitation for these methods is the minimum film thickness measurable. Since the light's wavelength typically ranges in a few hundred nanometers, and only films around ¼ of the wavelength will cause interference, film thicknesses only a few nanometers thick are not immediately measurable. This problem has previously been solved by adding a spacer layer of another material (typically chromium) a couple of hundred nanometers thick, thus enabling film thickness measurements close to 0 nanometers.

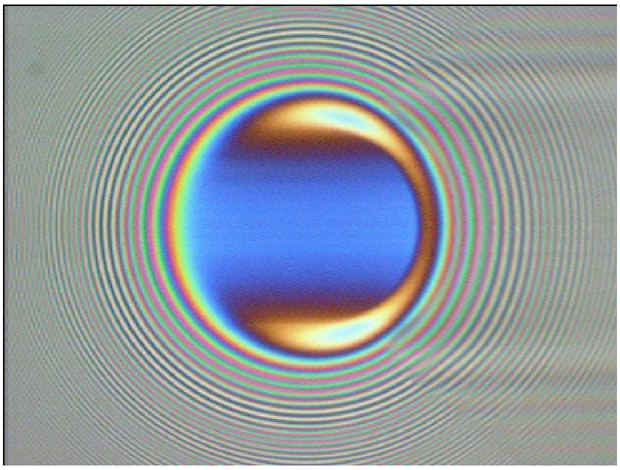


Figure 3: Spectrometry photograph taken by the previous equipment on the rig

While interferometry and spectrometry are powerful contact profiling tools, they were both deemed complicated and time consuming. It would have been very difficult to get a live reading of the film thickness given the amount of computer power needed to evaluate the images. Spectrometry was the main method previously used on this rig, and much of the equipment was still available. Because of the complication of using this technique during live measurements as well as not being able to use metal discs, an alternative was preferable.

2.4.2 RC measurement

Since EHL contacts are often made up of conductive elements, and have a thin separating film made up of a dielectric liquid, they can be expected to have a capacitance and/or a resistance dependening on the lubrication regime and film thickness. Indeed, estimating EHL contacts by measuring their electrical properties has proven successful in the past, and positive results have been presented at several large conferences. Examples include the STLE/ASME Joint tribology conference in 2003[3] (by the previously mentioned John Lord) and 2006[4], as well as the IMTC in 2000[5]. When John Lord did experiments using this method, he chose to interpret the EHL contact as equivalent to a capacitor and a resistor connected in parallel. Since his results were encouraging the same equivalent circuit interpretation was used for this thesis as well. The simultaneous acquisition of the contacts resistance and capacitance will be referred to as “RC measurement” in this report. Some

3 Lord, Mixed and full-film EHL contact condition analysis by simultaneous acquisition of its resistance and capacitance
4 Liu, Zhang, Zhu and Wang, EHL Experimental Techniques and Experimental Numerical Result Comparisons
5 Zheng, Zhang and Sun, The new development of measuring EHL oil film thickness for thrust bearing

advantages of the RC measurement principle, as opposed to optical measurements are:

- Capable of handling the film thickness ranges expected.
- Enables use of metal discs as compared to transparent discs.
- Could be calculated live, while running the tests.
- Far less complicated to develop and implement than spectrometry.
- Potentially very high bandwidth.

Being able to use metal discs is a big advantage for the RC method since most bearings are made out of metal. Being able to use the same materials in tests as in practice removes a lot of speculation on how the validity of a test is affected by using differing materials. The RC method also allows for testing how different metals and alloys affect the contact.

The main drawback is the inability to fully profile the contact in multiple dimensions. A single value would have to represent the entire contact.

Since used by John Lord, some equipment was left to perform these measurements. As a result of a lack in equipment documentation and the discovery of large calibration tables needed, a new method was sought. The intention for the new solution was to have a better engineering approach that should not rely on any experimentally derived linearisations. It was also deemed appropriate to look at the layout of the machine to see if improvements could be made to increase reliability and relevance of the results. Specifically, it was desirable to make sure that the ball-disc contact was being measured and nothing else.

Searching for an answer to the question, "is there a better way to implement the measurement circuitry?", a more ready-made solution was sought that might not have existed at the time of John Lord´s experiments. A candidate for an appropriate IC was found, called "AD5933". This chip was made by Analog Devices and was capable of determining the complex impedance using sophisticated digital techniques and delivering the answer in clear text. In the datasheet it was capable of measuring both the capacitances and resistances expected. However, when applying more criticism to the datasheet, it was still deemed incapable of the measurement range expected. While it could probably measure impedances low enough, it could do this with a maximum frequency of 100kHz. According to the previous work by John Lord, and preliminary measurements done in this thesis while borrowing an impedance meter, the capacitance would be ranging in the tens or hundreds of picofarads, while the resistance (when relevant) would range from 10-1000 Ohm. Using these values in some preliminary simulations made by "Oregano" for Linux (powered by Ngspice or Gnucap), it was deemed unlikely that this chip could measure the imaginary component of the impedance at those frequencies. It was therefore excluded.

Another appropriate candidate chip was found; the AD8302. This chip did not use sophisticated digital techniques to deliver the complex impedance in clear text. However, using analog techniques, it was capable of determining the phase and gain of two signals from low frequencies up to a few GHz. This permitted the use of the same method of RC measurement as used by John Lord, but likely with far better result and less effort. The basic principle is illustrated in Figure 4.

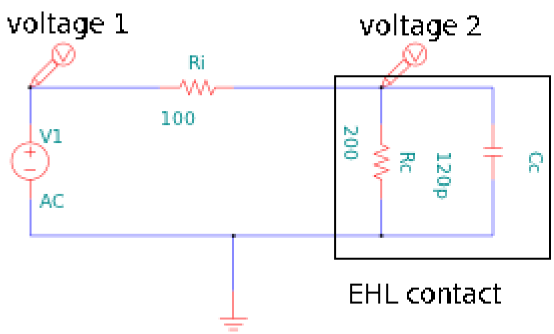


Figure 4: Measurement principle

A known resistance (Ri) was connected in series with the contact. The contact and the resistance was then injected with a signal of known frequency. The two voltages displayed in Figure 4 (voltage 1 and voltage 2) were then connected to the AD8302, which calculated the phase shift and the gain/loss. Knowing these two variables, it became possible to separate and determine the resistance and capacitance of the contact. Any inductance that might be present would be neglected. Previous experiments had shown this to be a reasonable approximation.

A representation of the equipment as a block diagram is presented in Figure 5. Within the AD8302 and oscillator blocks, other components could be included (capacitors, resistors and similar required for their operation). The resistor “Rsh” that was connected in parallel with the contact was inspired by the previous work by John Lord, and simply limited the dynamic range of the resistance measured.

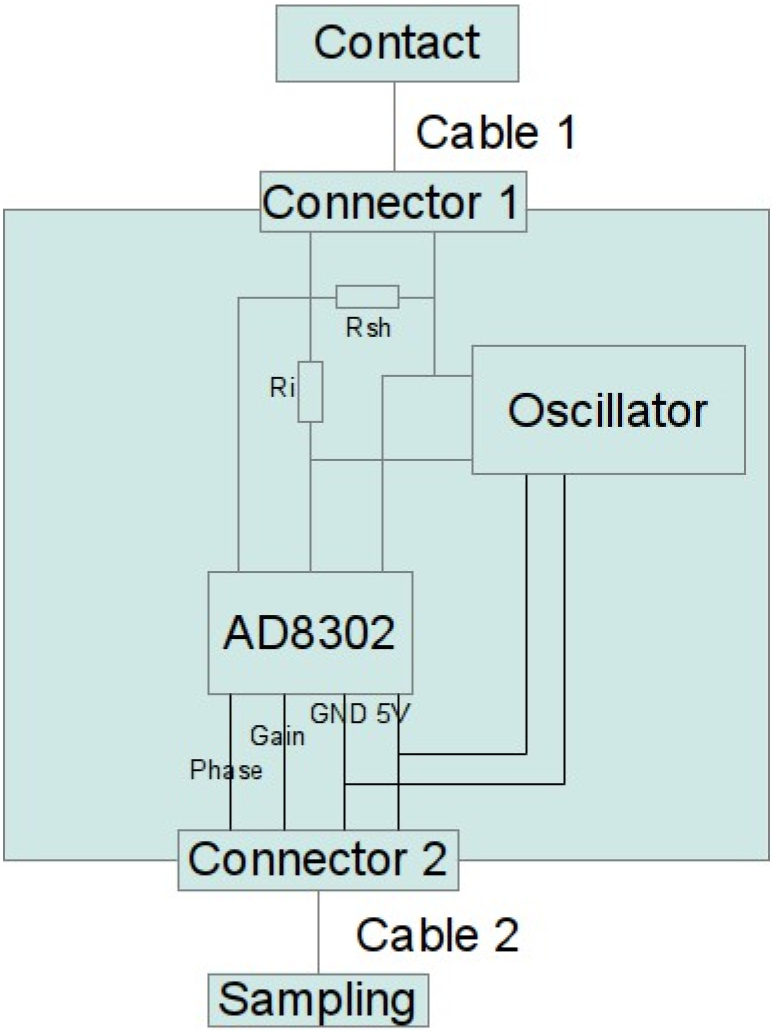


Figure 5: Block diagram of measurement circuit

The final design contained the following additions and modifications:

- All connectors except the power supply were given separate coaxial connectors.
- Oscillator block included a voltage divider to set signal level and avoid short-circuiting the oscillator at zero film thickness.
- Resistor “Rsh” could be added externally if needed, suggestively integrated in a coaxial adapter along the cable. This also permits additional capacitance to be added if warranted.
- Power supply through common 2.5mm barrel jack (+5V at center pin and GND at barrel).
- AD8302 reference voltage was also given a coaxial connector. Measuring this voltage (otherwise assumed to always be 1.8 volts) allows more accurate results.
- Inductance was added to power supply line to suppress interference.

The complex impedance of the contact , Z_c , assumed to be a capacitor , C_c , and a resistor, R_c , in parallel, can be described by

$$Z_c = \frac{1}{\frac{1}{R_c} + j\omega C_c} \tag{1}$$

Comparing the voltage across this impedance , V_2 , to the voltage across the complete circuit, V_1 , (return to Figure 4 for reference) gives the following equation

$$\frac{V_1}{V_2} = \frac{Z_c + R_i}{Z_c} \tag{2}$$

Inserting the expression for Z_c into this equation, the above expression can be reduced to

$$\frac{V_1}{V_2} = \frac{R_i}{R_c} + 1 + j\omega C_c R_i \tag{3}$$

The quote $\frac{V_1}{V_2}$ is a complex quantity, where $\left|\frac{V_1}{V_2}\right|$ is the gain of the circuit and θ is the phase. The imaginary part contains the capacitance information and the real part contains the resistance information. Extracting them was done using

$$\left|\frac{V_1}{V_2}\right| \sin\theta = \omega C_c R_i \Rightarrow C_c = \left|\frac{V_1}{V_2}\right| \frac{\sin\theta}{\omega R_i} \tag{4}$$

$$\left|\frac{V_1}{V_2}\right| \cos\theta = \frac{R_i}{R_c} + 1 \Rightarrow R_i = \frac{R_i}{\left|\frac{V_1}{V_2}\right| \cos\theta - 1} \tag{5}$$

The last equation presented a potential problem. The denominator of the *Ri* expression has to be rather close to zero in order to represent high resistance values. However, the denominator also has the potential to return negative values. Negative resistances should never occur since they are impossible outside theory. Errors in phase and/or gain measurement could render such mathematically possible. If noise were to make the resistance readouts swing between +/- infinity, the results would be useless. The capacitance equation does not encourage such a behavior. A shunt resistor in parallel with the contact could be used to limit the maximum resistance and suppress nonsense readouts.

This shows that impedances can be determined knowing the phase and gain of the principle circuit described in Figure 5.

The AD8302 delivered the phase and gain in the form of analogue voltages, both between 0 and 1.8

volts. The phase was represented by 1 degree per 10 millivolt drop (starting at 1.8 V), thus spanning 0-180 degrees. Negative and positive phase shifts can therefore not be separated, but that was not relevant in this application. The gain channel determines power gain, not voltage gain, on a decibel scale. The slope was 1 dB per 30 mV, thus spanning a total of 60 dB of power, corresponding to 30 dB of voltage (a dynamic range of 1000 times). This range was centered around 0.9 volts, representing no gain or loss. Some simple calculations were required to get the gain in a more relevant form, starting with

$$d=(v-c)\Delta \tag{6}$$

where d is the gain in dB, Δ the slope (1/0.030 dB/V), v the measured voltage of the gain channel and c the offset (zero gain voltage, 0.9 V). The power gain P_1/P_2 is then calculated

$$10\,lg\left(\frac{P_1}{P_2}\right)=d\Rightarrow\frac{P_1}{P_2}=10^{d/10} \tag{7}$$

where *P* denotes power. Power, resistance and voltage are related as follows

$$P=VI \tag{8}$$

$$V=RI\Rightarrow\frac{V}{R}=I \tag{9}$$

Combining (8) and (9) gives

$$P=\frac{V^2}{R} \tag{10}$$

Expressing (10) as a power gain gives

$$\frac{P_1}{P_2}=\frac{\frac{V_1^2}{R}}{\frac{V_2^2}{R}}=\left(\frac{V_1}{V_2}\right)^2 \tag{11}$$

which shows that the power gain can be expressed as a voltage gain by combining (7) and (11)

$$\frac{P_1}{P_2}=10^{d/10}\Rightarrow\left(\frac{V_1}{V_2}\right)^2=10^{d/10}\Rightarrow\frac{V_1}{V_2}=\sqrt{10^{d/10}} \tag{12}$$

Inserting (6) into (12) gives

$$\frac{V_1}{V_2}=\sqrt{10^{(v-c)\Delta/10}} \tag{13}$$

This can be rewritten as

$$\frac{V_1}{V_2} = 10^{(v-c)\,\Delta/20} \tag{14}$$

Equation (14) returns the voltage gain which, in combination with the phase information, was used to calculate the complex impedance and thus the capacitance and resistance.

The performance properties of the AD8302 can be found in its data sheet[6], but a few properties required special consideration.

Firstly, waveform affects measurements. If the two signals being measured has different waveforms the measured gain and phase will not be linear. This would cause faulty measurements since interpreting the phase and gain information was done assuming a linear dependency. For example; if one were to initiate the contact with a square wave, the second waveform might look very different. Figure 6 was a simulation made of Figure 4 with a square wave input (white curve, corresponding to Voltage 1 in Figure 4) of 60 MHz (white curve, corresponding to Voltage 1 in Figure 4) and an amplitude of 0.22 volts.

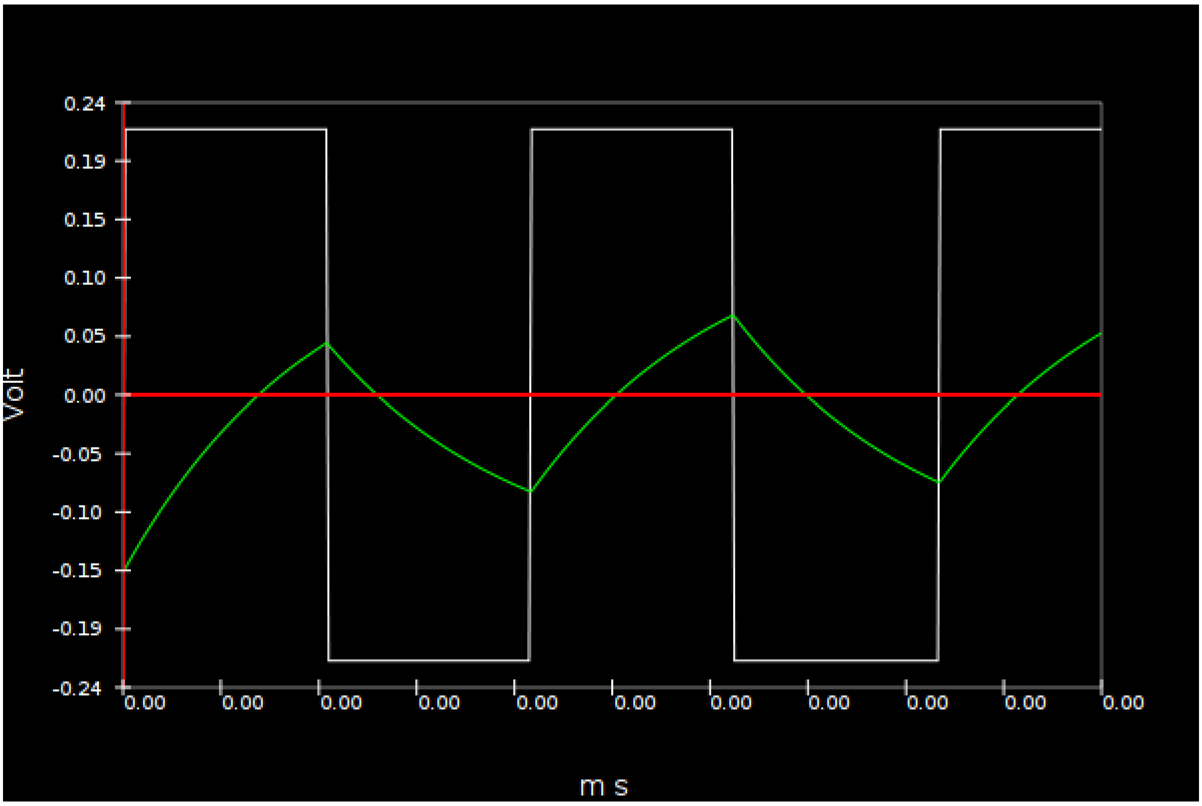


Figure 6: Square wave input response

Note that the waveforms were distinctly different, with the output (green curve, corresponding to Voltage 2 in Figure 4) resembling a triangle wave. If using a sine wave excitation however, this was

6 www.analog.com/static/imported-files/data_sheets/AD8302.pdf (2013-10-03)

not a problem, as illustrated in Figure 7.

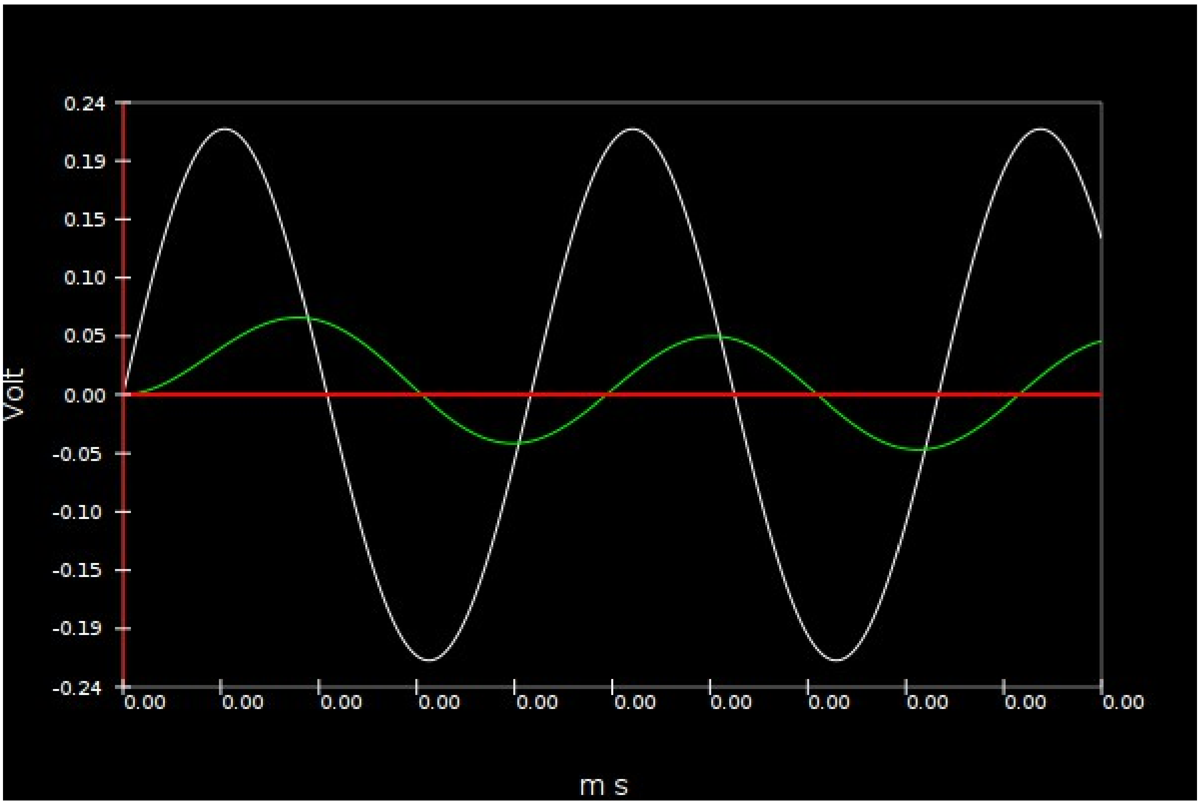


Figure 7: Sine wave input response

The waveforms in Figure 7 were both sinusoidal, avoiding distortion of results.

Another important consideration was the non-linearity close to the ends of the measurement range. This included problems near 0 or 180 degree phase shift, signals near max/min gain readings, signals near max/min frequency of the chip, signals around min/max of the signal strength detectable, and where outgoing bandwidth was close to ingoing bandwidth. In short, one should generally strive to build a circuit so as to measure in the center of the measurement range. To comply with this, the following adaptations were made:

- Initiating signal level about -20dBm (range being 0 to -60dBm and center at -30. Since the initiating signal always would be higher or equal to the second signal to be measured, it was placed above center of range).
- External filter capacitors of 3.3 pF limiting outgoing bandwidth to 10 MHz (well below the ingoing frequency of 60 MHz). Additional capacitance could be added through PCB connectors if used with slower sampling equipment.
- Frequency was chosen to get a phase shift that generally was above 20 degrees (placing

results between 20 and 90 degrees, the theoretical maximum phase shift for the capacitive load).

- Series resistor Ri was chosen to get appropriate gain/loss.

Figure 7 showed that phase shift and gain was (in simulations at least) easily discernible in what was expected to be a typical situation.

2.5 Film thickness measurement

Besides refurbishing the old ball-on-disc machine, this thesis was also intended to attempt a study of the effects of lubricant starvation in a grease-lubricated contact. In essence, the challenge was to measure the inbound film thickness entering the contact, and examine the affect this had on the film thickness in the contact.

2.5.1 Measurement methods and limitations

Finding a method of measurement based on vaguely known variables, as well as evaluating their limitations against each other was no easy task, for several reasons. Little was known in the area, meaning that little was known about the required measurement range. If activity of relevance had started while inbound film thickness was in the micrometer scale, ultrasonic sensors could had sufficed as a measurement method. If relevant activity had started in the range of a few hundred nanometer scale, interferometry or spectroscopy could have worked. All of these were available as ready made solutions, which would have been a great time-saver.

However, if it had turned out that nothing happened until the film thickness approached that of the typical contact film thickness, the measurement range needed to reach nanometer scale. This would not have been easily measured using ultrasonic methods, which was typically limited to about one micrometer. Neither was it suited for optical methods, that were typically limited to film thicknesses in the area of a quarter of the lights wavelength, meaning several tens of nanometers at best. A typical way of circumventing this problem was by adding a spacer layer, but this was probably not feasible when measuring a bare lubricant. It was difficult enough getting good optical measurements already since one cannot add a reflective layer on a lubricant, but had to rely on light reflected off of the lubricant itself to get light interference. It was also difficult to fit a spacer layer somewhere, especially since transparent materials are rarely conductive and the film thickness of the contact was to be measured using RC measurement. In conclusion, when trying to maximize the potential measurement range, both optical and ultrasonic measurements were limited.

Besides measuring the film thickness directly, there were a few other methods of estimating it.

Measuring the inbound lubricant film thickness, one could have measured or controlled the lubricant applicator. This could have been done by applying lubricant at a controlled rate, but doing so would probably not have created a flat film and thus would not have given consistent results. Seeking to improve this, an excess amount was applied and then scraped off using a controlled and measurable gap. The accuracy of this method was questioned, since for an example if the lubricant film undergoes some swelling after passing the scraper the measurement would be flawed. Such swelling was however assumed to be negligible.

If using this method of scraping off excess lubricant, the gap between the scraper and disc had to be measured. A scraper could have been placed on the ball instead, but this would have required a curved or even spherical scraper with very tight tolerances to get the conformity required. The disc offered a flat geometry, which was much easier to work with. When choosing to use a scraper and already having ruled out optical or ultrasonic methods of measuring the inbound film thickness, RC measurement was used here as well.

Finally, one must not forget that there were two bodies in contact, the ball and the disc. If measuring the lubricant flow on one body, the other body must be free of lubricant in order to get useful results. Thus the ball needed to be scraped dry, and this was to be done using a simple rubber scraper.

2.5.2 Physical implementation

Designing the scraper itself was certainly no trivial task. A list of some of the properties that was required by the scraper was that the scraper:

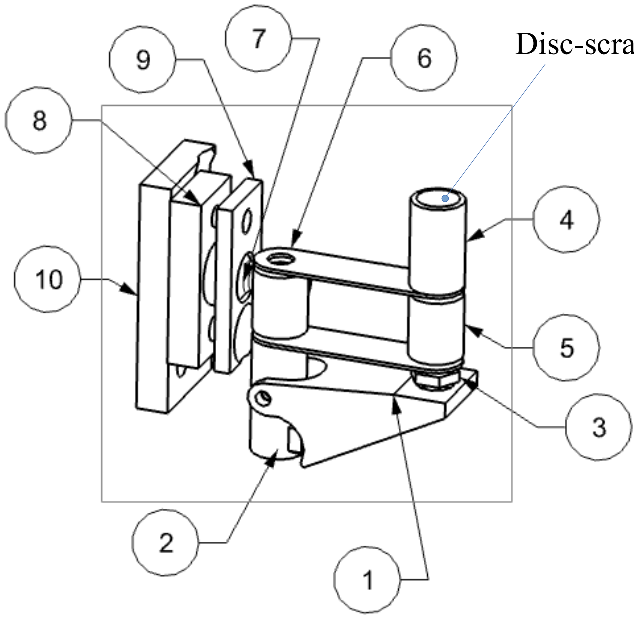
- Had to provide measurable capacitance, thus a certain area facing the mating surface, placing high demands on flat-on-flat geometry.
- Had a smooth scraping surface.
- Had a gap adjustable with high precision, preferably even while running, and must affect nothing else.
- Had to be reasonably easy to set up.
- Had to fit in a limited space.
- Had to have negligible hysteresis.
- Had to have negligible flex in most directions.

- Had to be electrically conductive but be isolated from rig.
- Had to permit non-ideal circumstances, such as disc wobble (when working on a nanometer scale, this was almost unavoidable).
- Could not affect friction force measurement.

This list of needed properties required a lot of thought to be put into the design. Reinterpreting these to sub-solutions that would give the desired result yielded the following design outline:

- Use flexible elements instead of hinges.
- Design parts to be manufacturable in a lathe when possible to permit high precision with relative ease.
- All degrees of freedom had to be available during setup and then constrainable by a single screw.
- Use converging gap to get hydrodynamic lift, and apply force to regulate gap.
- Force was to be applied using an easily accessible adjustment screw and a spring-element to convert screw position into force.
- Scraper should be mounted to the disc holder, as the disc motor was.
- Mostly metal was used to maintain stiffness.

To enable a single screw to fully release or constrain the mechanism, the screw was located in a vertical slot which then tightened a ball joint (approximately indicated by part 8 in Figure 8). When released the ball joint (part 7, Figure 8) allowed the scraping surface (top of part 4, Figure 8) to be placed parallel with the disc, and the vertical slot (approx. part 10, Figure 8) allowed adjustment of the starting distance from the disc. Small adjustment of the track (on what radius the scraper was to be placed on the disc) could also be done because of the ball joint. Larger adjustments of the track were done by releasing one of the screws (approximate part 6, Figure 8) in the parallelogram. The parallelogram was made out of two bimetal blades (part 6, Figure 8), and effectively permitted only one degree of freedom, namely the vertical freedom that determined the scrapers gap. To apply force, a rocker (part 1, Figure 8) was implemented to allow a horizontal (rig was open at the sides but not at top or bottom) and thus accessible adjustment screw (placed behind the rocker approximately at bubble 2, Figure 8). The spring-element intended to convert screw position into force was two O-rings glued on top of each other, placed between the rocker and its bolt (approximately part 3, Figure 8). This resulted in a progressive spring constant, hopefully avoiding the need to estimate required spring stiffness as if using a coil spring or similar.



PC NO	PART NAME	QTY
10	ISOLATOR	1
9	BOWL2	1
8	BOWL1	1
7	BALLPIN	1
6	BLADE	2
5	MIDDLE_SCRAPER	1
4	TOP_SCRAPER	1
3	SCRAPERSIDE_BLADEBOLT	1
2	ROCKER_MOUNT	1
1	ROCKER	1

Figure 8: Assembly drawing and parts list

A design was sketched in Siemens NX, and after repeated revisions to make it fit inside the limited space the final design was displayed in Figure 8. It was designed to be fitted to a clamp manufactured for attaching general equipment to the disc holder, illustrated in Figure 19. For a better understanding of how the scraper works, refer to chapter “3.6.1 Scraper“ in the result section of the report, as well as Figure 30.

The scraper head was given a slight chamfer to create a converging gap giving hydrodynamic lift. Great care was taken to ensure an otherwise flat geometry.

3 Results

In this part the final choices made, equipment constructed and adapted, program interface and functions are presented.

3.1 Measurements

The measurement areas and their calibration (if applicable) are presented here.

3.1.1 Temperature

The temperature of the lubricant was measured in proximity to the ball, this was done with a thermocouple. The thermocouple was connected to an amplifier that was inherited from the previous use of the machine. The amplifier put out a signal from 0V to 5V representing a temperature range from 0 to 500 degrees Celsius (linear scale).

3.1.2 Friction force

The friction force the ball experienced was an important point of measurement. The measurement of friction was derived from the measurement of torque from a load cell. This could then be used to calculate the amount of friction force experienced by the ball.

The load cell used was inherited from the machines earlier use and no data sheet was found. The load cell therefore needed calibration. This was done by applying a known force with a dynamometer (see Figure 9 and Figure 10).

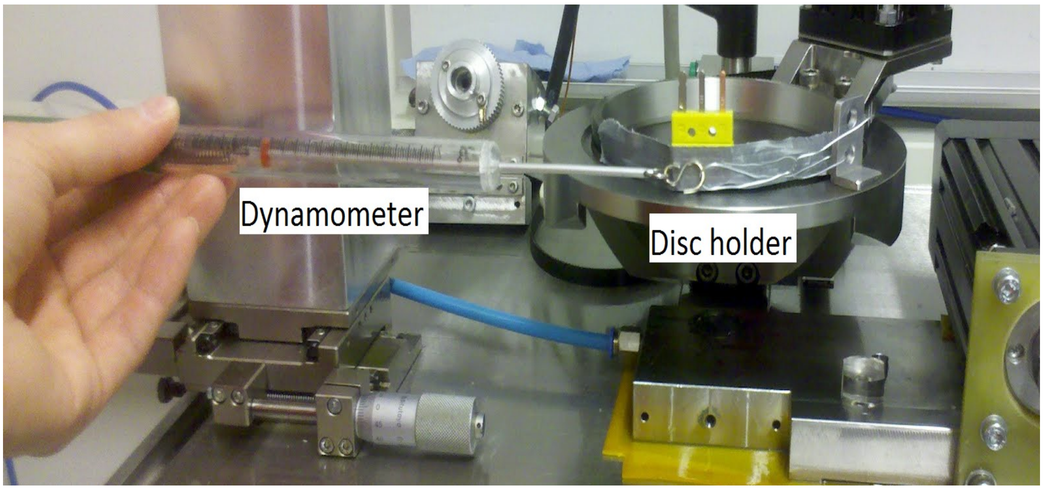


Figure 9: Calibration of torque/friction

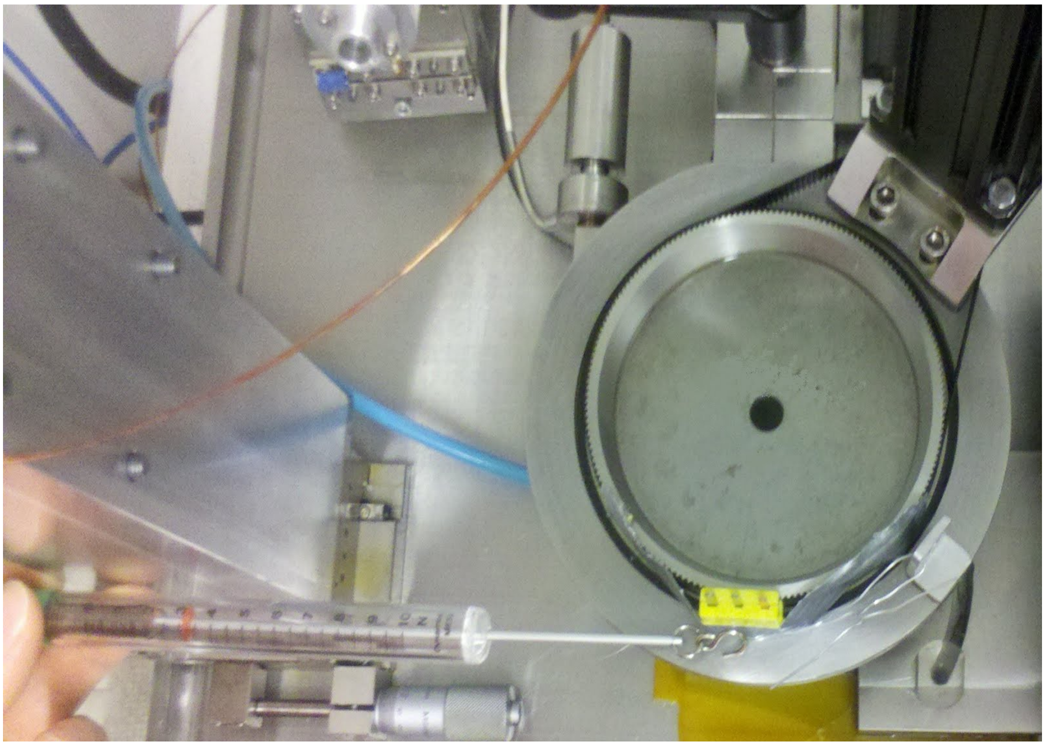


Figure 10: Calibration of torque/friction from above

The force applied was then multiplied with the distance from the fulcrum giving the torque. This data was then used to create a graph. The graph shows the voltage given from the load cell against the applied torque, in Nmm. The equation describing the plot created from this data was then used to calibrate the value collected from the load cell to correctly represent it in the LabVIEW program.

The result can be seen in Figure 11 together with the resulting equation. As the results were very nice and straight it was assumed that the conversion was completely linear within any measurement range relevant to the rig. These calibration assumed that the gauges indicates correctly and that any reading errors were negligible.

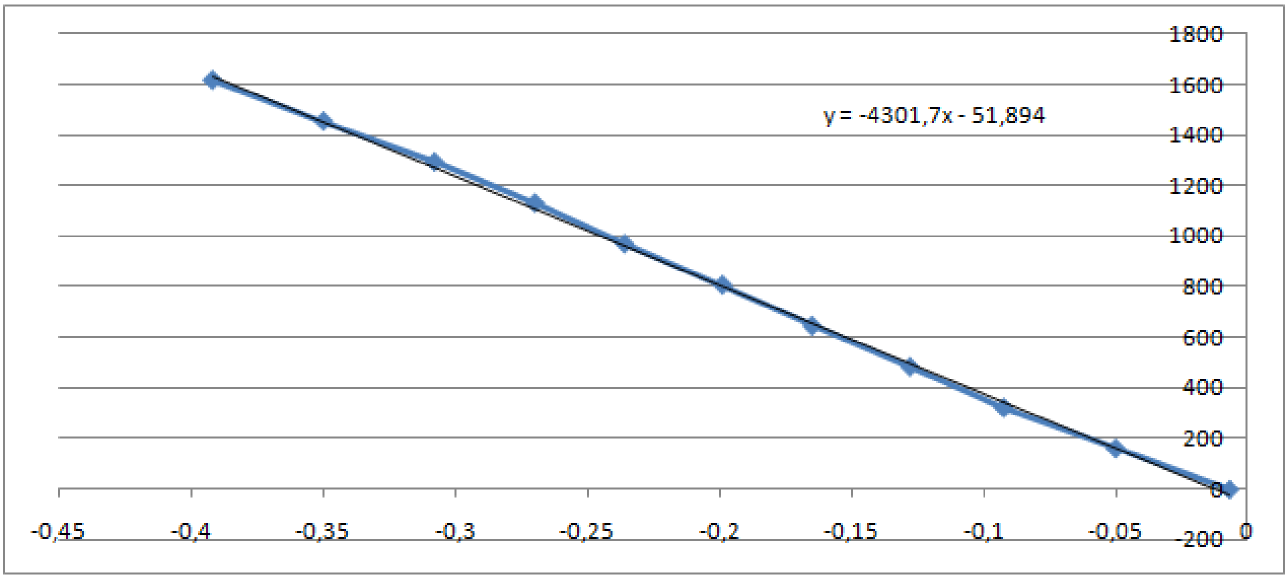


Figure 11: X is output in volt and Y is torque applied in Nmm. Resulting equation included

The equation was then used in the LabVIEW program to calibrate the measured value from voltage to Nmm.

3.1.3 Applied force

The force applied to the contact was an important data point to measure since this represents the load applied to the contact. Any tribological contact is usually heavily influenced by its load.

The force was applied to the contact by applying air pressure to a piston. The piston then pressed upward applying force to the contact. Measuring this was done with a pressure cell gauging the air pressure applied to the piston.

The pressure cell used was inherited from the machines earlier use and no data sheet could be found. The pressure cell therefore needed calibration. Calibration was done by applying known air pressures and reading the output voltage to create a plot. The pressure cell gave a voltage that related to the pressure experienced. Therefore a plot was created with the voltage output from the gauge against the applied pressure. The equation describing the plot could then be used to convert from voltage to bar.

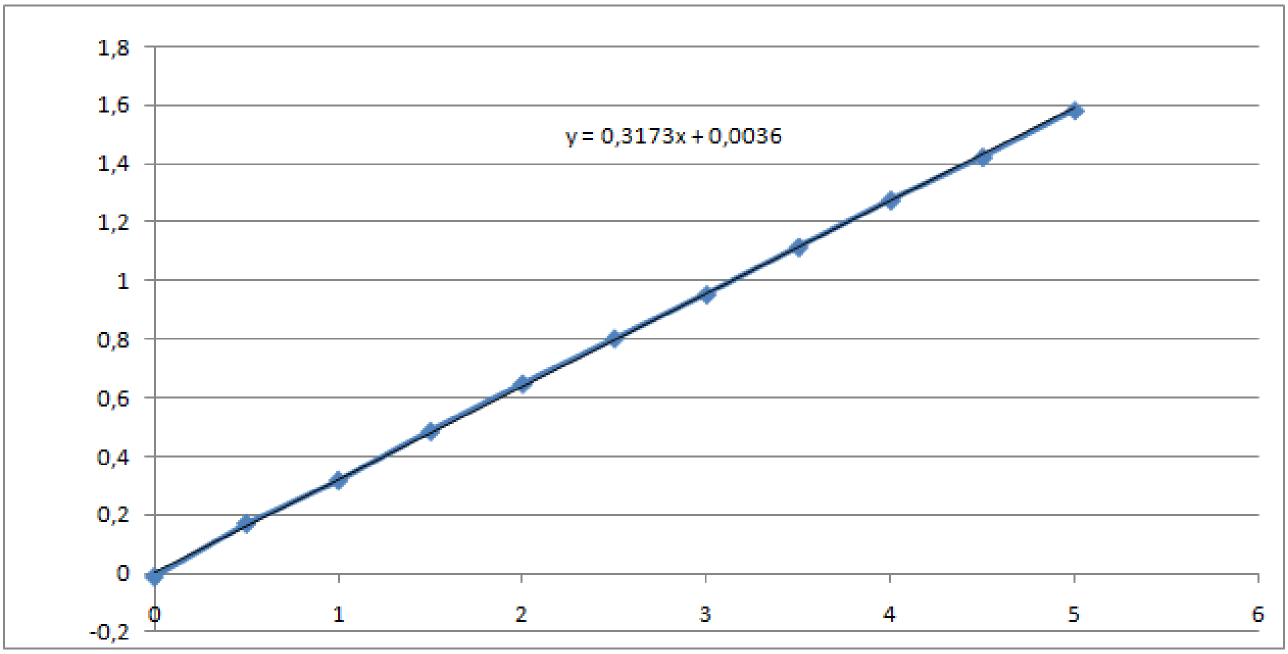


Figure 12: X is in bar and Y is in volt

As the results were very nice and linear it was assumed that the conversion always would be linear within the measurement ranges relevant to the rig. These calibrations assumed that gauges indicated correctly and that reading errors were negligible.

To then convert this into the force applied to the contact in Newton, the pressure was multiplied with the area of the piston applying pressure. The pistons diameter was 21.09 mm giving it an area of 350 mm². This can be seen in Figure 12. In the LabVIEW program this information was directly translated to contact force in Newtons.

3.1.4 Film thickness

The measurement of the lubricant film thickness in the ball-on-disc contact was a major element and challenge during the project. Devising a method for measuring the film thickness in the contact was the main interest. The film thickness itself was a very useful data point but from it one could calculate all kinds of interesting and useful data depending on what other variables were known. If the film thickness could be measured on-line inside bearings a lot of possibilities were available for such a technology. For example it could have been used to actively influence lubrication for optimal performance. Another example could be to collect data over time. Such data could then have been used to better plan production and maintenance.

The film thickness measurement in this thesis was derived from measurements done on the contact by the RC measurement equipment. Seeking to make this equipment useful for further studies, appendix 1 was created, documenting circuit diagrams, components used, and other useful information. This way the circuit could be reused, modified or reproduced as necessary by anyone.

Two complete circuit boards were populated and completed. Additionally, a third set of components and another circuit board was ordered, in the event of something breaking or another board should be needed for some other application. One of the finished boards can be seen in Figure 13.

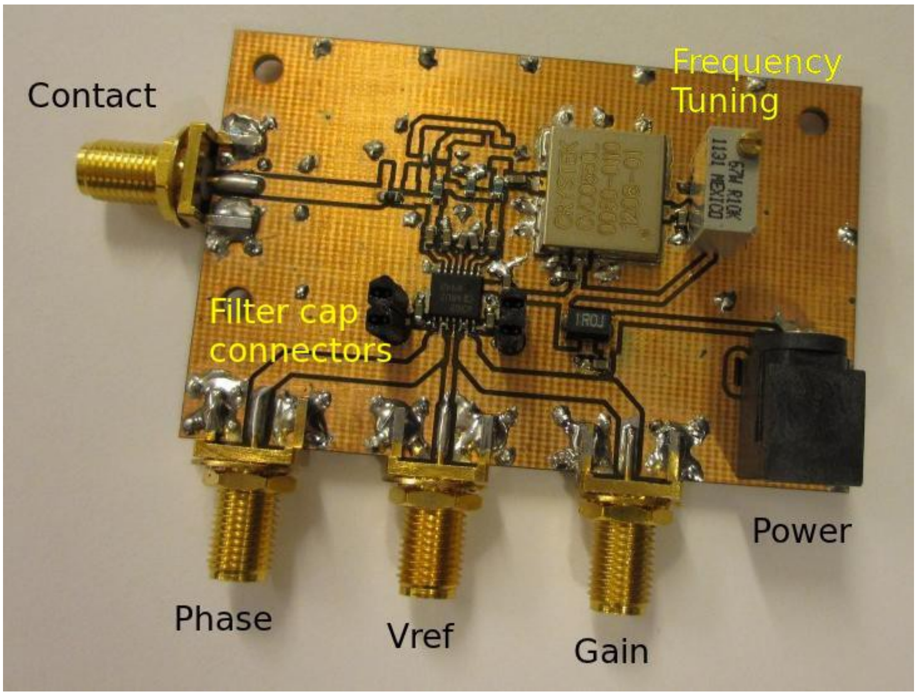


Figure 13: RC measurement card

Finally, not forgetting to enable the use of RC measurement, some work had to be done on the rig itself. Firstly, the ball had to be electrically isolated from the disc. This was already implemented, however there was room for improvement. Ideally, the ball and the disc should also be isolated from the rest of the rig to minimize stray capacitance and interference. To accomplish this, hybrid bearings were ordered for the ball spindle. These bearings had ceramic balls and the inner and the outer ring were thus electrically isolated from each other.

Another critical point was the ability to actually connect to the ball and the disc while measuring. Since they are both rotating, some sort of sliding contact was deemed most practical. A pair of ready made graphite brushes with springs and brass guides were ordered. One was fitted to the rig and one kept in reserve. The contact used for grounding was a rotating contact filled with liquid metal, which minimizes noise. The liquid metal contact used was inherited from older equipment connected to the rig. Preferably both contacts should have been of liquid metal type to reduce the amount of noise as much as possible, but due to problems with procuring a second contact of this type the graphite brush was used instead. When fitting these to the rig, special care was taken to make sure that the rotating connectors were also isolated. More information on the film thickness measurements are available under “3.5 Contact film thickness measurement“ and “3.6 Film thickness measurement”.

3.2 Hardware

Here the hardware will be presented along with some adaptations and structuring made to the equipment inherited.

3.2.1 Installation and organizing

After some serious cleaning out and refurbishment, much of the electrical equipment could be placed safely inside the protective container used to store the motor controllers. This can be seen in Figure 14.

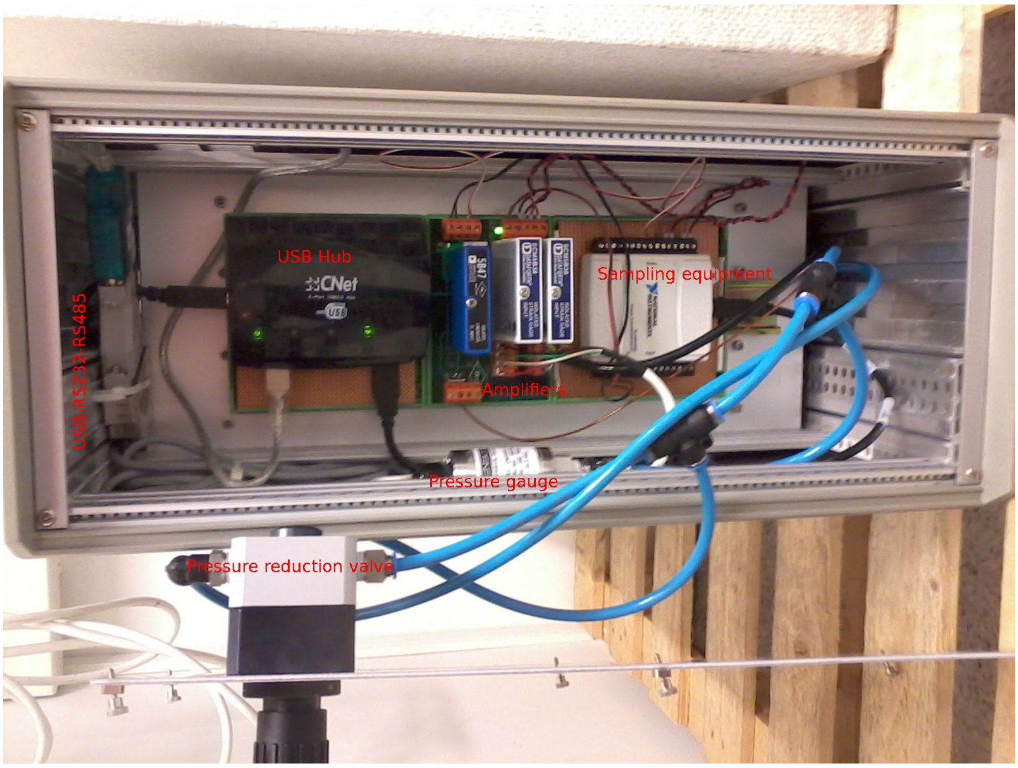


Figure 14: Control and sampling equipment installation

3.2.2 Machine body

When this project started the machine looked like Figure 15 and Figure 16 with some of its associated equipment. The white box on the left in Figure 16 was the housing for the motor controllers.

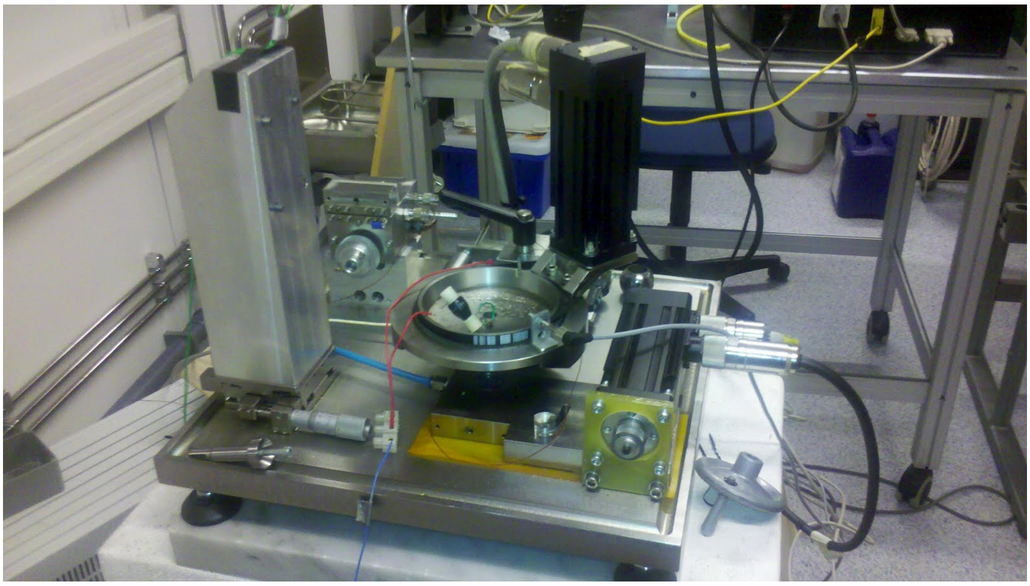


Figure 15: First view of ball on disc machine

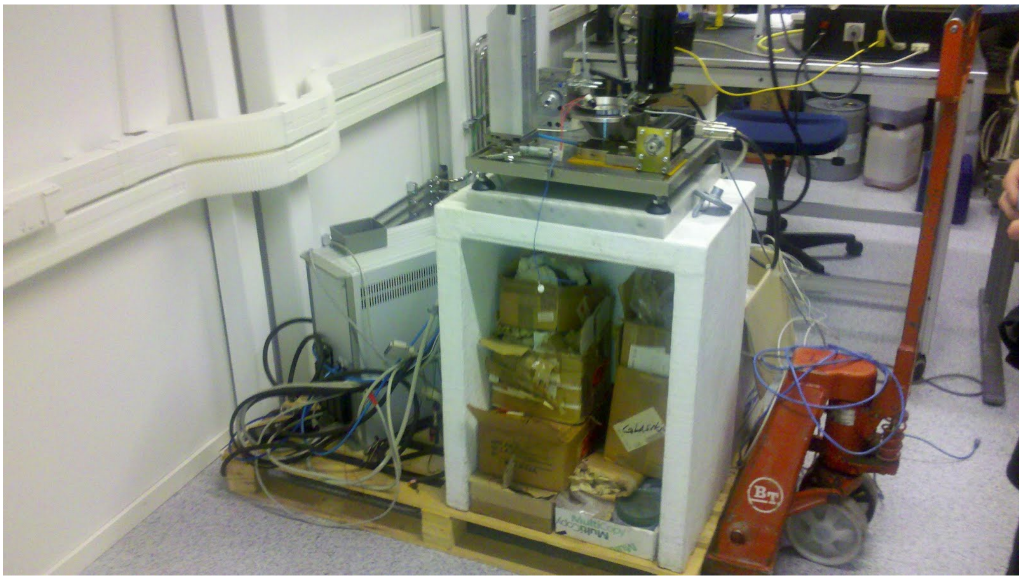


Figure 16: First view of ball on disc machine with associated equipment

After cleanup and sorting the machine body looked like Figure 17.

Figure 17: Machine body and motors after cleanup

The machine body had no major damages but the main bearing had suffered some wear due to unknown causes. At the end of the project the machine looked like Figure 18.

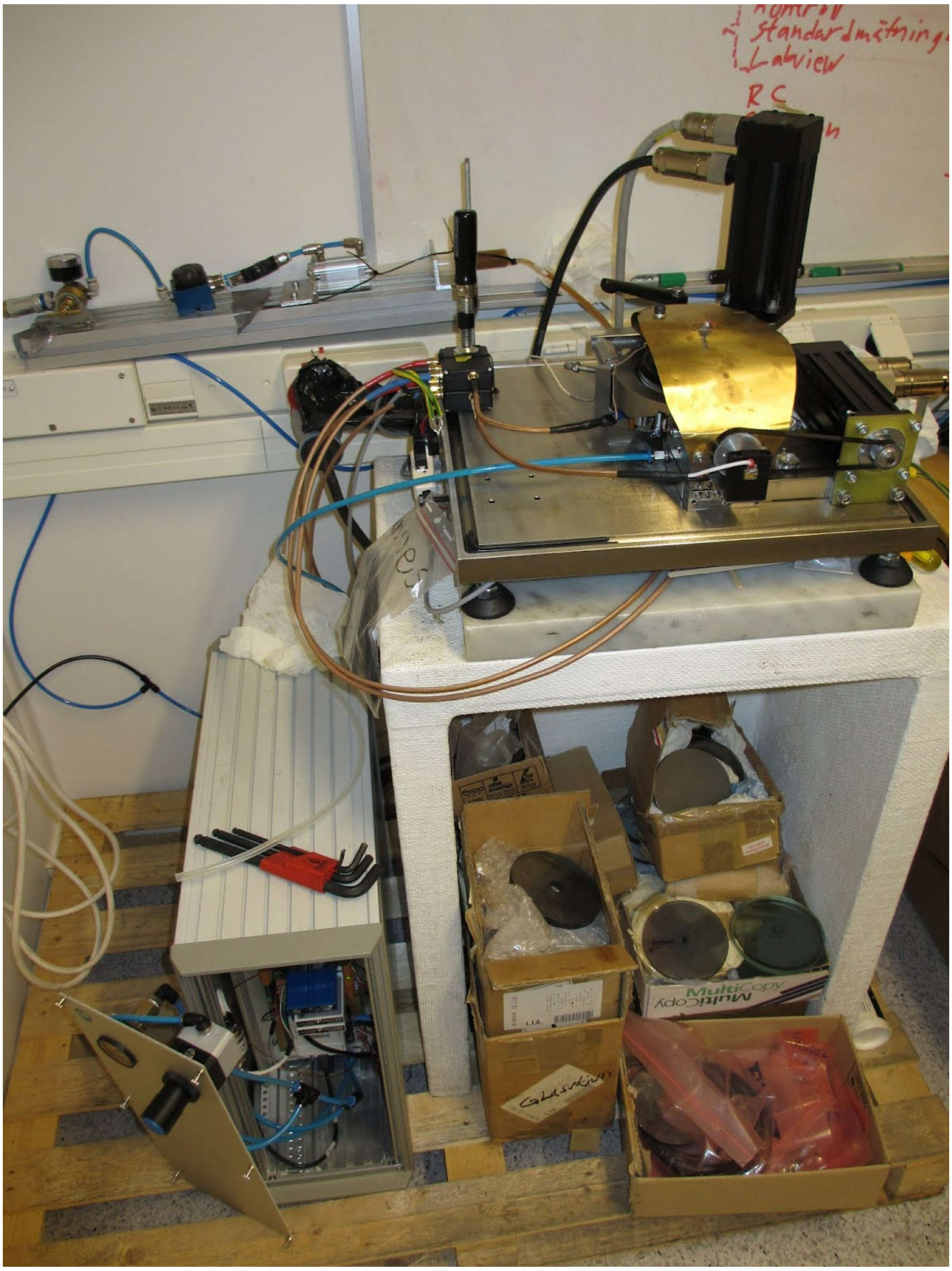


Figure 18: The complete machine at the end of the project

The bearing produced a lot of noise and heat when rotated which could have introduced noise and other unwanted effects to measurements. The bearing was a Kaydon JA045CPO and new bearings were available for purchase but had a long delivery time. The bearing currently installed during the start of this project was used throughout the thesis since no viable option was available within the time frame.

3.2.3 Attaching equipment near the contact

In order to attach equipment near the contact ball-disc contact, with minimum risk of affecting the friction force measurements, a clamp was constructed. The clamp can be seen in Figure 19 and is designed to attach to the disc holder. It was made to be easily moved and adapted for future projects.

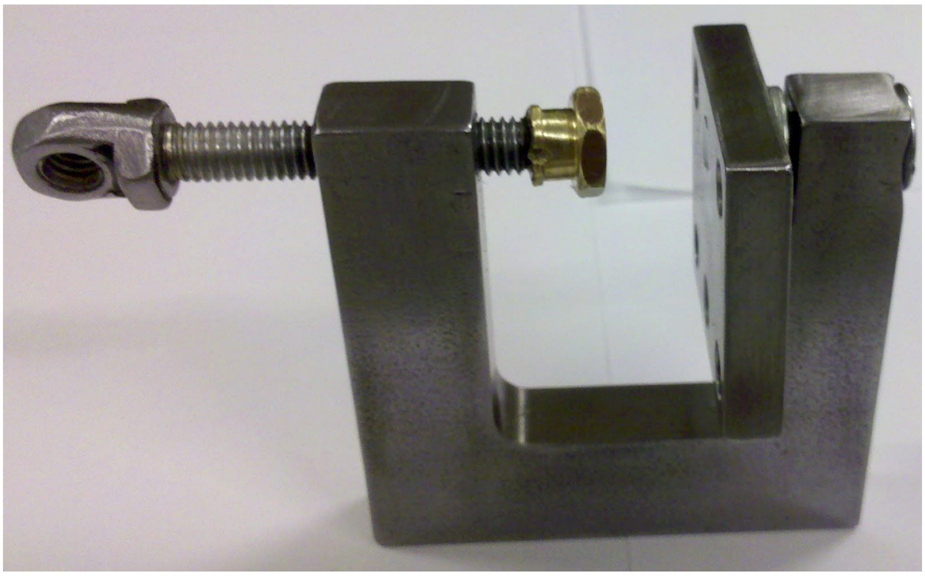


Figure 19: Clamp for attaching general equipment beneath disc

The metal plate in Figure 19 is placed on the inside of the ball on disc machine, as seen in Figure 20.

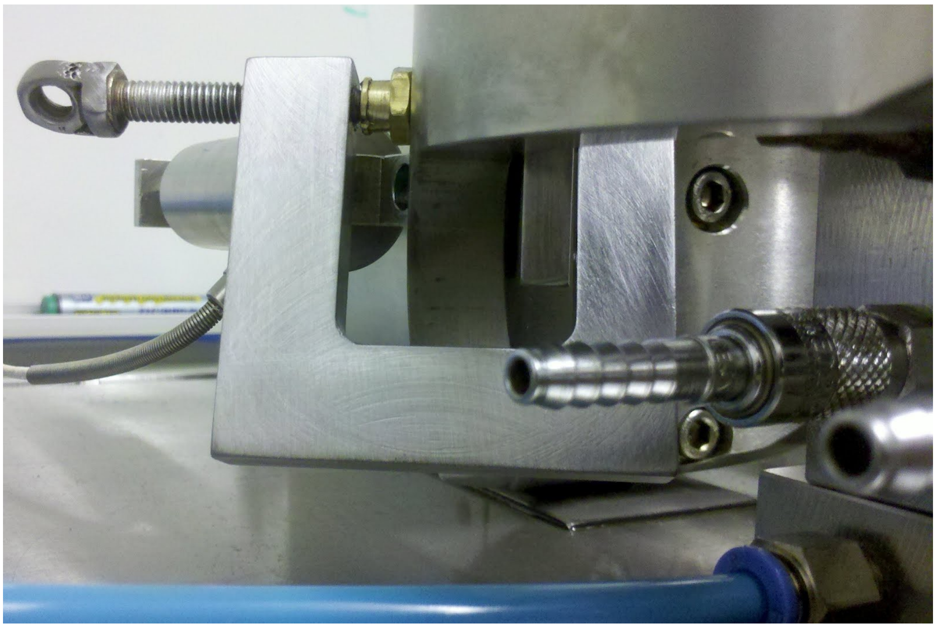


Figure 20: Clamp fastened to ball on disc machine

The ingenious thing about the clamp was its two supporting points on the inside (the steel plate) and one on the outside (the brass knob). This ensured that the clamp was always pointed at the middle of the disc holder. The steel plate had five M5 threaded holes for attaching equipment such as the scraper for RC measurement. Two clamps were constructed in case of failure or more equipment needing to be attached.

3.3 Motor control

The serial control method offered very precise control of the speed since the required speed was sent digitally in clear text. The motor speed controllers had a good precision, which was tested by setting the motors up as clocks:

A pair of clocks were drawn on two pieces of paper, one fitted over the disc and the other over the ball motor pulley. The ball motor pulley was marked and set to rotate at 1 rpm. The disc motor was set to rotate at 5.625 rpm, meaning that the disc rotated at 1 rpm. Letting this run for 24 hours, the ball motor drifted an estimated 20 seconds when compared to a real clock, and the disc drifted an estimated 3 seconds. In conclusion; as far as speed control went, there was no lack in precision. Adding to this that the power output of both the motors and controllers were more than sufficient for the application, one could simply set the desired speed and safely assume that this speed was delivered.

Contact velocity was decided by the balls tangent velocity in m/s, assuming that the balls axis of rotation was parallel to the disc (may not always been entirely true). Disc speed was determined by ball speed, factoring in the contact radius (as reported by digital gauge on rig) and the slide/roll ratio. If this resulted in a disc speed beyond the available range, a red light in the program was lit and the speed was set as close as possible to the request.

The serial control method did have a few disadvantages. Firstly the issue rate of new speeds was limited by the time it took to transmit and acknowledge the previous speeds. Secondly, it was not possible to change the speed of both motors simultaneously. It was however possible to stop and start both motors simultaneously. This was done by using a “broadcast telegram” function. Both motors would obey this telegram, but neither sent a confirmation. Thus, when pressing stop or start “Both”, there was no feedback printed in the serial window.

The motor control system was deemed reliable, having displayed no issues during use. For more on the motor control results, refer to appendix 2 - Ball on disc user manual.

3.4 Data acquisition

Here everything pertaining to the data collection, its related equipment and programming is presented.

3.4.1 Program

The program LabVIEW was chosen to be the programming environment. This was done for a couple of reasons.

- First and foremost there was much previous experience on the university working with this program. It was decided that this familiarity could be useful for future users to be able to get familiarized quickly.
- Secondly LabVIEW was (as the name might suggest) made to create measurement and control systems in scientific and engineering applications.
- Thirdly, National instruments, the company responsible for LabVIEW also provided a lot of testing and measurement equipment which was easily and fully integratable with LabVIEW, such as the NI USB 6009[7] device.
- Fourthly, LabVIEW had a big and comprehensive training/learning capability,[8] through example code and training resources both offline and online.
- The fifth and final point was that LabVIEW had many ready made add-ons, interfaces and toolkits for both domestic and foreign hardware (including the Arduino[9]).

LabVIEW programs generally consist of two parts, the front panel and the block diagram. The front panel was where the end user could manipulate dials, gauges, buttons and so on that were created to control the program. Meanwhile, the block diagram was where all the code is.

The block diagram was split in two main parts. One part managed the communication with the motor controllers while the other managed sampling, signal conditioning, storing and graphic representation of data. Most functions commonly needed for running a test (such as sample rate, length etc) were given some sort of toggle on the front panel.

Some functions might have required the user to enter the block diagram for changes to be made. The most likely of these is presumably to make changes in how the data is to be stored, to add or remove channels and/or devices for sampling or to change the way the data is presented.

To change how the data is to be stored, the user simply enters the block diagram and looks inside “Main loop for measurement, plotting and signal processing” for the icon tagged “4. Write To Measurement File”. When this sub-vi has been found the user double clicks the icon and edits how the data is to be stored.

7 http://sine.ni.com/nips/cds/view/p/lang/en/nid/201987 (2012-05-08)
8 http://www.ni.com/academic/labview_training/ (2012-05-08)
9 http://sine.ni.com/nips/cds/view/p/lang/en/nid/209835 (2012-05-08)

To add or remove channels, the user enters the block diagram and looks inside “Main loop for measurement, plotting and signal processing” for the icon tagged “1. DAQ Assistant”. The user then double clicks to enter the sub-vi and make the desired changes. A neat feature with this is that after a channel has been added the user can click the “connection diagram” bar above and get a graphical guide for connecting the wires to the physical device. In the DAQ assistant changes to sample rate, acquisition mode, sample rate and other values can be made. The acquisition mode for the NI USB 6009 was set to “continuous samples”. The sample rate and samples to read are both available from the front panel. All other functions in this sub-vi are utilized at the user's own hazard. The standard procedure for doing basic measurements is presented in appendix 2.

3.4.2 Sampling equipment

Choosing data acquisition device for this project was somewhat difficult since no firm data was available on how high sample rates was required or how many channels would be needed. Two main competitors emerged when searching. Both of these were quite inexpensive and both could be connected to a computer via USB port, which was important to make the new setup independent on which computer it was connected to. Both were compatible with LabVIEW.

The devices were the Arduino MEGA 2560[10] and the NI USB 6009. The NI USB 6009 device was fully integrated with LabVIEW while the Arduino MEGA 2560 had a free interface[11] for LabVIEW. The free interface was a bit less stable and had somewhat less support than the NI USB 6009 device. The Arduino Mega 2560 had an internal sample rate of 77 kHz and a 10 bit resolution. The NI USB 6009 device had a 48 kHz sample rate and a 14 bit resolution. The Arduino 2560 was a full (but small) computer in its own right and code could be uploaded to its memory, making it able to work without LabVIEW. This would require some more classic, text based programming but it made the Arduino more flexible in its functionality. In the end, the NI USB 6009 device was chosen since it had a 14 bit resolution.

The sample rate of NI USB 6009 device was split evenly over seven channels giving a theoretical maximum of 6857 samples/second for each of these channels. It was decided that during measurements 6000 samples/second would be the maximum sample rate, just to be on the safe side of any stability issues.

The NI USB 6009 device turned out to have a bug that caused the relatively small on-board FIFO (first in, first out) memory to overflow after starting and stopping sampling a couple of times. This

10 http://arduino.cc/en/Main/ArduinoBoardMega2560 (2012-05-08)
11 http://sine.ni.com/nips/cds/view/p/lang/en/nid/209835 (2012-05-08)

bug was known[12] by National instruments and a workaround existed. Unfortunately all attempts to implement this workaround failed. The effect of the bug was that after a seemingly random amount of starts and stops of sampling, the NI USB 6009 device stopped working. A "device memory overflow" error occurred. Stopping the program with the "Abort execution" button followed by unplugging and replugging the device relieved this problem. Since this manual reboot of the device rendered the bug a mere inconvenience it was decided that further attempts to implement the recommended workaround would be too time consuming. Instead, an addition to the program was made. This addition engages when the bug occurs giving the user instructions on how to relieve the problem. This solution goes against the approach wanted in this project where stability and well engineered solutions would be given extra focus, but priorities had to be made. Since this solution worked well enough to run the program and time was short, this problem was left "as is".

3.4.3 Graphic layout

The graphical layout was divided into six groups. These groups are "motor control" (see Figure 21), "data graphing and measurement control" (see Figure 22)," error handler" (see Figure 23), "test output information" (see Figure 24), test input data (see Figure 25), and stop everything (see Figure 26). The functions of each group was made to be as simple and self explanatory as possible.

12 http://digital.ni.com/public.nsf/allkb/611475F9BE62881E86256FDC0062B1BB (2012-05-08)

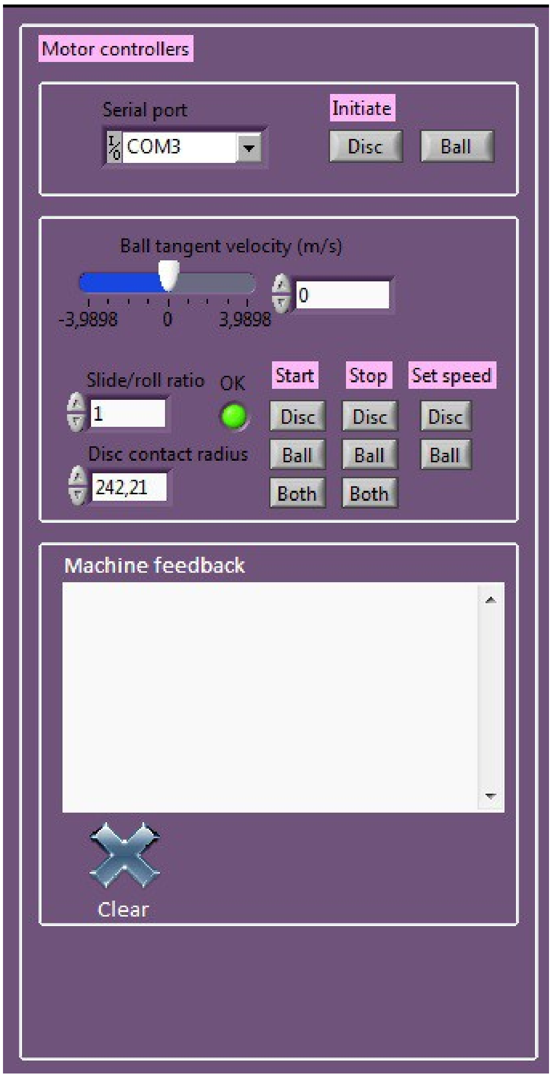


Figure 21: Motor control group

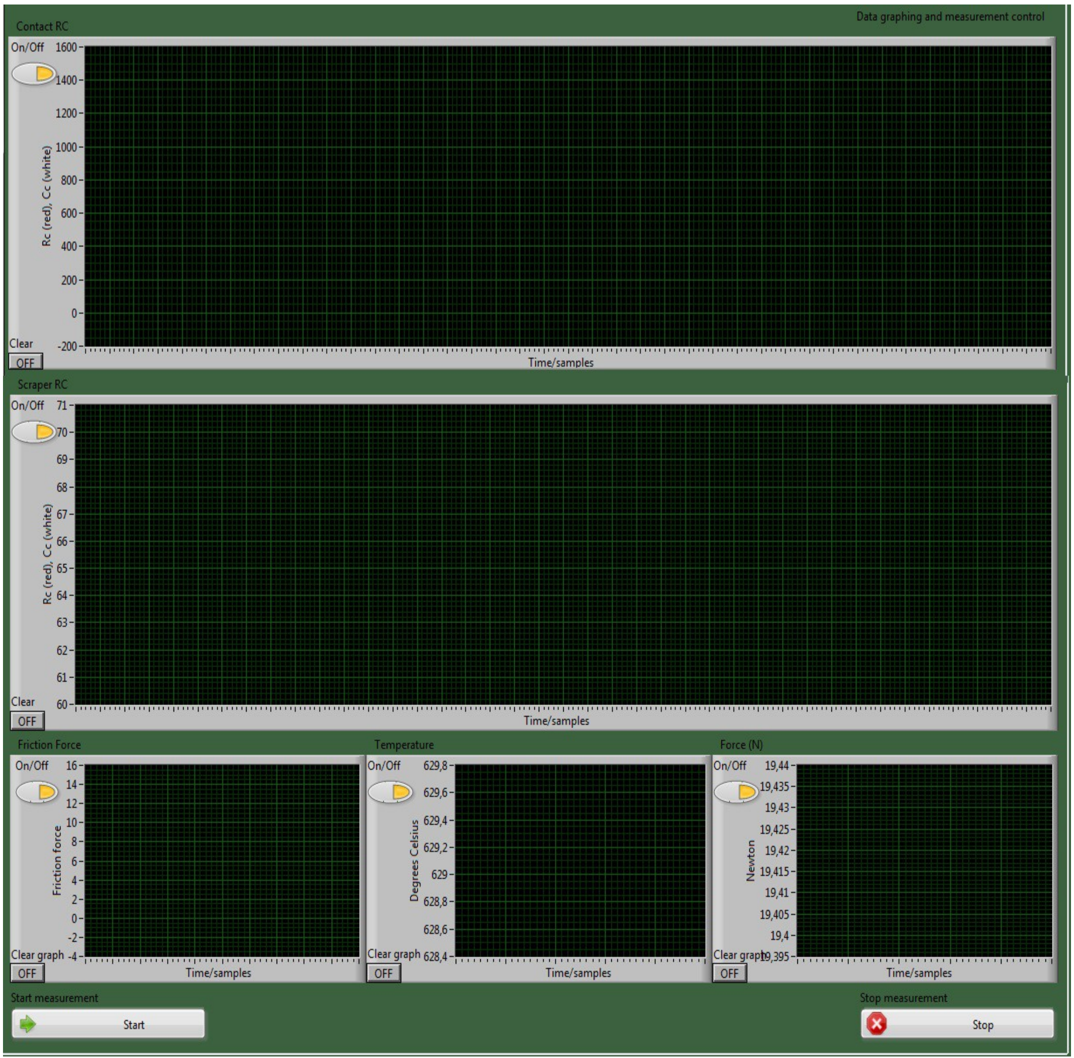


Figure 22: Data graphing and measurement control group

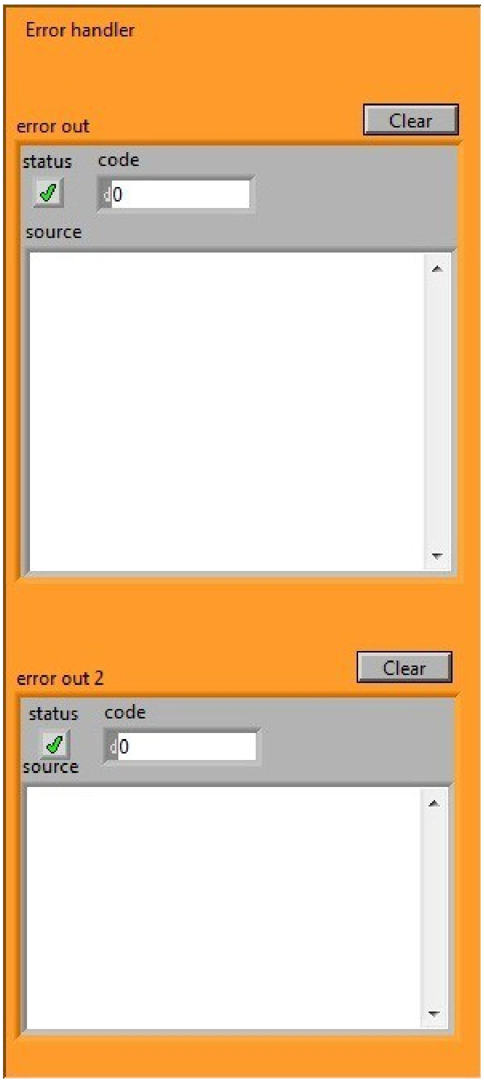


Figure 23: Error handler group

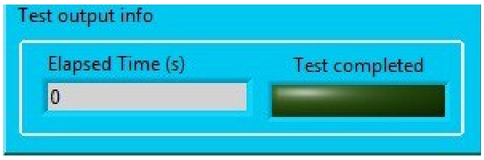


Figure 24: Test output info group

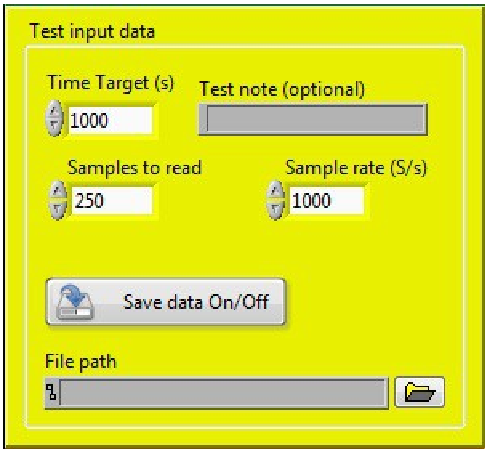


Figure 25: Test input data group

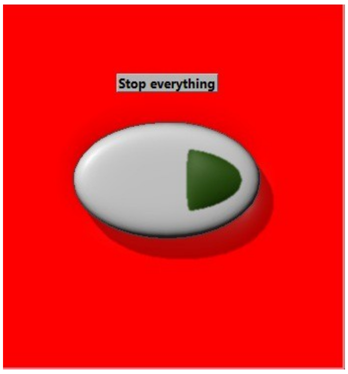


Figure 26: Stop everything group

These groups all came together into one greater graphical display, as can be seen in Figure 27. The interface fits perfectly on a 1920x1200 screen which relieved the user from scrolling around the program to find desired functions.

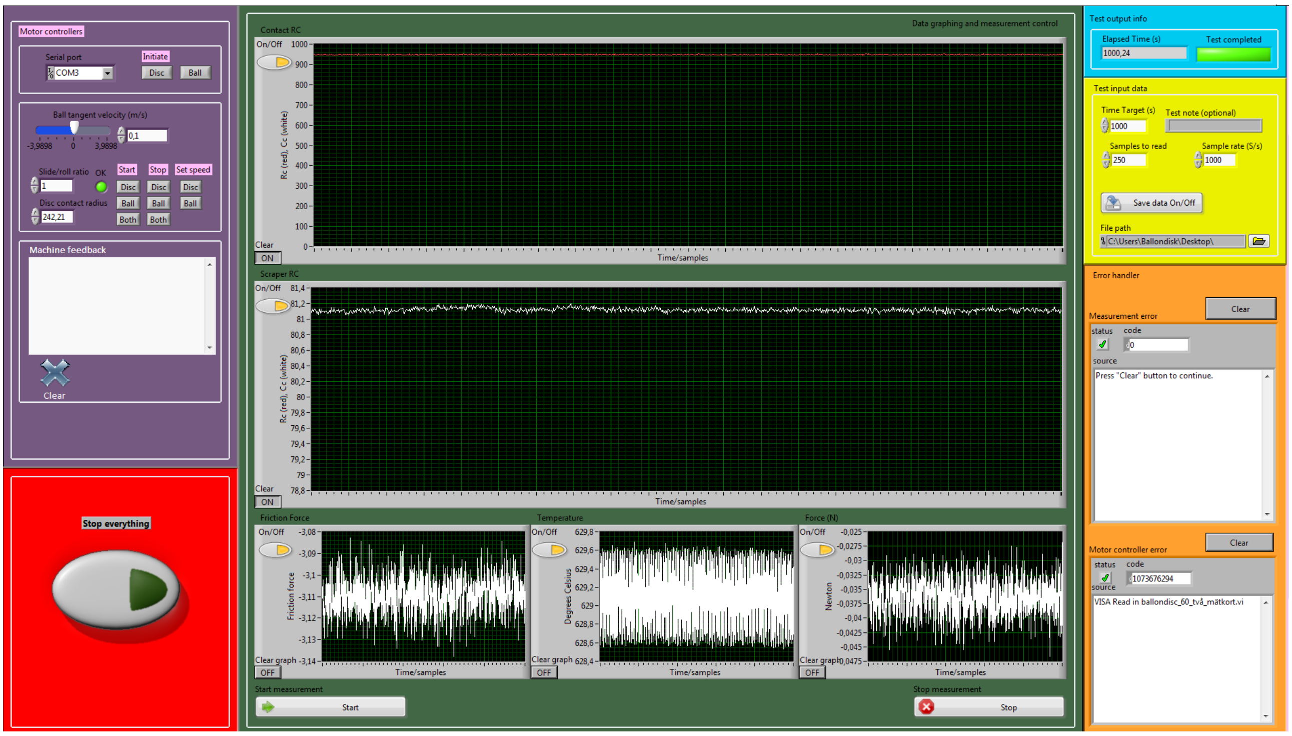


Figure 27: Complete interface

3.5 Contact film thickness measurement

The film thickness measurement was done using some RC measurement cards developed during the thesis. The cards used a method already verified as practical for the job, but some of the parameters were not quite optimal. The finished equipment was shown not to be reliable for quantitative measurements (telling exactly what the resistance and capacitance is). However, it can still be used in qualitative measurements to draw some conclusions in its intended field of study: lubricant starvation. Hopefully, it will at least be able to show that the setting of the scraper that was manufactured does have an effect on the contact. Thus it gives a lead on how to continue in further studies.

The equipment had, however, proven capable of reading resistance and capacitance reasonably well within a certain range. For more details on this and other properties of the RC measurement equipment, refer to appendix 1 - RC measurement user manual.

3.6 Film thickness measurement

3.6.1 Scraper

To measure when lubrication starvation in the ball-on-disc contact occurred, the ingoing film thickness had to be known. Therefore a scraper to control the ingoing lubricant film thickness was constructed. Presented in Figure 28 where it was attached to the disc holder. Note the allen keys connected to the adjustment screw and the setup screw, and that the photo was staged with disc holder removed and turned upside down.

Mounting the scraper onto the disc holder was somewhat complicated since there was very little space under the disc holder. Other than the spacial issue it was quite trivial to mount and adjust the scraper using the built in screws.

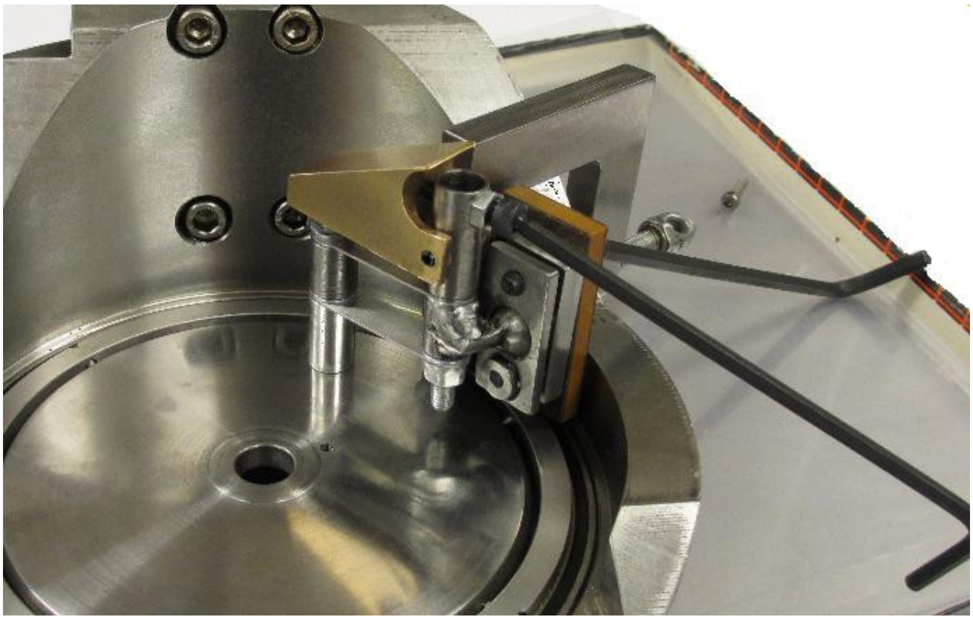


Figure 28: Scraper attached to clamp attached to disc holder

For further understanding of the scraper and its placement refer to Figure 30.

3.6.2 RC measurement

To know how thick the film set by the scraper was, the same RC technique as used in the contact measurement was chosen. The scraper would, however, rely mostly on the capacitive part of the range since it was expected to have a fully separating lubricant film. This made it somewhat easier to measure. Translating the capacitance to actual film thickness could have been done by measuring the capacitance when the scraper was set to different known distances from the disc. If compensating for stray capacitance, it should be possible to do this externally, bringing the scraper and the disc holder to a lab with appropriate equipment for measuring small distances. It would, however, be important to have the intended lubricant present in the gap, since this will affect the capacitance. Unfortunately the RC equipment used was not precise enough to warrant doing this, and time was also an issue.

3.7 Lubricant starvation measurement

Unfortunately, both the equipment used and the time left after arranging this equipment prevented a thorough study on lubricant starvation. However, some tests were made and some conclusions could be drawn. An arbitrary test presented in Figure 29, where the relevant measurements were filtered and graphed. The exact parameters of the test are irrelevant, since no exact measurements could be made. Look instead at what the different areas of the graph show about true or false correlation.

First of all, note how the scraper capacitance was not affected when load was applied to the contact. This shows that that the equipment does not cause false correlation. This was an important find, since there was reason for concern. When using two RC measurement circuits, connected to the same computer and the same ground, they could possibly affect each other and ruin the reliability of measurements. This was not the case for this rig.

Secondly, look at the area called “Adjusting scraper”. In this area, one would like to see changes in scraper capacitance followed by a change in contact parameters. This verifies that the scraper was capable of causing a change in lubricant flow that affects the contact. There was also a slight lag between changes in the scraper capacitance and contact parameters, this disproved false correlation. When adjusting the scraper, it took a while before change in lubricant flow reached the contact, since they were separated by some distance and had a finite speed.

Look finally at the “Changing speed/load” area. At first (to the left in the area), the load on the contact was changed. This affected only the contact parameters, as it should. Changes in speed affected all parameters simultaneously, again as it should.

In conclusion, the methods used were useful in making a study about lubricant starvation. The scraper was indeed capable of controlling the lubricant flow in the relevant range, and the RC measurement method could evidently be used to measure both of the quantities simultaneously.

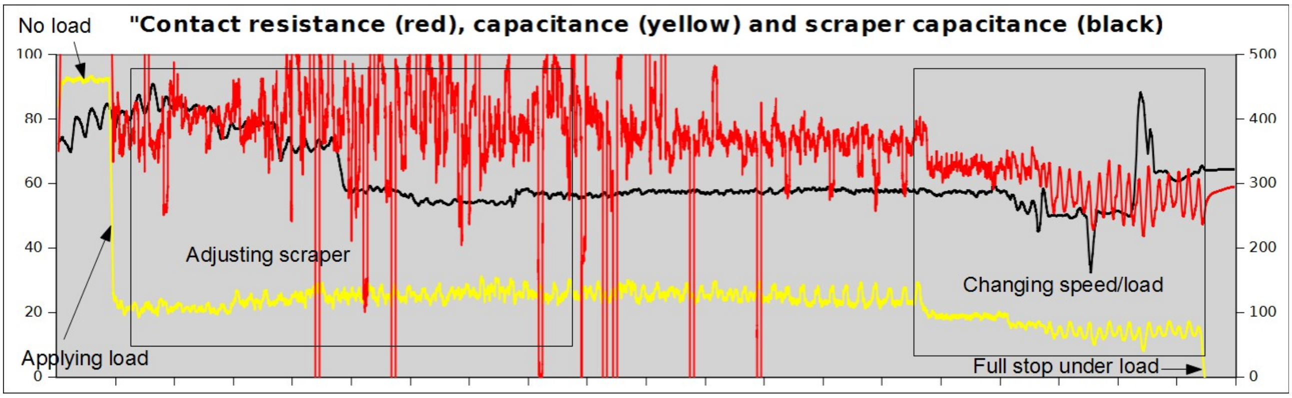


Figure 29: Full scale test over 1000 seconds.

The graph was made using the open source spreadsheet Gnumeric (since no other spreadsheet could handle the size of the data series), and a moving average filter over 1000 samples.

The test was made using grease, applied through a hose attached to the scraper. Everything was monitored using a modified web-camera. Refer to Figure 30 for a better understanding of the setup used.

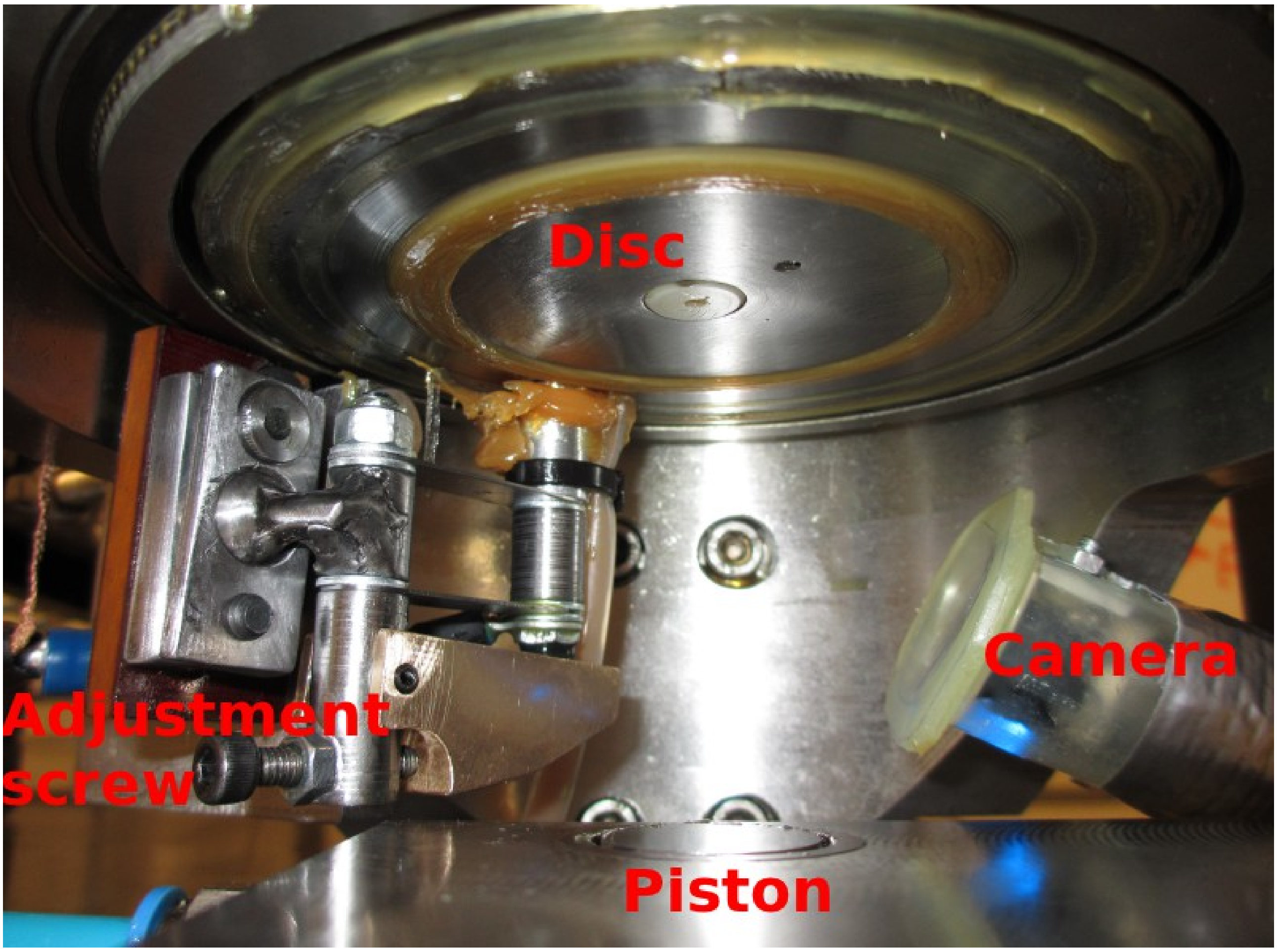


Figure 30: Equipment setup during test

4 Suggested future work

Once the equipment was built, it was easy to identify some things that could have been done better or differently. Other things could also have been implemented if more time and/or resources had been available. Things of this nature will be presented here as suggestions for future work and improvements to the machine and its equipment.

4.1 RC measurement

Several things about this could be improved, and these are presented here. Also refer to "appendix 1 – RC Measurement" for more ideas and information.

4.1.1 Measurement Frequency

The oscillator used was changed in a hurry to about 60 MHz to get the circuit finished in time. Originally, a crystal of about 40 MHz was chosen, with the intention of using the ISM band at 40.66-40.7 MHz. This oscillator was out of stock and could not be procured in time. ISM bands were frequency bands available for applications such as this, without requiring a license. Using such a frequency would have been a better engineering practice. Both of these crystals did however limit the outgoing bandwidth of the circuit. To reach the potential 30 MHz bandwidth of the AD8302, one could have replaced the 60 MHz oscillator and instead aimed for the amateur radio band at 144-146 MHz. This was also to avoid license obligation. Increasing the outgoing bandwidth to 30 MHz would also have required that all external filter capacitors were removed. However, increasing the frequency could also have brought complications difficult to predict. The first thing to improve would have been to shorten cable lengths and connections.

Changing the frequency even higher would only be a good idea if very high temporal resolution was required. Many problems could instead have been overcome by lowering the frequency to only a few MHz.

4.1.2 Reducing interference and faults

Hybrid bearings were used for the ball spindle in order to reduce stray capacitance primarily from the oil tub. This was especially important since the oil tub could otherwise have caused a non-static stray capacitance since it moved with the ball. If this change in stray capacitance was large enough to be relevant was difficult to predict, however with the chosen frequency reducing stray capacitance could be an advantage. To further reduce stray capacitance, it would have helped if the disc bearing had been insulated.

4.1.3 Rotating couplers

Another issue with the current design was the large separation of the graphite brushes. Having the rotating couplers far apart required long cables, causing much interference given the high frequencies used. This separation could have been dramatically reduced by fashioning a plastic oil tub, with the brushes integrated. Such an oil tub would have shortened cable length and thereby reduce disturbances drastically. One would then simply have to connect to the tub with a coaxial connector to perform RC measurement. This could have been combined with using a liquid-metal rotating coupler, to avoid graphite particles contaminating the oil. Using such a coupler would also have reduced interference greatly.

4.1.4 Commercially available equipments

There were certainly equipments available for purchase that could measure complex impedances (RC measurement) much better and over a wider range than the circuit designed here. For future studies it may be best to simply invest in one of these, despite the high cost.

4.2 Laser Doppler vibrometry

A vibrometer could have been used to detect vibrations without the need for direct contact. A laser Doppler vibrometer could measure vibrations in the micrometer range with minimal interference to the rest of the equipment. This data could have been useful both for the sake of knowing how much the machine vibrates but also to see if and how vibrations affected other measurements and where these vibrations were located. Since the technique is contact free, many points could have been measured simultaneously.

Some basics about this was found on Wikipedia[13]. Both the math and the equipment were simple which could make this an easy and cheap measurement to implement.

4.3 Hardware

4.3.1 Measurement equipment

Using a USB based sampling equipment had the advantage of not being computer dependent. Any computer with the proper drivers could have been used, and since modern USB hubs could deliver a fair amount of power it was usually sufficient to power external amplifiers as well. USB was a widely used standard, and was likely to be around for many years to come. The typical downside was a limited bandwidth compared to PCI based cards. This was not much of a problem in this

13 http://en.wikipedia.org/wiki/Laser_Doppler_vibrometer (2012-05-21)

application, but the specific USB sampling card used (NI USB-6009) was a problem, at least when used with Windows Vista or 7 (according to National Instruments). It repeatedly threw a “Device memory overflow” error, that could only be circumvented by physically unplugging the device and plugging it back in. To add to the frustration, if one did not first press the stop button in LabVIEW, BSOD[14] occurred when unplugging the device. After spending far too much time trying to circumvent this problem in software, the only reasonable way seemed to be to buy another sampling card (USB-6008 was also affected by this issue, so not that one). Therefore it was an advice to future users to procure a different sampling equipment. Constantly having to unplug and re-plug the measurement equipment poorly matched the vision to provide a robust, reliable and long term viable refurbishing of the old ball-on-disc machine.

As the number of channels to measure increased, the amount of samples/second for each of those channels decreased. This could have been a problem if high sample rates were required. This could have been solved by either buying different data acquisition equipment (which would probably have solved the device memory overflow problem as well) or buying further NI USB 6009 devices to run in parallel with the one used for this project.

4.3.2 Contact force

The piston used to apply force to the contact used a seal-less design to counteract friction interference. While this worked fairly well, a “bellow” or similar could have further improved results. This could have further improve the precision of the force applied, and would have stopped the leaking sound from the piston. Also, the weight of the ball assembly was not compensated for in the pressure-to-force calculations, so some oversight of these calculations would have been necessary for increased precision.

4.3.3 Driveline

There seemed to be some disturbances in the driveline for either the disc, the ball or both. Friction force readings were more irregular than they should have been. There were a few possible sources of disturbance. For one thing, one of the motors vibrated periodically when run at low rpm (caused by the motor controller, not the motor). For another thing, the belt drive precision was poor since the pulleys were not quite concentric to the motor shaft. Lastly, the belt-guiding washers on the ball motor were not chamfered, so the teeth of the drive belt may have caused some vibrations when contacting the edge of the washer. A part of this issue was the fact that the ball pulley was tilted when force was applied to the contact, and this angle also depended on the disc thickness. This

14 http://en.wikipedia.org/wiki/Blue_Screen_of_Death (2012-05-19)

tilting caused the belt to wander towards the guide washers on the motor pulley.

Attending to these problems could be an important, future step to further improve performance and reduce disturbances. Another way of filtering these disturbances might have been to add flywheels to the motor axles and/or ball/disc. This could have decreased noise from belts and motor vibrations.

4.4 Software

Suggested improvements of primarily the LabVIEW program will be presented here.

4.4.1 Sampling

The DAQ assistant used to control the channels and sampling from the NI USB 6009 device was a ready made sub-vi. This could have been coded differently to give the user ability to control how to distribute the sample rate manually between the channels instead of them automatically being distributed equally between them. The reason for not implementing this in the program from the start was simply because it would have taken more time and more learning about LabVIEW to implement. This was therefore given a low priority since the DAQ assistant was already doing an adequate job.

4.4.2 Motor control

The final control type did not permit simultaneously changing the ball speed and the disc speed, but it did permit simultaneous stop/start. If a simultaneous speed change was required for some reason, the best solution would be to simply disengage one of the drive belts (preferably the one on the ball). However, this would only allow for a slide/roll ratio of 1, and some slip could occur during sudden changes in speed.

The second best thing to a simultaneous speed change, could have been to change both motor speeds very quickly. Firstly, a “set both” button could have been implemented under “speed” in the interface. This button should have caused the speed of the ball to be set first, then the program itself should then have listened for the “acknowledge” signal and immediately have changed the speed of the disc. Secondly, the controllers did offer significantly higher baud rates than the one used in this project. Increasing the baud rate would of course have decreased latency and improved some results. This reconfiguration could have been done through the serial port, but also with the “KP100” hand-held configuration device included with the controllers. Lastly, the use of several adapters in series (USB-RS232-RS485) was likely causing some latency as well. Also communicating through a real RS485 port (or just a USB-RS485 adapter could be enough) should further have improved results.

Furthermore, perhaps a program that could ramp speeds automatically could have been useful. If logging the speed changes this could have been used for calibrating the slide/roll ratio, looking for the speeds giving the lowest friction force and assuming these to represent slide/roll=1. This function could also have been used for longer and more complicated measurements representing different running conditions, without the need for monitoring or manual control.

4.5 Other

4.5.1 Optical measurement and its combination with RC measurement

While optical measurement was not implemented due to the complexity, technological advances during the last 10 years was particularly noticeable in this field. Both digital cameras and computer processing power, two key ingredients in spectrometry/interferometry, had improved immensely. One could have either assemble a perfectly useful spectrometry equipment at a fraction of the original cost, or increased performance (speed and/or resolution) to find new applications.

Since optical measurements still required glass discs, it was deemed difficult to combine with RC measurement. This was unfortunate since it would have been an excellent tool for verifying the RC measurements results. One could imagine, though, that the typical chromium plating of the discs could possible have enabled RC measurements.

5 Special thanks to

Our supervisor Pär Marklund for help, support and understanding throughout the project.

Johan Borg at the department of Computer Science, Electrical and Space Engineering for help with the RC measurement circuit.

Tore Serrander at Tribolab for finding tools, materials and aiding construction.

The volunteer workers behind such open source projects as:

- Linux operating system.
- Ubuntu and Lubuntu Linux distributions.
- Ngspice and gnucap circuit simulation packages.
- Oregano and KiCad circuit design suites.
- LibreOffice productivity suite.
- GNU Octave.
- The Arduino hardware and software tool set.
- Gnumeric.
- CuteCom.

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Appendix 1

RC measurement user manual

This document describes how to use the RC measurement cards developed during the thesis, based on a AD8302 chip. It's primary use is to characterize EHL contacts, and it's functionality is largely described in the main thesis report. The equipment is only a first attempt at managing RC measurement, and could use some improvement. However, since one of the best improvements would probably be to lower the operating frequency, this card could still be useful if seeking a high outgoing bandwidth solution. A high enough bandwidth may be able to study individual asperity contacts, or conductive contaminants entering the contact. It is advisable to also read the main thesis report for a better understanding of the inner workings and limitations of the equipment, especially to be able to change parameters used in impedance calculation. It also illustrates which connectors carry which signal.

Measurement range

The measurement range is limited in several ways. Staying within the range is important to get useful results.

Two properties of the contact are measured: the phase and the gain as compared to an input signal. The gain roughly represents the absolute value of the contact impedance, and the phase tells the capacitance apart from the resistance. Gain is on a logarithmic scale and is therefore sensitive to noise and the sampling equipments measurement offset. The phase measurement cannot separate positive phase shift from negative phase shift. It also has problems accurately representing phase shifts near zero or 180 degrees. Assuming that the EHL contacts impedance only contains resistive and capacitive components, the phase should never get close to 180 degrees, but it may be close to zero. Specifically, if the resistance is low compared to the capacitance (near short circuit situations). Another similar issue is that large resistances cannot be accurately measured in the presence of a large capacitance, since in this situation the capacitance will act as a near short circuit and the phase will be very close to 90 degrees. Phase measurement precision is excellent around 90 degrees, but separating e.g. 89.93 degrees from 89.98 degrees is still difficult. As mentioned in the main thesis, this could also cause the resistance readout to become negative, which would make little sense.

To get around this problem, a shunt resistor in parallel with the contact may be warranted. Somewhere around a few hundred Ohms, assuming a contact capacitance in the range of 100 pF. It would also be wise to attempt to reduce stray capacitance. For an example, not grounding nearby metal unless it is needed as a shield.

In conclusion, when measuring capacitance around 100pF (as is expected according previous studies), resistances in the range of 10-200 Ohms should be readable. When measuring resistances lower than this, capacitance readout will suffer. Attempting to measure higher resistances will not effect capacitance measurements but resistance readout will be unreliable. Reducing capacitance moves the resistance range up, and increasing capacitance lowers it. This is why reducing stray capacitance may be wise.

When performing the grease starvation study, the ball spindle holder and oil tub were grounded to shield the EHL RC measurement from the scraper RC measurement. This adds approximately 56 pF between ball and ground (as measured by a borrowed complex impedance meter at 200 kHz). When measuring only the EHL contact it may be useful to again isolate the ball holder to avoid this capacitance. A ready cut polymer sheet exists for this purpose.

Finally, depending on the sought outgoing bandwidth, filter capacitors must be added/removed. Filter capacitors should be chosen such that the outgoing bandwidth is lower than the sampling frequency. To choose capacitors, there is a “rule of thumb” formula in the data sheet of the core chip:

$$T(ns) = 3.3 * C(pF)$$

Where T is the time constant in nanoseconds and C is the filter capacitance in pF. Internally, the core chip has about 1.5 pF. In addition to this, 3.3 pF surface mount capacitors are mounted to the circuitboard. This limits the outoing bandwidth to 10 MHz. To further reduce the bandwidth, a pair of headers are available for adding further capacitance. Knowing all this, the bandwidth depends on the capacitance on the header according to:

$$B = \frac{1}{2\pi * 3.3(C + 4.8) * 10^{-9}}$$

Where B is the bandwidth in Hz and C is the capacitance added to the headers in pF. Note that there are separate headers for the phase and gain channel, but there is never a reason to have different value capacitors on them. Also remember to check polarity before connecting new capacitors.

Transmission line effects and remedies

When frequencies are so high that the measurement cable becomes a non-negligible fraction of the wavelength, eventually one will have to take the transmission line effect[1] into account. This did not initially seem relevant, since the cables are less than one tenth of the wavelength in the cable at 60 MHz, and transmission line effect should therefor be negligible. It was eventually evident that this was not the case, since results was greatly effected.

There are equations describing the transmission line effect, meaning it can be compensated for. When attempting the first calibration measurement, the equipment was capable of accurately measuring known impedances applied directly to the RC equipment. However, when applying the same impedances at the end of a cable, the results were inconsistent. Seeking to explain this, calculations verified that the results were consistent with what should have been measured, knowing that the transmission line was there. Calculating what the error should be is easy enough, but unfortunately it is not as easy to use this to calculate the correct impedance. The main reason is that with a transmission line in place, it is possible for the phase across the contact to become negative. As previously mentioned, the AD8302 is not capable of separating positive and negative phase shift. Thus it is not possible to know when accurately measuring the contact impedance.

Seeking a way around this problem, there are three primary methods. One way is to simply make the cable between the RC equipment and the contact as short as possible, hoping that the cable length will really become negligible. This is probably the easiest way to do it. Another way is to choose the cable length such that the sign of the phase is again always known. If it is constantly negative or constantly positive is irrelevant, since this can be consistently compensated for in software. Specifically, if the cable length is a multiple of half a wavelength long, it turns out that the transmission line can again be neglected. However, this would make the cable at least 2.5 meters long at 60 MHz, and could be a bit impractical. Another alternative is to use a cable that is an odd multiple of a quarter wavelength. This could be done with a cable of about 1.25 meters, and will also produce a consistent phase shift sign. To then determine the actual contact impedance when knowing the measured impedance, use:

$$Z_c = \frac{Z_0^2}{Z_{in.}}$$

[1] http://en.wikipedia.org/wiki/Transmission_line (2012-06-14)

Where Z_c is the contact impedance, $Z_{in.}$ is the measured impedance, and $Z0$ is the characteristic impedance of the cable (typically 50 ohms). If attempting this method of a specific wavelength fraction cable length, consider tuning it using the potentiometer inside the RC equipment. This potentiometer will adjust the operating frequency of the device, and will thus change the wavelength such that it can be matched to the cable. 60 MHz is however about as low as it will go, so aim to cut the cable slightly to short and then increase the frequency. Also remember, when calculating the cable length to be used, that the phase velocity of the wave is lower in the cable than in vacuum.

The third method is to use an arbitrary cable length and simply calculate within which areas the phase will be determine correctly, and either attempt to switch the phase when knowing that it should be wrong or simply neglect these results. A variation of this is to switch the phase if either the resistance or, more appropriately, the capacitance readout turns negative, since a negative capacitance is an obvious sign of something being wrong. Both of these two variations are very dirty solutions, and are neither reliable nor very practical. They can however be implemented entirely in software, and are therefor easy to try out.

Grounding, connecting, wiring

Cable inductance is undesirable, since the calculations of resistance and capacitance assumes that there is no inductance present. This can be done by using coaxial cables and using wide, flat cables where coaxial is not possible. Furthermore, short cables are always better than long cables.

Grounding is another important area. A stiff ground is important to get consistent results, and is essentially achieved by grounding as much as possible. Using wide, flat ground cables increases the capacitive coupling between the grounding cable and the object to be grounded, thus suppressing inductive effects and improving results. Grounding metal that surrounds the measurement can improve interference rejection (acting as a shield), but may increase capacitance between ground and signal. As mentioned in “measurement range”, this may not be desirable. One may have to compromise between thorough grounding and stray capacitance.

Connected equipment

Sampling equipment

The sampling equipment should have a high resolution within the RC equipments output range of 0-1.8 volts. This is especially important on the gain channel, since it has a logarithmic scale. However, it is also somewhat important on the phase channel, since certain areas in the measurement range require precise phase determination. One such situation is when resistance is high and capacitance is high. In this area, errors in phase readings could cause the resistance readout to swing between +/- infinity, as mentioned in the main thesis. Luckily, the RC measurement equipment itself does determine phase quite well in this specific situation.

Also remember to adapt the filter capacitors in the RC equipment to the sample rate, as discussed in “Measurement range”.

Surrounding area

Any other equipment connected to the rig could cause interference. It is advisable to take reference measurements with and without each new equipment to determine if it causes interference.

Program, calculations

To get the actual capacitance and resistance from the phase and gain information, simply implement the equations from the main thesis, then add transmission line compensation if required. The program included transmission line compensation for an arbitrary cable length. As discussed in the "Transmission line effects and remedies" chapter, arbitrary cable lengths are not appropriate. The cable from the RC equipment to the contact should be replaced as discussed in the chapter "Transmission line effects and remedies". Assuming that the new cable has the same velocity factor[1] as the old cable (0.66) and still operates at 60 MHz, simply input the new cable length. If, however, the frequency or the velocity factor changes, also recalculate the parameters "w" (frequency in radians/second) and "wave number[1]" in the impedance calculation.

[1] http://en.wikipedia.org/wiki/Wave_propagation_speed (2012-06-15)

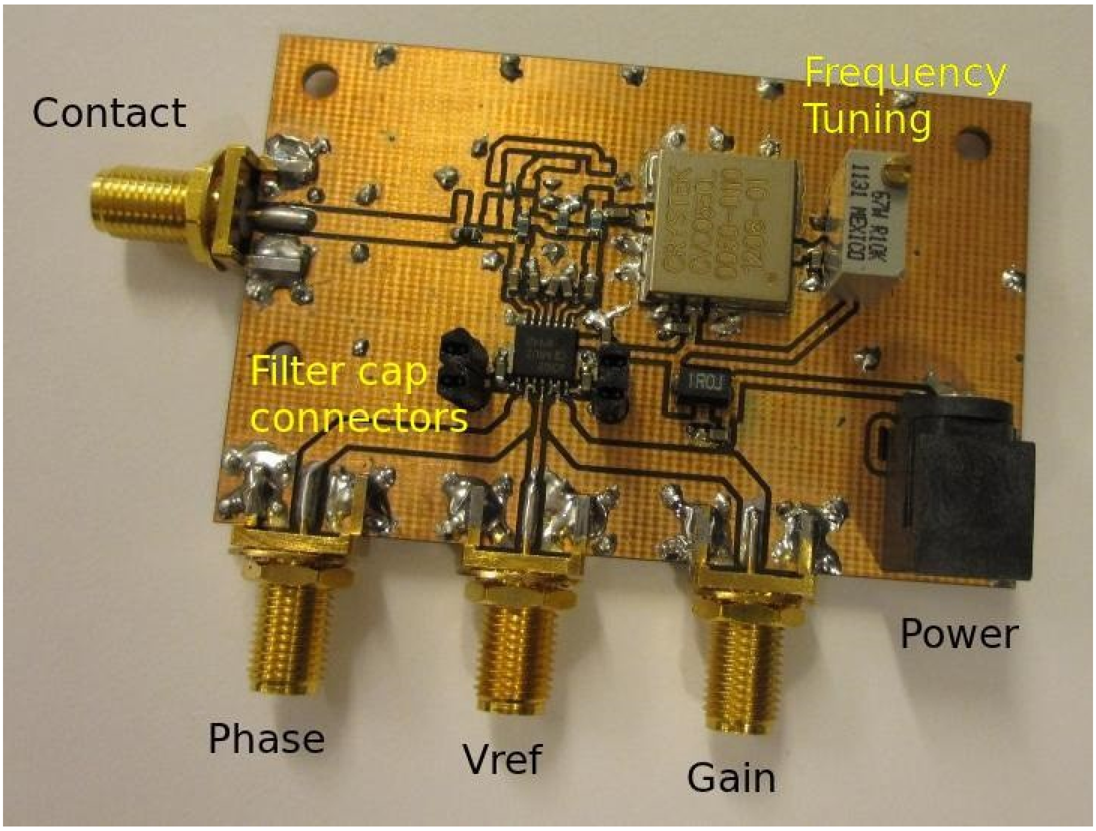

Figure 1: RC measurment board

Another function that may be worth implementing is to use the Vref output (refer to Figure 1) to improve accuracy of measurements. Rather than to assume that the max value of the outputs is 1.8 volts and the center of range is 0.9 volts, the max value could be dynamically set equal to Vref and the center of range to Vref/2. The scaling of especially the phase could also be recalculated knowing that 0 volts represents 180 degrees phase shift and the max value (Vref) represents 0 degrees, instead of assuming 30 mV/degree. This should improve accuracy near the edges of the measurement range.

Also already implemented is compensation for the input impedance of the AD8302 itself. According to the data sheet, it can be modeled as a 3 kOhm resistor and 3 pF capacitor in parallel.

Other considerations

When connecting the RC equipment or any other external equipment, do remember that cables, shields, sliding connectors, scrapers and other things may effect the friction force measurement. Even the weight of new equipment could effect readings, especially if mounted to rotating parts. The friction force measurement is rater sensitive, it is easy to forget but it could cause inconsistent results whenever friction force is relevant.

Please note that this device is sensitive to static electricity. This includes the inputs/outputs, so special care must to be taken when handling open cable ends connected to the device.

Appendix 2

Ball on disc user manual

This document describes how to use the ball on disc machine as configured in the thesis. In addition to reading this manual, you may also benefit from reading the main thesis to find more information about the equipment. Another source of useful information about the rig is the PhD thesis of John Lord.

Motor control

The motors are controlled by the leftmost panel on the interface (Figure 1). To use motors, first make sure to power on the motor controllers using the switch at the back of the electronics box. Also ensure that the COM port is correctly set. After each power on, first press the “Initiate” buttons on the panel for each of the motors. This reads out the serial error word of each device (refer to the “feedback” chapter).

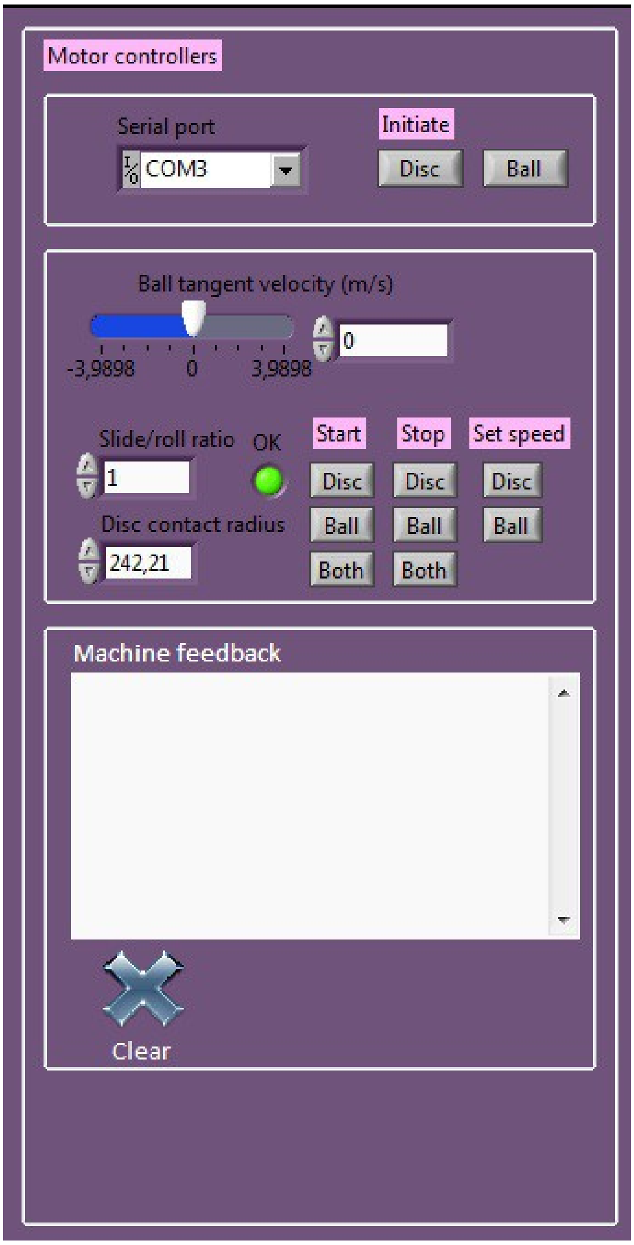

Figure 1: Motor controller interface

After the power-up procedures, proceed to set the desired speed. At this point it is important to remember that the correct contact radius must be entered in order for the speeds to be calculated correctly. This is done by reading the digital gauge on the rig and entering its value in the “disc contact radius” box. Remember to turn the gauge off after use since it is battery powered. After this, enter the ball tangent velocity and desired slide/roll ratio. If precise slide/roll ratio is required, please read the calibration section of this manual. If pure rolling is sought, consider detaching the balls drive belt. The ball will then be spun by its contact with the disc. If precise speed is required when doing this, first perform the slide/roll ratio calibration procedure (before detaching the drive belt) to ensure that the disc revolves at the correct speed, since it alone will now determine contact velocity.

Once setting up the speeds as desired, continue by pressing the “set speed” buttons of both motor and disc. This can be done at any time, whether the motors are in motion or not. If starting the motors before setting the speed, nothing will happen, assuming that the device was just turned on (in this situation the speed will be set to zero). However, in some situations the last speed used may still be set so that when pressing start, the motors could set off in any direction or speed. So, after pressing “set speed”, proceed to press “start both”. If disconnecting the ball drive belt, you need only press “start disc”. To stop either or both of the motors, press the corresponding stop button.

Changing speed while running cannot be done synchronously for the ball and the disc, one must instead press “set speed” for both disc and ball separately. If the specimens are sensitive to sudden sliding conditions, consider releasing the load while changing speed, or pressing “stop both” before changing speed then restarting with “start both”. Neither of this is of course a problem if disconnecting the balls drive belt. For more on these issues and possible improvements read the “Motor control” and “Suggested future work” sections of the main thesis report.

Motor feedback

To provide feedback, the speed control program prints out the motor controller response in a serial window. Many of the characters being sent are control characters and do not really have a graphical representation. However, LabVIEW does instead assign them some other characters that do. As a result, one might expect responses such as:

- A- When changing a disc parameter (means “disc acknowledge”).
- B- When changing a ball parameter.
- A 20085=00 When pressing initiate disc (reads out present errors, 00 means no error).
- B 20085=00 When pressing initiate ball.

The serial error word returned when pressing “initiate” should typically be “00” or “01”. This means “no error” or “power on error” respectively. A “power on error” simply informs you that the device has been powered off since last used. Any other error words can be interpreted using the parameter list of the motor controllers under parameter 85 (available in paper form and on the manufacturers website).

Lastly, should a chosen speed and slide/roll ratio require speeds beyond the range of the disc motor, an otherwise green light (labeled “OK)” will turn red, and the speed will be set as close as possible to the request.

Calibrations

In this chapter information regarding calibrations will be presented. Some calibrations can be made in the programming and some can be made physically.

Mechanical

The initial load on the load-cell can be adjusted since it is mounted on a screw. Turning the load-cell adjusts the initial load effectively shifting the y intersect point on the graph.

Program

In the program code both the y intersect and the slope of the gradient can be adjusted. This is done in the block diagram part. Each measurement has its separate wire (graphical representation) wherein the data is sent. To this wire a multiplier and an addition part has been added to do calibrations. The multiplier is of course the slope adjuster and the addition part adjusts the offset. An example of this can be seen in Figure 2, also pointing out the sample compressor and the collector.

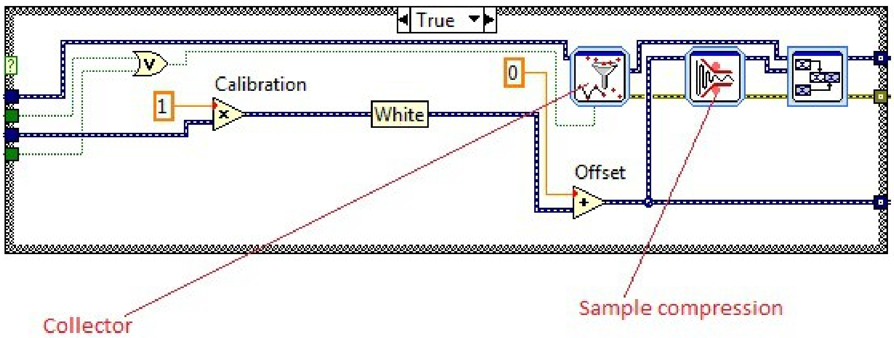

Figure 2: Calibration and sample compression in block diagram

Slide/roll ratio

To calibrate the slide/roll ratio (and by extension the speed of the disc at the contact radius, and the friction force measurement), start by initiating measurements and confirm that without load or drive, the friction force is zero. If not, stop the program and change the offset parameter for the friction force readout. Then restart measurement. Continue by setting slide-roll ratio to 1 and then follow the startup procedure until the disc and ball motors are both spinning (both drive belts must be connected). You may want to do this using running conditions that cause minimum wear to the ball and disc, because the ball and disc must be in contact and loaded to give a useful friction force readout. Proceed by incrementing the “disc contact radius”, each time pressing the “set disc speed” button, until finding the point of minimum friction force. This is commonly assumed to prove that slide/roll=1. Note the difference between this value and the original value, and (after stopping the program), apply this difference to the parameter “Roff” in the motor control section of the program. This parameter is also used in the friction force calculation, thus it is important if seeking a correct scale. After correcting this factor, return the “disc contact radius” to the original value (as read on the digital gauge on the rig).

Finish by testing a few different speeds (remember to “set speed” of both disc and ball each time) and loads to confirm that as long as slide/roll=1 the friction force remains close to zero. You may also try disconnecting the balls drive belt and confirm that this returns a similar friction force.

The rig is made with rather high precision, and has guide pins with tight tolerances to ensure that disassembly and reassembly has a minimum effect on calibration. However, if high precision is required, it is best not to move anything after calibration.

A potential error not taken into account is if the balls axis of rotation is not parallel to the face of the disc. If wanting to take this into account, the motor speed calculations will need to be completely redone.

Friction force

To get an accurate reading, please begin by performing the Slide/roll ratio calibration since the “disc contact radius” parameter will affect the friction force readout. Proceed by calibrating the equipment as described in the main thesis under Results->Measurements->Friction force

Contact load

The force applied to the contact is measured by a pressure cell. The pressure cell used is part of the the machines original equipment but no data-sheet was found. For an idea of how to calibrate this cell, refer to the main thesis under Results->Measurements->Applied force

Setups

The steps do a basic setup and measurement is presented in Table 1.

Table 1

Step 1. Check that the correct COM port is selected for the motor controllers.
Step 2. Initiate disc and ball.
Step 3. Perform calibration of slide/roll ratio as presented in the calibrations part of this manual.
Step 4. Select ball tangent velocity and slide/roll ratio.
Step 5. Check that the value for disc contact radius is correct.
Step 6. Press set speed for disc and ball.
Step 7. Press start both (if both are to be used).
Step 8. Select desired time target, sample rate, samples to read and file path.
Step 9. Press start measurement.
Step 10. Wait for test to finish.
Step 11. Press stop both or stop everything.

Graphs

In LabVIEW a lot of changes can be made to how graphs present data, the inherit functions for this will not be presented but there are some aspects that are controlled from the program. The first thing is that the data presented has a time (x) axis presented in samples instead of absolute time. The amount of samples shown can be changed in the collector sub-vi. To lessen the amount of data that the computer has to keep in active memory a compression of data points is also made. This compression also effects the amount of samples shown in the graph and is done in a sample compressor sub-vi. To get the absolute number of samples shown in the graph take the amount of samples chosen in the collector and divide by the number chosen in the sample compressor.

Secondly a function was added to clear the graphs of its data, to do this simply press the "clear" button on the graph. This will not effect stored data, only the graph itself.

Thirdly, an on/off button was added to toggle the specific measurements. This does effect if the data is to be stored or not.

Save files

To store the data collected, the "write to measurement file" sub-vi is used. On the front panel the user can choose if data is to be stored or not by using the "store data" toggle. The user can also choose which file path to use for the save-file. Comments can also be added by simply typing in the “test note” window. This text can be changed over the time of test giving the ability to mark special events and/or simply make notes. Some notes are automatically sent to the “write to measurement file” sub-vi, these are the following:

- slide/roll ratio.

- disc contact radius.

- sample rate.

- ball tangent velocity.

- time target (test length).

To make changes to how data is stored simply enter the “write to measurement file” sub-vi where a lot of options are available, such as file type, maximum file size and so on. This will not be presented in more depth here since the “write to measurement file” sub-vi is a native and standard function in LabVIEW.

Buttons

Here all toggles, buttons and switches will be presented along with a brief explanation of their function, this can be seen in Table 2.

Table 2

Toggle/button/number etc	Control or function
Sample rate.	Amount of samples taken per second.
Time target.	Length of test/sampling.
Test note (optional).	Adds a note into the stored data. This note can be changed over the course of the test if variable notes are desired.
Samples to read.	Amount of samples to be read from input buffer.
File path.	Where save file data is to be stored.
Start measurement.	Starts measurement.
Stop measurement.	Stops measurement.
Save data.	Toggles if data should be stored or not.

Clear temperature/torque/force/film thickness graphs.	Clears the graphical plots (no effect on stored data).
On/Off.	Toggles if the data should be incorporated in the measurement, this effects both the data stored and the graphical representation.
Stop everything.	Stops all measurements, shuts down the motors and finishes the program.
Clear (error).	Clears errors and warnings, if an error or warning has occurred this must be pressed to start new measurements.
Clear (machine feedback).	Clears messages from the motor controllers.
Serial port.	Chooses COM port for communication with the motor controllers.
Ball tangent velocity (m/s).	Controls the ball tangent velocity in m/s, to activate/update the chosen value the user must then press the relevant “Set speed” button.
Slide/roll ratio.	Sets the slide/roll ratio and thereby controls the disc speed. To activate/update the chosen value the user must then press the relevant “Set speed” button.
Disc contact radius.	Here the radius of the balls contact onto the disc is entered. This value can manually be viewed on the digital ruler/caliper attached to the machine body for this specific task.
Initiate.	Initiates communication with the respective motor controller.