Low Cost Cutting Force

INDUSTRIENS FOND DAMRC

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This project is made in collaboration with:

Funding:

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1. Executive Summary

This project aims to revolutionize cutting force measurements in CNC-turning operations by developing a low-cost, accurate sensor system. Building upon a previous attempt in 2021, the project's primary objective is to measure cutting forces in three-dimensions, while keeping cost down to have widespread use. The project has given DAMRC great internal improvement, as the previous only had one measurement bridge and thus could not distinguish between effects of forces in different directions. The sensor made in this project has 3 bridges and thus can measure the cutting force in all three directions.

The success criteria of being within 15% accuracy and cost under 1000kr is met. As the raw material price is 800ddk, and the steady state repeatability is within 1,9% for the x-axis. This sensor is now capable of measuring cutting forces if calibrations of 0-load is made every two minutes, but with higher expected uncertainty from the operation than at steady state.

During operational testing, the project faced problems with heat of the cutting and likely also impacts. If strain gauges will be used for further projects, focus on thermal stability is needed.

2. Introduction

The aim of this project is to redefine the landscape of cutting force measurements in CNC-turning operations. In today's manufacturing environments, the existing sensor systems for such measurements are expensive fragile and inaccessible. However, a low-cost, accurate sensor that has the potential to revolutionize tool wear detection and operational optimization while saving invaluable process time and costs.

Building upon a previous attempt in 2021 by a DAMRC employee, where measuring the feed force was successfully achieved, this ambitious project sets out to deepen our understanding and expertise in utilizing strain gauges as cutting force measurement tools. By overcoming the setbacks encountered in the previous attempt, our primary objective is to measure the three-dimensional axis of cutting forces, including the feed (y) and axial force (z), as well as the tangential force (x).

The core of this project lies in demonstrating the feasibility of employing cost-effective strain gauge sensors in real-time machining. Drawing upon the knowledge gained in 2021, this project will undergo multiple iterations of prototyping to establish a seamless flow of input and output signals from the strain gauge sensors during turning operations.

Phase 1 of the project will focus on prototyping, involving the development of both hardware and software components necessary for measuring the feed and axial force (z), along with the tangential force (x) within turning operations. This crucial step will lay the foundation for subsequent phases.

Moving forward to Phase 2, real-time logging through turning operations will be implemented, enabling us to rigorously test the prototype in practical scenarios using materials representative of real-world conditions. This pivotal phase will provide valuable insights, consolidating our understanding and validating the project's potential impact.

3. Pre-analysis and literature search

Turning is a type of machining process where material is removed by moving a cutting tool—typically a non-rotary tool bit—along the surface of a revolving workpiece (Othman et al., 2022). Metals, polymers and wood are just a few of the materials that can be turned. Turning's goal is to create a cylindrical or conical shape with exact measurements, a smooth surface, and geometric tolerances. Producing items like shafts, bolts, and bearings via turning, which can be done manually or with computer numerical control (CNC) equipment.

When measuring cutting force in turning, tangential, feed and radial force components are combined to create a resultant force (Isakov, 2013). The F_c is the main cutting force action which as it names indicates it is tangential to the rotational direction. The feed force (F_f) and the passive force (F_p) can be measured directly during turning. The following Figure 1 shows the mentioned cutting forces in turning.

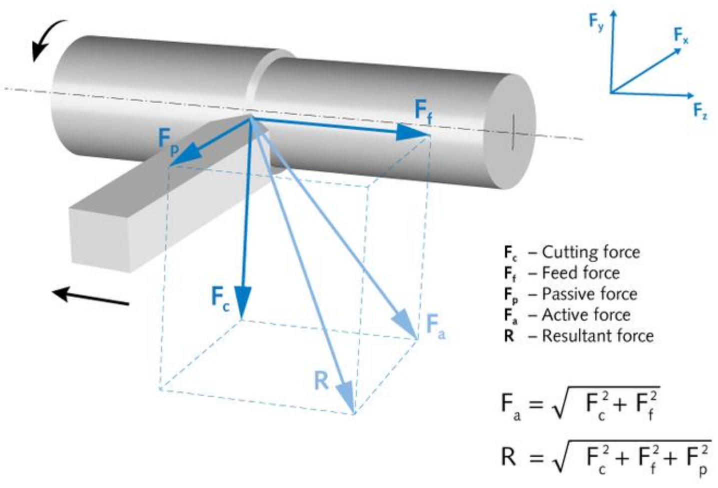


Figure 1. The orthogonal force components occurring during turning operations: Fc, Ff and Fp. The vectorial sum force components Fa and the resultant force R (Kistler Group, n.d.).

3.1. IMPORTANCE OF MEASURING CUTTING FORCE

Cutting force is an essential parameter that influences the quality of machining operations in manufacturing processes. Measuring cutting force can provide valuable information for optimizing machining conditions, improving product quality, reducing tool wear, and increasing productivity (Sousa et al., 2020).

One of the primary reasons for measuring cutting force is to ensure the safe and efficient operation of cutting tools. Excessive cutting forces can lead to tool wear, breakage, and poor surface finish. By measuring cutting force, operators can adjust the machining conditions to maintain the optimal force level and prolong the tool's lifespan. Additionally, cutting force measurements can help to identify the cause of tool failure, which can be used to improve the design of cutting tools (Zhao et al., 2018).

Another reason why cutting force measurement is essential is to improve the quality of machined parts. The cutting force can affect the surface finish and dimensional accuracy of the finished product. By monitoring the cutting force, operators can optimize the machining conditions to achieve the desired surface roughness, flatness, and other quality parameters (Sousa et al., 2020).

Finally, cutting force measurements can be used to evaluate the performance of different machining processes and materials. By comparing the cutting forces generated during different machining operations, engineers can identify the most efficient process for a specific application. This can help to reduce manufacturing costs and increase productivity.

In conclusion, measuring cutting force is an important aspect of machining operations that can help to improve the quality of machined parts, prolong the life of cutting tools, and increase productivity. With the development of new sensing technologies and measurement techniques, cutting force measurement has become more accessible and accurate, allowing manufacturers to optimize their processes and stay competitive in the global market. In a few words, important KPIs like quality, cost or environmental impact can be improved by optimizing the machine.

3.2. MEASUREMENT OF CUTTING FORCES

Cutting force can be measured directly or indirectly. Indirect measurement is based on tool vibration detection, motor current measurement, etc. It involves detecting the power consumption of the spindle or feed drive motors for example and using this information to calculate the principal and feed forces. The measured current/power or vibration is converted into cutting force by theoretical model or empirical formula. Although it is less accurate than direct methods, it is valuable for monitoring numerically controlled machine tools which have motors with high sensitivity and control (Childs et al., 2000). From internal market research, Jakob, Jan and Lynge (2023), it is concluded that almost every machine industrially used has the capability to measure current/power consumption. This is taken from a small sample of lathes, of up to 15 years old.

Direct measurements require the use of force sensors such as piezoelectric, strain gauges, capacitance or dynamometers. These devices will correlate elastic deformation to electrical signals (Panzera et al., 2011). In a few words, the measured signal of the sensor is transformed into a change of resistance or voltage which is proportional to the measured force in the charging amplifier. The following Figure 2 represents the different ways that cutting forces can be measured regarding direct and indirect methods.

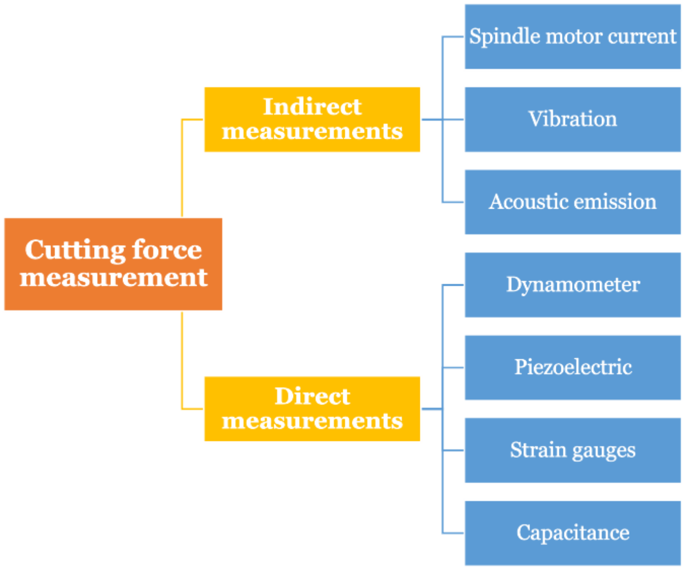


Figure 2. Taxonomy of indirect and direct methods to measure cutting forces.

In a few words, direct measurements involve utilizing effects that are directly caused by cutting force, while indirect measurements involve detecting changes in related parameters that are influenced to some extent by cutting force. In the indirect method the current signal, vibration signal or power signal is converted into cutting force by model or empirical formula. It is reported that the best way of measuring cutting forces will be combining different methods to obtain the most accurate results (Sousa et al., 2020).

In the critical review made by Sousa et al., traditional methods for cutting forces assessment, such as dynamometers and force sensors, as well as the recent advances in non-invasive and indirect methods, such as acoustic emission monitoring, vibration analysis, motor current monitoring, image processing, and finite element simulation are discussed. The authors provide a comprehensive comparison of the advantages, limitations, and challenges of each approach and suggest that the integration of multiple methods and the development of smart sensors and machine learning algorithms can enhance the automation and efficiency of cutting forces assessment in CNC machining processes.

Various reports indicate that combining indirect, direct and prediction methods is the most accurate way to measure cutting force. Indeed Lian et al., made a report where they compare the sensor system they applied with already proven methods (Table 1).

Table 1. The performance comparisons with some proven reference sensors (Liang et al., 2016a).

Developer	Approach & Measurement Principle	Size (mm)	No. of axes	Sensititvity	Maximum Relative Error
Tuysuz, Altintas, Feng	Indirect and prediction model	n.a.	5	n.a.	8,5%
Rao, Gao, Friedich	Direct and piezoelectric	Integrated into system	1	7 mV/gm	9,8%
Kim, Kim	Direct and strain gauge and piezo-film accelerometer	40 x 70 x 26	2	3 mV·N^{−1}	n.a.
Yaldiz, Ünsa	Direct and strain gauge and piezoelectric accelerometer	100 x 100 x 50	3	0,1 mV·N^{−1}	<5%

Liu, Zhou, Tao, Tan	Direct and strain gauge and Bragg grating sensor	n.a.	3	n.a.	6,23%
Approach of the study (Liang et al., 2016a)	Direct and strain gauge	ф 80 x 42	6	0,0134 mV·N^{−1} 0,345 V\ left(Nm\ right)^{−1}	<5%

Even though combining methods seems to be the most accurate way to measure cutting force, this paper will be focused on the measurement of cutting force with direct measurements, namely with force sensors.

3.3. DIRECT METHODS – FORCE SENSORS

Force sensors measure force in various directions and magnitudes. These devices transform mechanical input forces such as, tension, weight, strain… into an electrical output signal that can be measured, converted and standardized (Engineering, 2023). The signal obtained is used to represent the magnitude of the force. Although force transducers and force sensors are not the same, both terms are used interchangeably (Industrial Quick Search, n.d.).

The basics of force sensors is that they respond to the force being applied and change it value into measurable one. Depending on the sensing components there are many different types of force sensors. Therefore, depending on your needs there are many factors that need to be considered.

Firstly, the cost is one of the main considerations when you must select a force sensor. Depending on the application, the sensor can be too expensive which would limit the project’s final viability. Repeatability checks a sensor’s consistency against itself. This way you can determine whether a sensor consistently produces the same result under the same circumstances (Futek, n.d.). Accuracy is typically associated with this value however a sensor can be inaccurate but still be able to repeat observations.

Accuracy is an important factor to consider when selecting a force sensor. The work area where the device will be used also determines the choice of the sensor as its exposition to wide range of environments could affect how accurately it reads. Temperature changes or humidity can impact on sensor outputs, so it is important to take note of these levels.

It is also important to choose a force sensor with suitable response times; if the forces applied are rapid and successive a faster response times sensor will be required. However, if the force is steady and slow, a slowly responding force sensor will be needed. There are many other factors such as, stiffness, frequency bandwidth, sensitivity… that may also be considered.

For the design of a force sensor stiffness and sensitivity are two basic requirements. While sensitivity is crucial to detect the local deformation, rigidity is important to withstand fluctuations.

According to Vasquez there are many different types of force sensors, including strain gauge sensors, piezoelectric, dynamometers or capacitances. These sensors can be used in a variety of applications, including measuring forces in industrial machines, testing materials for strength and durability, and measuring forces in medical equipment.

Dynamometers are force sensors that can measure both the cutting force and the tangential force during machining operations. They are usually placed between the tool and the workpiece and can measure the forces in three orthogonal directions. They can provide accurate force measurements but are generally more expensive and complex to set up than other types of sensors.

Piezoelectric sensors use the piezoelectric effect to generate a voltage signal in response to mechanical stress. They are small, lightweight, and can measure high-frequency signals, making them suitable for measuring dynamic cutting forces in milling and drilling operations. They have high sensitivity and high rigidity. However, they are not suitable for measuring stable or static cutting force due to electric charge leakage (Zhao et al, 2018). Piezoelectric sensors are also relatively inexpensive compared to other types of sensors, making them a popular choice for research and development projects. Nevertheless, if these devices are used to measure static cutting force, a high-impedance electric charge amplifier will be needed which is expensive.

Capacitive sensors can be used for measuring cutting forces, but they may not be the most cost-effective solution. Compared to strain gauges, capacitive sensors tend to be more expensive and require more complex electronics for signal conditioning and data acquisition. The cost of capacitive sensors can vary depending on factors such as the sensing range, resolution, and accuracy required. However, they do have some terms of their ability to measure dynamic forces and their immunity to electromagnetic interference.

Strain gauges are sensors that measure changes in the strain or deformation of a material in response to an applied force. They are commonly used to measure the cutting force in turning and grinding operations and can provide accurate force measurements with high sensitivity. However, strain gauges can be affected by environmental factors such as temperature and vibration, which can reduce their accuracy.

The choice of sensor for measuring cutting forces depends on the specific application and requirements of the machining operation. Dynamometers are ideal for high-precision machining applications that require accurate and reliable force measurements, while piezoelectric sensors are suitable for measuring high-frequency signals in dynamic machining operations. Capacitive are used when there are electromagnetic interferences. Strain gauges are a cost-effective solution for measuring cutting forces in a wide range of machining operations. The following

Table **2** gathers the properties of each force sensor making it easier the comparison between them, where the cost refers to the cost of the required sensor equipment. Accuracy is the ability of the sensor to provide measurements that are close to the true value of the cutting force. Sensitivity refers to the ability of the sensor to detect small changes in the cutting force and to finish stiffness is the ability of the sensor.

Table 2. Comparison table between the different direct measurements considering cost, accuracy, sensitivity, and stiffness.

METHOD	COST	ACCURACY	SENSITIVITY	STIFFNESS	NOTES
Dynamometer	High	Very high	High	High	Suitable for high-precision machining application that require accurate and reliable force measurement. Their complexity and high cost may limit their use.
Piezoelectric	Medium	High	High	Low	Suitable for measuring high-frequency signals in dynamic machining operations. Not able to withstand high loads or provide accurate measurements for static forces due to their low stiffness.
Capacitance	High	High	High	High	Suitable for high-precision machining applications that require accurate and reliable force measurements. Their high cost limits their widespread use.
Strain gauge	Low	High	Very high	Low	Cost-effective solution for measuring cutting force in wide range of machining operation. Their low

stiffness may limit their use in high loads or deformation applications.

As the aim of this project is to measure cutting force in an inexpensive way, strain gauges are going to be used for that.

3.3.1. STRAIN GAUGES

Strain gauges are a common method for measuring cutting forces in manufacturing processes. They work by measuring the deformation or strain of a material subjected to a force. In cutting processes, strain gauges can be mounted on the tool or workpiece to measure the forces involved.

Strain gauges have a very high sensitivity to small changes in force which is one of the main advantages of using them. Therefore, it´s high accuracy, good stability and low cost make them ideal to work with (Liu Y et al., 2013).

The contradiction between stiffness and rigidity is difficult to avoid when using strain gauges. The use of strain gauges with a highly sensitive coefficient like micro-electro-mechanical system (MEMS) strain gauges, are a good way to obtain a satisfactory sensitivity and keep a high stiffness. Zhao et al., used a cutting force sensor based on MEMS strain gauge to measure cutting forces to reduce cross-interference error and improve sensitivity. What they achieved was that sensitivity was 27-30 times greater than with previously used methods and that cross-interference error was reduced in the range of 0,14 - 4,46%, which means that accuracy increased.

You et al., used XJTU-2 type strain gauge to measure cutting force. This strain gauge is composed of 2 perpendicular orthogonal rings. To convert the cutting force into electrical signal a Wheatstone bridge was used. Cutting force acts on the turning tools and causes deformation on the elastic-sensitive element and changes the resistance value of the strain gauge. This makes the Wheatstone bridge produce a voltage output corresponding to the cutting force. Then this output signal is converted into digital signals and collected by a data acquisition card. In this study they make 4 different groups of experiments where they can compare commercial piezoelectric with the developed strain gauge. They conclude that the last can be used for dynamic cutting force measurements as the experiments showed feasibility and good performance indexes. The results they obtained were a force resolution of 0,2N, a sensitivity of 0,32 mV/N and a natural frequency 771Hz, being the relative error of average 6-7%.

In 2015 Reyes Uquillas and Yeh attached the strain gauges directly inside the tool holder sensor, measuring strain and estimating the cutting force. To measure the strain caused by the tangential and feed forces, four strain gauges are positioned on each face of the tool. This allows for the estimation of the resultant value. In this case strain gauges were placed inside the tool holder, and they designed a sensor which signals needed to be conditioned and after calibrated. They used a half Wheatstone bridge for signal conditioning to measure bending strain. An instrumentation amplifier and an active filter in a printed circuit board (PCB) were used to amplify the signal. To acquire data LabVIEW software is used. In order to calibrate the sensor, known weights are applied to the tool holder and force values are estimated. The signal change in both directions is read using the half bridge design. This aids in evaluating the measurement's impact of cross-sensitivity. The average of five measurements for each weight was used to determine the relationship between the sensor signal and the applied force. The data collected allowed for the calculation and evaluation of the noise and offset.

A three-force component force dynamometer with 3 strain gauges mounted on its outer surface was used by Hanif et al. The dynamometer was additionally linked to the computer via a data acquisition card, and it has been statically calibrated to measure the voltage produced by a Wheatstone bridge. The high stiffness of the flexible mechanical component of the dynamometer causes the output from the circuit to be very low, therefore the data acquisition system not only amplifies the data but also transforms it into digital signals. Additionally, the DAQ programmable software can average and simulate graphically the force signal obtained from the circuit during cutting. To obtain optimized process parameters they used Taguchi method which provides and ease and efficient technology.

In a study done by Othman et al., they developed a cutting force measurement instrument using strain gauge and Arduino as the microcontroller for monitoring of a turning tool post. The strain gauge is used to detect the change in resistance and the signal is sent to the amplifier which amplifies it using a Wheatstone bridge for the Arduino to be able to detect this data. The data is processed for calibration and compilation into a table by Arduino and finally it is displaced in the PC for further analysis. In this research the calibration of the strain gauges has been done using a handheld weight scale by pulling in x and y directions. This study also highlights the importance of preparing the surface before bonding the strain gauges as well as its installation.

Although this technology is reliable in terms of measuring cutting forces, still has its drawbacks. Firstly, the measurement range is limited as it can only measure strain up to a certain point before, they become damaged or lose their accuracy. Therefore, very low or very high cutting force values may not be measured. Another limitation of using a strain gauge to measure cutting force in turning is that the gauge can only measure the force in the direction that it is oriented, so multiple gauges may be required to measure forces in different directions (Liang et al., 2016b) so they must be carefully mounted on the tool holder or tool. Additionally, strain gauges can be affected by environmental factors such as temperature or vibration, which may impact the accuracy of the measurements (Zhao et al., 2015). Finally, strain gauges may be sensitive to changes in the material properties of the workpiece or tool, which can affect the accuracy of the measurements over time (Thangarasu et al., 2018).

In conclusion, strain gauges are a widely used and effective method for measuring cutting forces in turning/lathe operations. However, careful attention must be paid to the mounting location, orientation, and thermal effects to ensure accurate and reliable measurements. Herein lies the compromise of the method. While saving on upfront cost compared to commercial dynamometers, those would likely have been easier to implement. The argument for using strain gauges is that by time, the procedures and signal conditioning necessary to make accurate measurements, merged to ready to use products.

It’s important to distinguish between parameters that impact the physical quantity and those which introduce inaccuracies. Accounting for the change of these may be used for in process modelling of e.g. wear. The right column is sources of faulty measurement but may not account for everything. Some inaccuracies are often described by their characteristics, such as short-term drift. The physical phenomena causing the drift may not be understood, but still be calibrated for though calibrations.

Table 3. Causes of variance in cutting force and measurement thereof.

Impacting the cutting force (Physical quantity)	Impacting the measurement (Inaccuracy)
Cutting speed	Temperature
Feed	Electrical noise - Ground lathe - Ground Arduino - VCC Arduino
Depth of cut	Induction from magnetic field of motors
Material - UTS - Ductility	Inaccuracy from Amplifier and ADC
Insert - Type - Chip breaker - Wear	Change of connection impedance
Temperature	Strain gauge creep
Cutting angle and direction	Incorrect strain gauge bridge coefficients
	Inertia/stiffness of cutting tool

4. HYPOTHESIS

It is possible to measure cutting forces with strain gauges and inexpensive DAQ with greater detail than what is integrated in industrial lathes.

The sensor system will be practically implementable in industrial applications within an effort small enough to be used in most machining processes.

5. SUCCES CRITERIA

The project is a success if the force measurements are accurate within 15%.

It must be made of a standard tool system so that it fits most industrial lathes.

The project is considered partly a success if the accuracy is failed to be met, if subsequent hypothesis on how to increase accuracy is made.

Without having a price of more than 1.000 to 5.000 DKK.

5.1 PROJECT BOUNDARIES

The project only seeks to make equipment for measuring the cutting forces of a square toolholder for a lathe. The project will only use static loads to calibrate the system. Therefore, not being certain of the readings if the load is changing rapidly with regards to time. Errors caused by response time, can therefore not be accounted for. It is anticipated to have some effect due to the inertia and dampening of the tool, but only relevant for high sample rates.

To measure the cutting force, it is necessary to address the following tasks:

- Make a data acquisition module,
- Make the cutting force transducer,
- Plan calibration,
- Plan test to determine accuracy,
- Proof of concept (Show in process to assess the second argument of the hypothesis).

5.2 RISK ANALYSIS

The accuracy is expected to depend on the normal strain, and therefore normal stress, in the area of strain gauge. Achieving a high local normal strain, without sacrificing the stiffness, which causes the tip to deflect. Another obstacle is to achieve this with a confined tool stick-out, which value has not yet been determined.

6. EXPERIMENTATION

Throughout the project there will be multiple tests with strain gauges and DAQ. These will have increasing requirements and are meant to determine the feasibility of the project early. This serves to cease the project to not waste time on details if fundamentals cannot be accounted for.

6.1 INITIAL TEST (Ruler and breadboard)

The initial test is meant to determine the feasibility of measuring cutting forces with strain gauges and an Arduino as the main electronic controller. The diagram, figure 3, is a proposal for a self-contained, electronic turning assistant. This project will only have to do with the processes in the red marking.

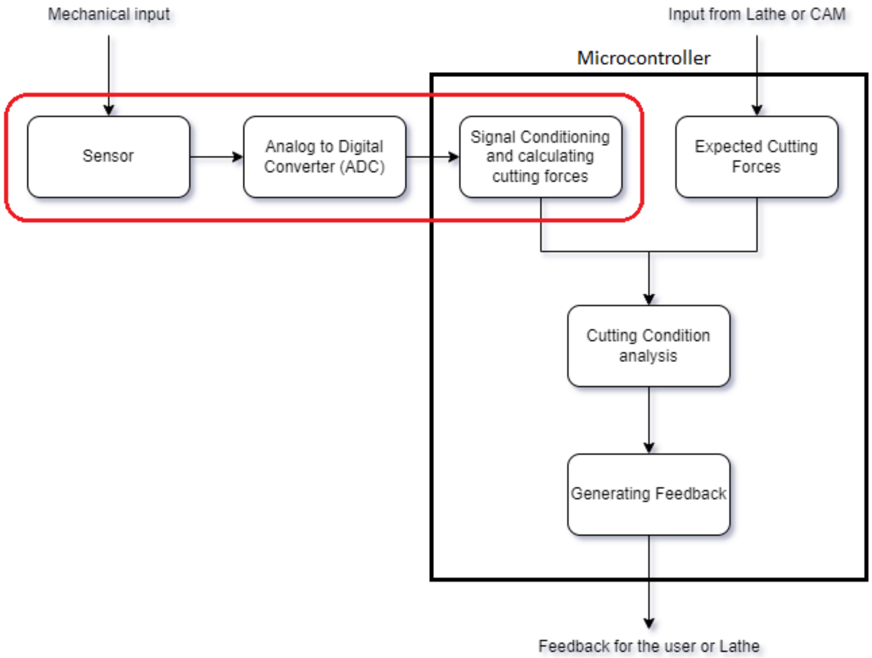


Figure 3. Subsystems of a cutting force analysis.

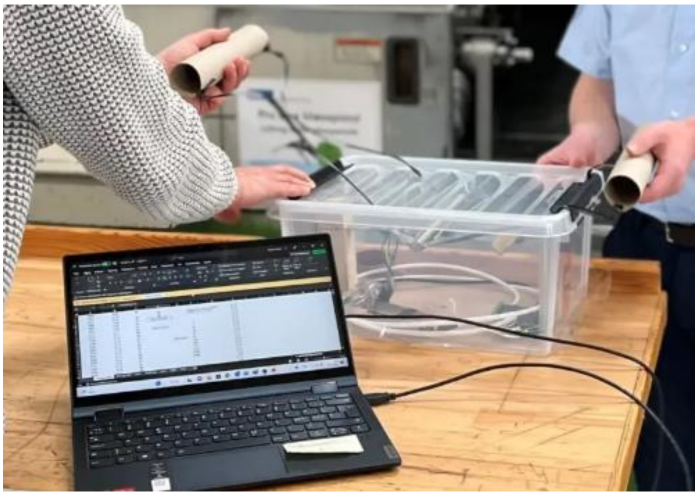


Figure 4. Initial tests of strain gauges in controlled environment.

This test has determined two major factors of imprecise measurements, being:

1. Strain gauge creep
2. Change in resistance of the connectors.

The creep of the polymer film or glue means the resistive wires return to their unstressed state over time.

Possible Solutions:

1. Calibrating the strain gauge by zeroing it between cuts.
2. Testing different strain gauges or bonding adhesives.

The unsoldered connections conduct electricity through the contact area, which varies depending on the connection forces. Although not by much, it still easily contributes to a change in hundreds of MPa.

Possible Solutions:

1. Soldering all connections and using PCBs when possible and enclosing all the electrical circuits in a polymer.
1. Having the amplifiers on the toolholder and thereby only sending digital signals by wire. (Digital signals are not affected by small resistance change.)

JR45 connectors used in Ethernet cables are for digital signals.

VGA or permanent cables(soldered) is an alternative for sending analogue signals.

6.2 THREE BRIDGE DAQ

The program has been made to sample three bridges independently at 10 Samples per second (SPS). The program writes the raw digital output to Excel to not burden the Arduino with further computations. As this data does not start at zero nor is it in a quantified unit, the initial point and scale need to be calibrated afterwards.

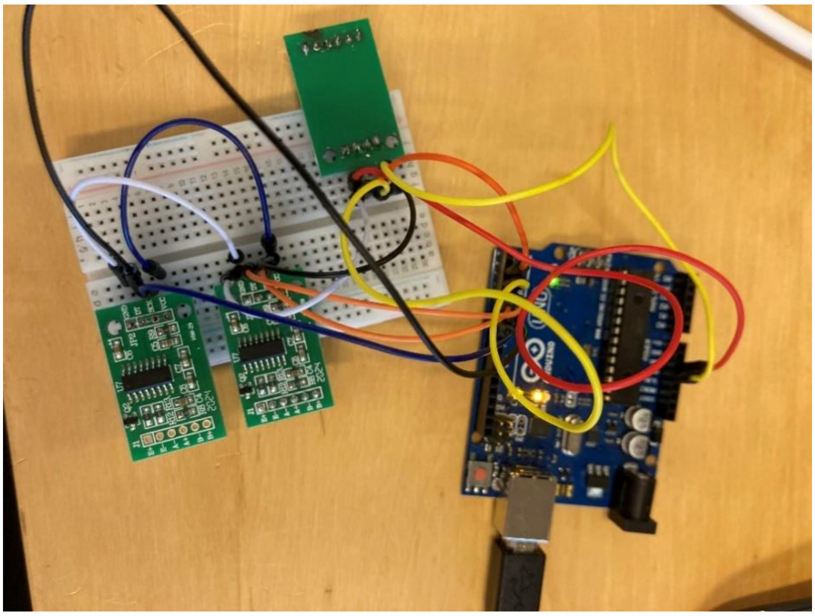
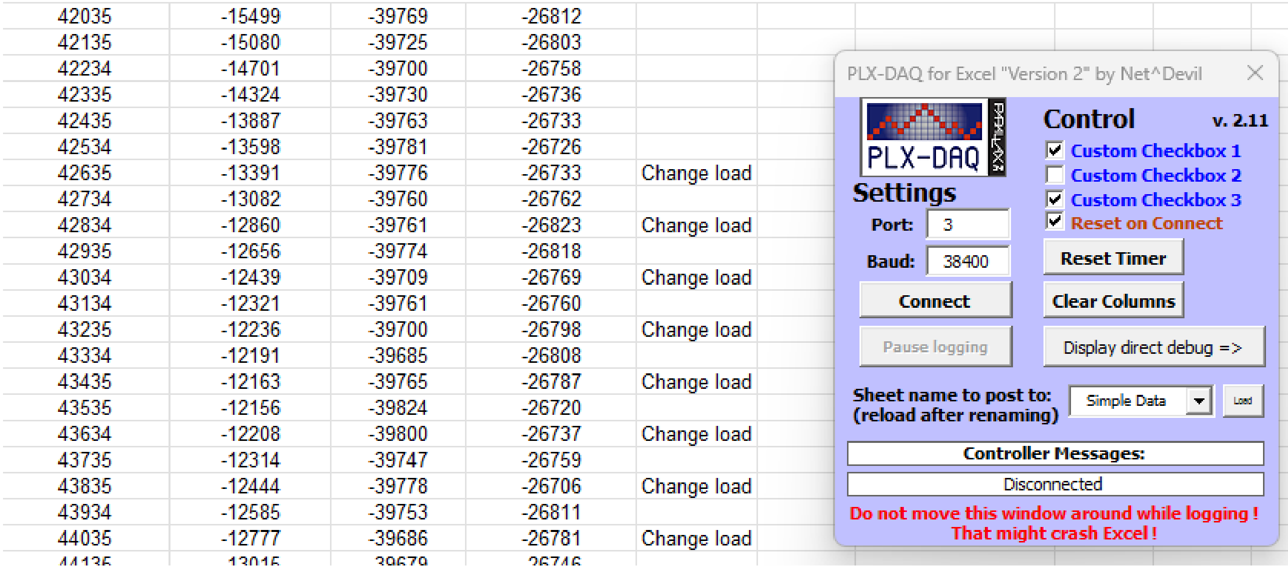


Figure 5. Test of three DAQs with an Arduino

The programs' "Custom Checkbox 1" is an option to display "Change load" after a predetermined time. The "Custom Checkbox 2" will reset the load timer.



42035	-15499	-39769	-26812	
42135	-15080	-39725	-26803	
42234	-14701	-39700	-26758	
42335	-14324	-39730	-26736	
42435	-13887	-39763	-26733	
42534	-13598	-39781	-26726	
42635	-13391	-39776	-26733	Change load
42734	-13082	-39760	-26762	
42834	-12860	-39761	-26823	Change load
42935	-12656	-39774	-26818	
43034	-12439	-39709	-26769	Change load
43134	-12321	-39761	-26760	
43235	-12236	-39700	-26798	Change load
43334	-12191	-39685	-26808	
43435	-12163	-39765	-26787	Change load
43535	-12156	-39824	-26720	
43634	-12208	-39800	-26737	Change load
43735	-12314	-39747	-26759	
43835	-12444	-39778	-26706	Change load
43934	-12585	-39753	-26811	
44035	-12777	-39686	-26781	Change load
44135	-13015	-39679	-26746	

Figure 6. Output of the Arduino program

6.3 FULL TEST OF AN UNALTERED TOOL HOLDER

The main objective of this section is to test the static precision of the sensor and calibrate it for operation in the lathe.

6.3.1 STATIC TEST SETUP

A way of carrying out static test loads must be made. It must be bolted to the toolholder at the point where the insert is. It will have to be loadable in the three perpendicular axes, and as a test for the superposition-based calculations, it must also be loadable in a combination of the axes.

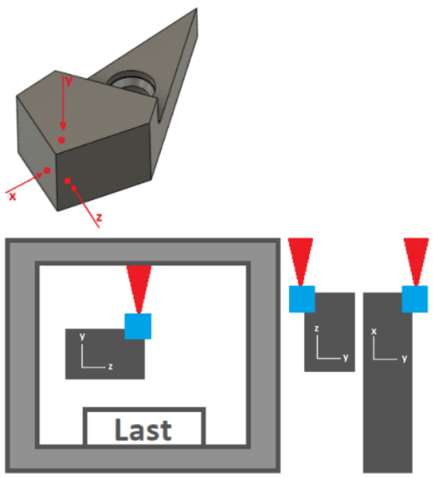


Figure 7. Scheme of the static test setup.

The purpose of the static test is to investigate the precision of the prototype, which consists of strain gauge, insert holder and electronic data acquisition. Previous strain gauge trials at DAMRC have shown significant measuring errors. It is assumed to be because of poor adhesion of the strain gauge. But unknown whether it resembled hysteresis or short-term drift. Therefore, it is desired to examine the sources/characteristics of uncertainty:

Type	Description	Setup is adequate to estimate
Variability	When the reading varies, under constant conditions, and can't be modelled from the previous measurements.	Yes
Short-term drift	A continues change of measurement, from start to stop of the sensor.	Yes
Long-term drift	A continues change of measurement, due gradual physical change of the instrument.	Yes
Hysteresis	When previous measurement values effect, the reading.	No
Response time	Errors due to the sensor not adjusting to the measurement-value immediately.	No
Calibration	The combined uncertainty off all the equipment used for calibration.	Yes

The secondary purpose is to calibrate the system for testing during machining. Here it is desired to find the force scalars for each strain gauge bridge. And if the linearity isn't acceptable, the points can be saved to be interpolated.

To load the prototype, an adapter insert must be manufactured. The tip must have three faces that are perpendicular to the three force directions. The desire is to get the calibration load to be perpendicular to the contact surfaces of the insert holder. To calibrate, weights with a known mass are used which load the insert-holder with gravity. The insert-holder is fastened with a level so that perpendicularity is achieved with the load. A centerpunch is used to transfer the force in a recess on the adapter-insert. If the load balances without influence, the reaction force in the adapter-insert becomes equal to the force of gravity in both magnitude and direction.

6.3.2 EXECUTION OF STATIC TEST AND CALIBRATION

Strain gauges will be adhered with Omega Engineering SG401 glue, confer the document "Strain gauge adhesion guidance".

A total of six strain gauges will be applied, at the locations shown on figure 8.

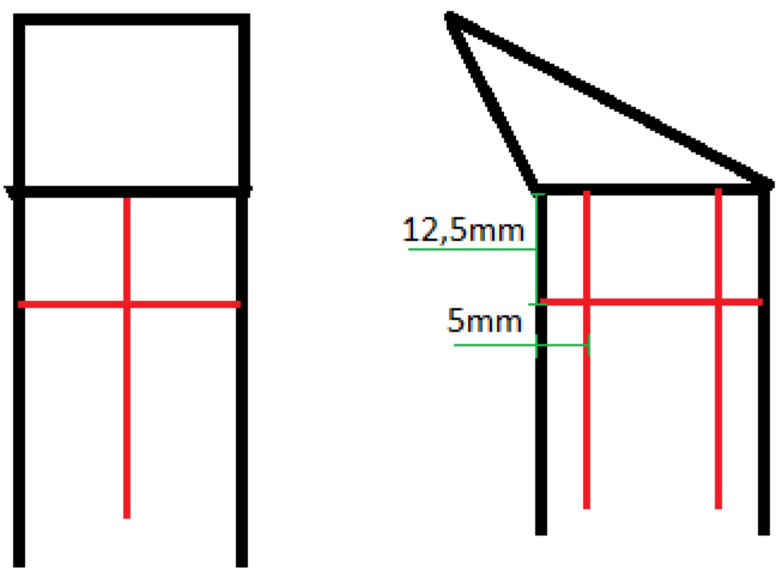


Figure 8. Strain gauge positioning

1. At first the 0-load stability will be tested. There will be recorded data for 10 min in order to check for drift.

2. Simple "springback" control: Apply a load large enough to be noticeable detected. When removed the strain gauge should return to its initial state.
3. Repeat step 1 and 2 on a different day.
4. Stair-tests. Loading applied in intervals of 500N. This will be done on all the 3 directions each day, for 4 days. On each day the last position will be used as the first on the following day. DAQ duration will be determined on the basis of step 1-3.

6.3.3 RESULTS OF STATIC TEST, ASSESSMENT OF PRECISION

Throughout this section it will be clear that more comprehensive data-analysis is possible with the recorded dataset. Further research can therefore benefit from this to a greater extent, but the time scope is not suited for testing the statistical validity assumptions about which effects is and isn't independent.

An example of the first two minutes of data sampling of the stair test is seen on figure 9. The measurements in blue, can be seen to have random noise. The orange line is a running average of 41 points (itself plus 20 points on either side). This is done to the entire dataset prior to data analysis. The following statistical metrics therefore assumes that the running average is part of the data-acquisition.

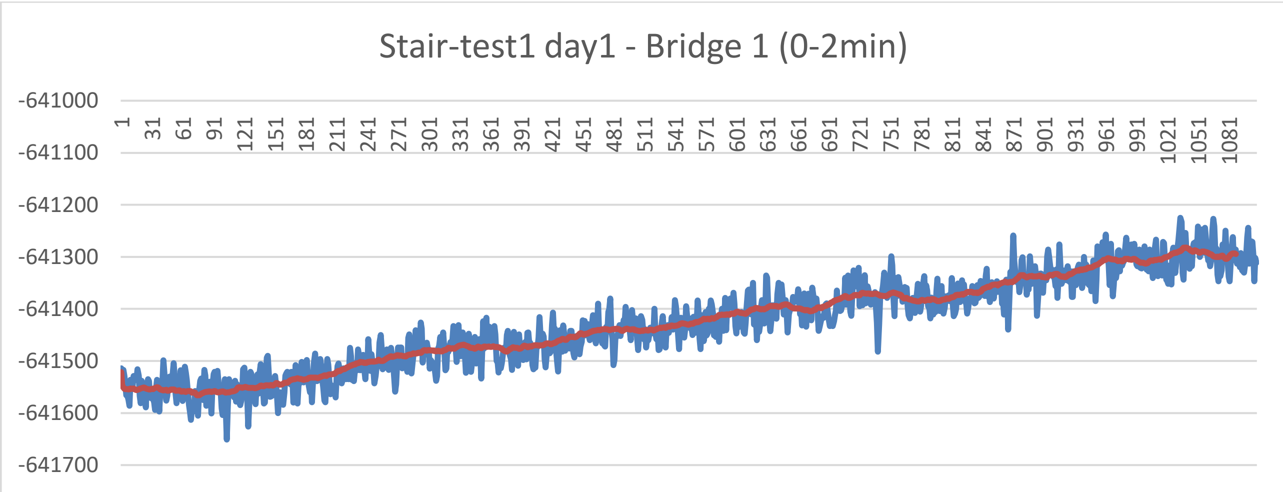


Figure 9. Drift while statically loaded in two minutes.

There is a visible drift within the two-minute interval, even though it has been with constant load of 0N. The usual method is to fit a straight line and accounting the individual error as random noise. Not all the two-minute ranges seem linear, instead the minimum and maximum value is found. This uncertainty will be applied to the entire two-minute range. If calculated the other way, the drift uncertainty could be modelled to increase the over time, therefore being more certain of the precision in short intervals. This way of modelling is done as it is simpler and will also give a more intuitive representation of the precision. It is furthermore considered to be just as if not a more conservative estimate.

For each bridge there is a total of 77 usable sections (7 not usable see diary *17-08-2023* in appendix). The difference between the maximum and minimum of each range is sorted in the histograms of figure 10. Small deviations withing the range of 100-200 are prevalent, whereas the absence of drift is less common.

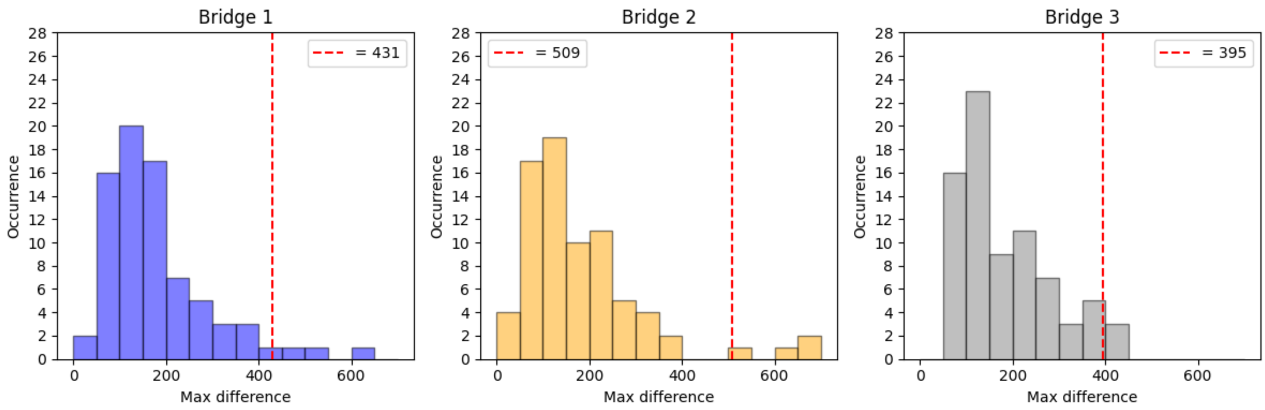


Figure 10. Histogram of drift within two minutes, for each bridge.

The measurement uncertainty of bridge[i] caused by drift is determined by selecting the fourth largest value, which is interpreted as the upper bound of variation within the dataset. This approach provides an estimate of the upper range of potential drift values, closely aligning with the typical 95% confidence level in statistical analysis. It simplifies the evaluation significantly as there's no need to find suitable distribution models.

The force functions are linear equations where each bridge is multiplied by their unique sensitivity to an axis. Due to the drift previously explained, the bridges are not expected to return to zero when the tool is at rest, due to drift. Whenever a measurement is initialized, it must have been following a moment of rest, to zero the instrument.

$$F_x = B_1 \cdot X_1 + B_2 \cdot X_2 + B_3 \cdot X_3$$

$$F_y = B_1 \cdot Y_1 + B_2 \cdot Y_2 + B_3 \cdot Y_3$$

$$F_z = B_1 \cdot Z_1 + B_2 \cdot Z_2 + B_3 \cdot Z_3$$

The assumption is that the standard deviation of each scaling coefficient remains constant across all load levels. However, it may seem like the deviation is decreasing at higher load levels. The relative uncertainty is thus lower a higher load. Due to the linear assumption therefore likely to overestimates the uncertainty of high load but underestimates the uncertainty of low loads.

Table 4. Force-function scalars and their confidence

Force-function coefficients (scalar)			
Axis\Bridge	1	2	3
X	-0,00474	-0,00454	0,00973
Y	0,000341	-0,0127	0,0171
Z	0,000344	-0,0188	0,0382

Force-function confidence interval, k=2 (+/-)			
Axis\Bridge	1	2	3
X	9,76E-06	8,67E-05	0,000156
Y	9,38E-06	8,34E-05	0,00015
Z	0,000134	0,00119	0,00215

Precision within a 2-minute operational window is determined by combining the maximum drift (δMax Drift) with a linear deviation (δScalar Deviation) that varies with the applied force. Calculating the worst-case scenario is unnecessary unless the uncertainties are interrelated. In this case they are assumed to be independent which allows the use of the following equation:

$$\delta Combined = \sqrt{(\delta Max\ Drift)^2 + (\delta Scalar\ Deviation)^2}$$

The opposite is expected for drift of the bridges, where their numerical values of contribution to uncertainty are summed. This is also the case for scalar deviation, which already are positive valued.

To compare the maximum relative error with other papers approach, some simple assumption must be made. The relative error is firstly dependent on the magnitude of the force since the drift will make up less of the deviation at higher forces. Even when applying a constant force, such as 1000 Newtons in the x-axis, the presence of interconnected bridges affects the precision (of F_x) when varying the forces in other axes. Therefore, it becomes necessary to make assumptions regarding the distribution of these forces to assess their impact on precision of each directional axis. The chosen values are:

Table 5. Example of calculating force and accuracy of digital measurement.

$$F_x = 1000N \quad F_y = 500N \quad F_z = 250N$$

$$\Delta B_1 = -199063 \quad \Delta B_2 = -99273 \quad \Delta B_3 = -40520$$

$$\delta Scalar\ Deviation[x\ y\ z] = [16{,}87N \quad 16{,}22N \quad 231{,}93N]$$

$$\delta Max\ Drift[x\ y\ z] = [8{,}20N \quad 13{,}37N \quad 24{,}81N]$$

$$\delta Combined[x\ y\ z] = [18{,}76N \quad 21{,}02N \quad 233{,}25N]$$

$$F_x = 1000N \pm 18{,}76N \quad F_y = 500N \pm 21{,}02N \quad F_z = 250N \pm 233{,}25N$$

Although it may be possible to measure the force with better precision, the deviation due to scaling increases when simultaneously having load in other directions.

Table 6. Table 1(Liang et al., 2016a), with the addition of LCCF from DAMRC

Developer	Approach & Measurement Principle	Size (mm)	No. of axes	Sensititvity	Maximum Relative Error
Tuysuz, Altintas, Feng	Indirect and prediction model	n.a.	5	n.a.	8,5%
Rao, Gao, Friedich	Direct and piezoelectric	Integrated into system	1	7 mV/gm	9,8%
Kim, Kim	Direct and strain gauge and piezo-film accelerometer	40 x 70 x 26	2	3 mV·N^{-1}	n.a.
Yaldiz, Ünsa	Direct and strain gauge and piezoelectric accelerometer	100 x 100 x 50	3	0,1 mV·N^{-1}	<5%
Liu, Zhou, Tao, Tan	Direct and strain gauge and Bragg grating sensor	n.a.	3	n.a.	6,23%
(Liang et al., 2016a)	Direct and strain gauge	ф 80 x 42	6	0,0134 mV·N^{-1}	<5%

				0,345 V\left(Nm\right)^{-1}	

LCCF precision when measuring a force[x,y,z] of [1000N,500N,250N]

DAMRC x-axis	Direct and strain gauge	Require additional overhang of 40mm	3	na	1,9%
DAMRC y-axis	-||-		3	na	4,2%
DAMRC x-axis	-||-		3	na	93,3%

SAMPLE RATE

The sample rate is initially at the ADCs rated value of 10SPS. As depicted in the graph, the measurement interval gradually extends to approximately 250ms. This represents a time increase of 150ms over the span of 10 minutes. At this point it is unknown, whether it is due to the ADC, the Arduino program, or DAQ. The running average used for data smoothing does not consider this factor. Consequently, the latter portions of each test exhibit a broader time-interval of included data, potentially resulting in more pronounced data smoothing. It's worth noting that for convenience, higher loads have been positioned towards the end of the tests. This arrangement hinders the ability to analyse the load's impact on drift, as any observations may have been influenced by altered smoothing conditions.

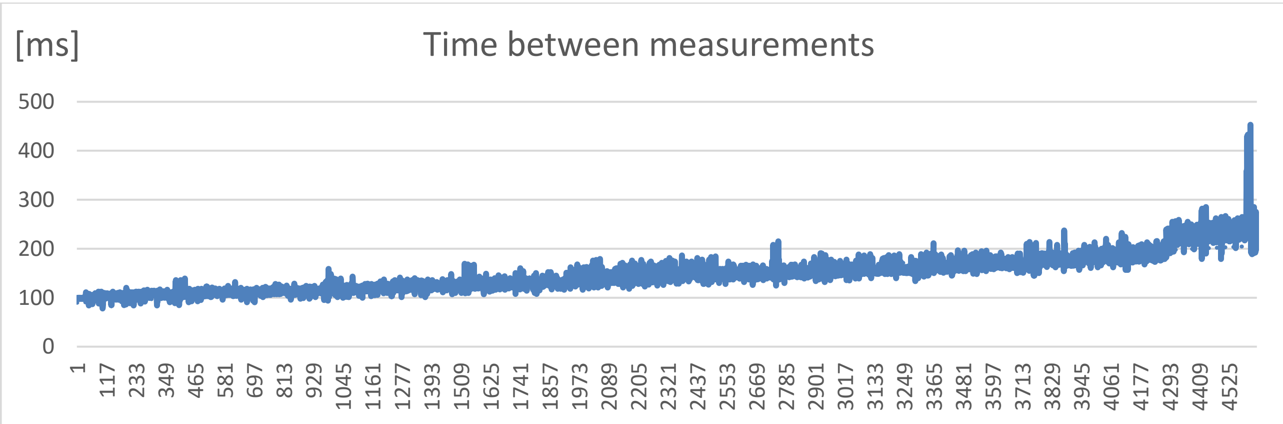


Figure 11. Time between measurements, of springback x-axis day 1.

A problem that can occur when using a low sample rate compared to the signal frequency is the phenomenon of aliasing. As seen on the figure 12, the measurements can show a gradual rise or fall, despite the signal not changing apart from locally. This could falsely suggest a gradual wear. The effect is worst, i.e. makes the longest measured period length, when the frequency is close to the SPS. It can also occur if the sample rate is a ratio of the frequency, so long as “n” is an integer. If n=2 the samples are only taken every second period.

$$Fq/n \approx SPS$$

Due to the local variance in sample rate, in combination with the much higher frequency, it is unlikely that aliasing will have an effect over many datapoints.

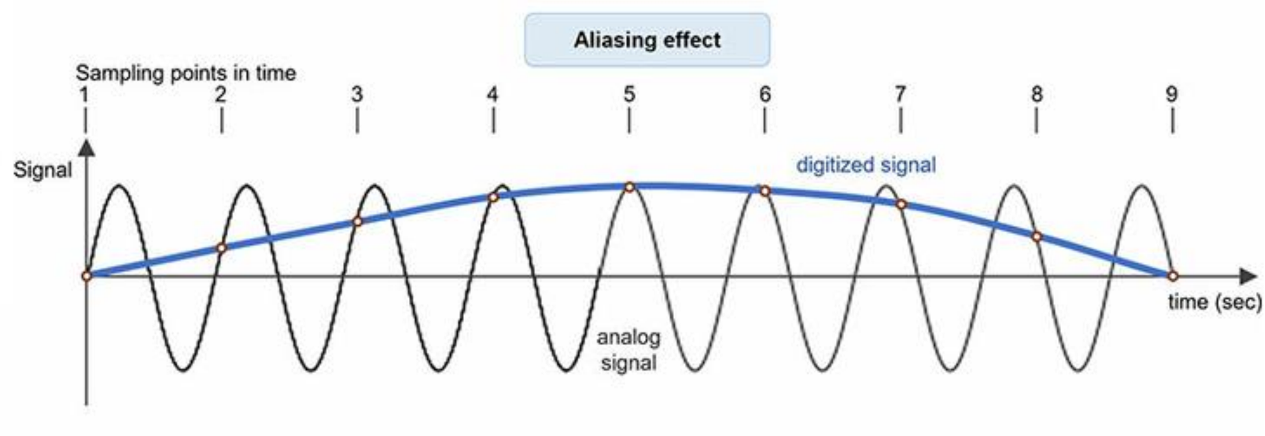


Figure 12. Aliasing effect, Kistler

6.3.4 CALIBRATION UNCERTAINTY

In the AU Mechanical Engineering student-project (Jakob, Jan, and Lynge, 2023) it is highlighted that the primary source of uncertainty during calibration stems from the positional uncertainty of the load. This positional information is crucial for compensating for the varying point of force during machining. Its significance becomes particularly pronounced when precise force measurements are required. This is useful when trying to reproduce a cutting process across different machines. However, during continuous operations with consistent parameters, the relative force-measurements are not expected to be influenced.

7. EXPERIMENTATION ON LATHE

The following section will investigate interference of the sensor when it is installed in the lathe, as well as measuring while machining.

7.1 MACHINE ELECTROMAGNETIC INTERFERENCE

The sensor will be inserted into the running lathe, in order to see the magnetic fields interference. The same will be done after shielding the strain gauges with HBM-ABM 75.

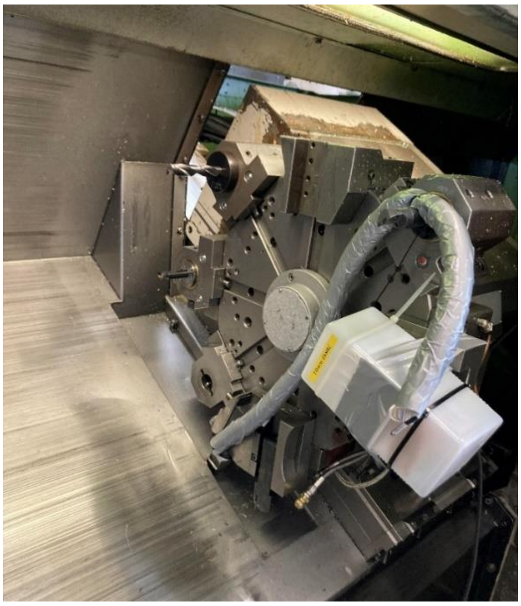


Figure 13. Cable routing and machine crash during revolver rotation.

The test of spindle noise has been made with two-minute intervals of 0RPM and 1000RPM. The last interval had the machine completely turned off.

On bridge one and two there is a subtle change whenever the spindle-speed changes. On the 3rd bridge there was a tendency to measure lower as the spindle ran. In the subsequent 2-minute interval of 0RPM there was a tendency to drift up, which only began after the motor had run.

There is no difference between the machine being turned on or not at 0RPM.

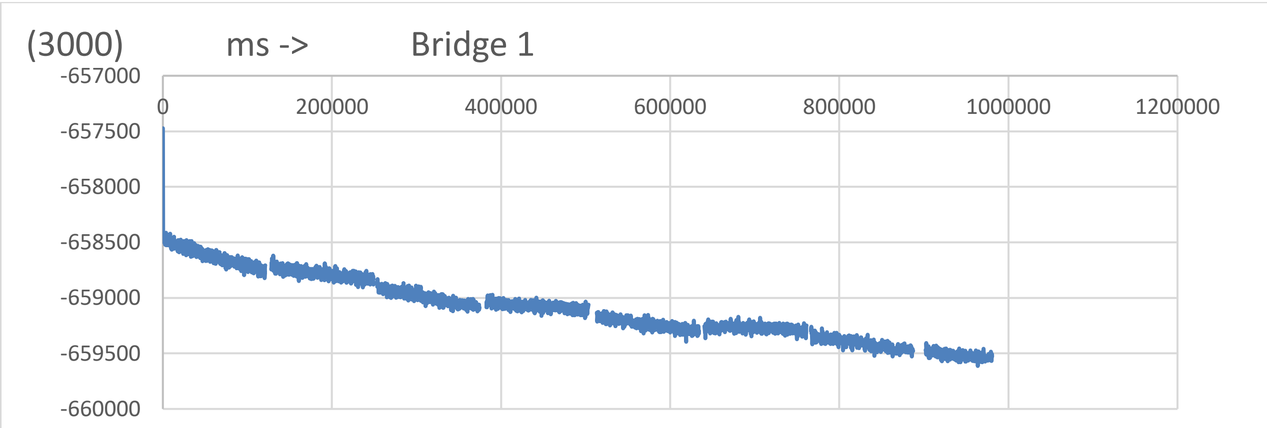


Figure 14. Bridge 1 reading in the lathe with 0 load. Spindle on every second interval of 2 minutes.

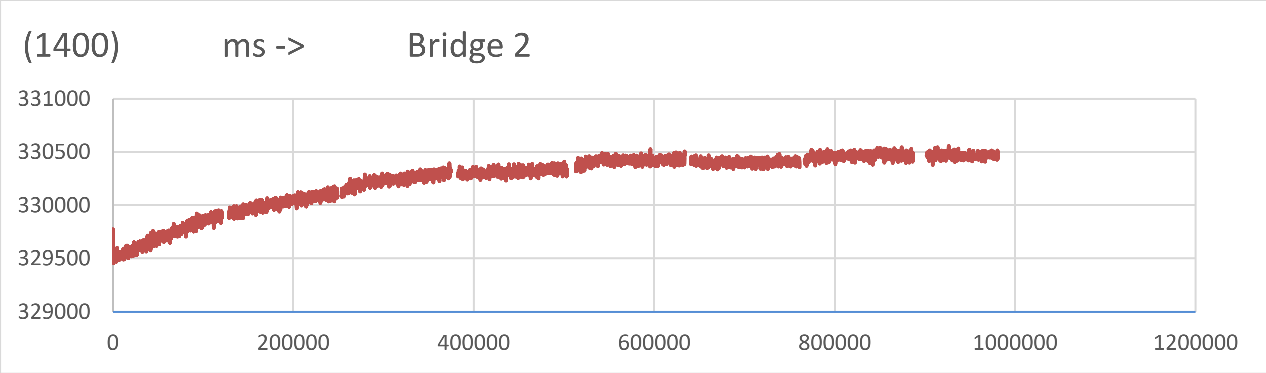


Figure 15. Bridge 2 reading in the lathe with 0 load. Spindle on every second interval of 2 minutes.

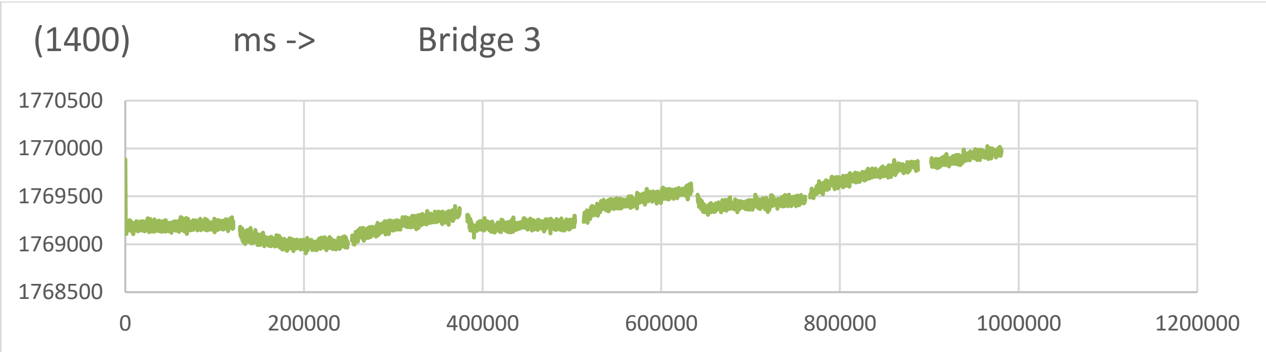


Figure 16. Bridge 3 reading in the lathe with 0 load. Spindle on every second interval of 2 minutes.

The variation, or "band thickness," does not appear to differ noticeably when visually comparing the graphs at 0 RPM and 1000 RPM

From this it seems that the only effect from the spindle might be that of thermal, due to forced airflow. This test does not investigate the influence of other machining conditions such as chips and cooling fluid. The tool must therefore still be protected by covering putty.

7.2 SPRINGBACK AFTER VIBRATIONS

The tool is positioned in the machine and held for two-minute intervals. In between a rubber mallet is used to induce vibrations.

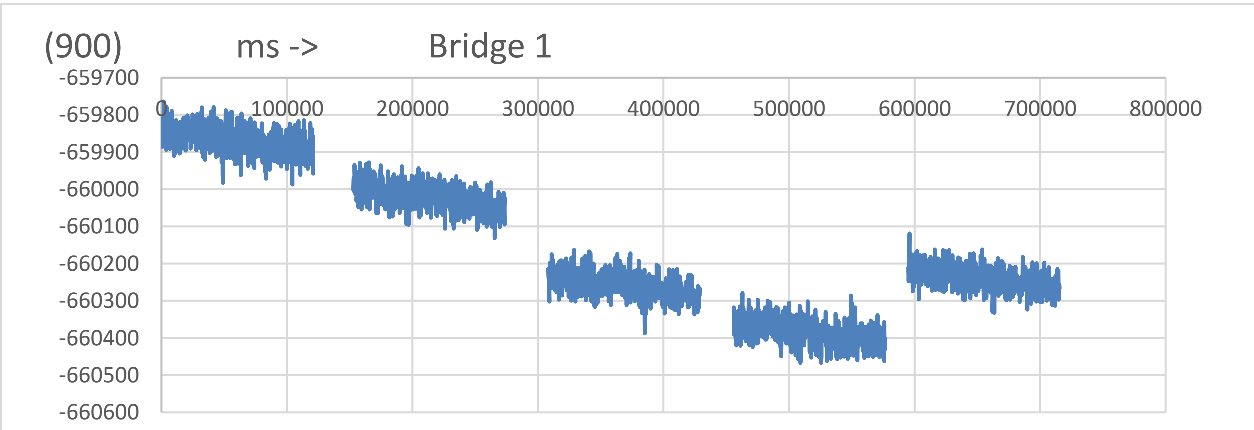


Figure 17. Bridge 1 reading in the lathe with 0 load, with vibrations in between intervals of 2 minutes

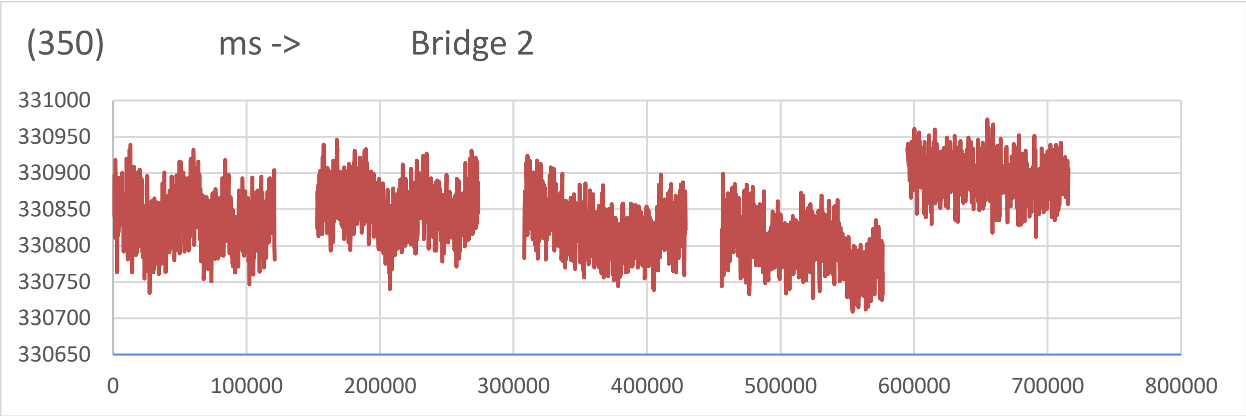


Figure 18. Bridge 2 reading in the lathe with 0 load, with vibrations in between intervals of 2 minutes

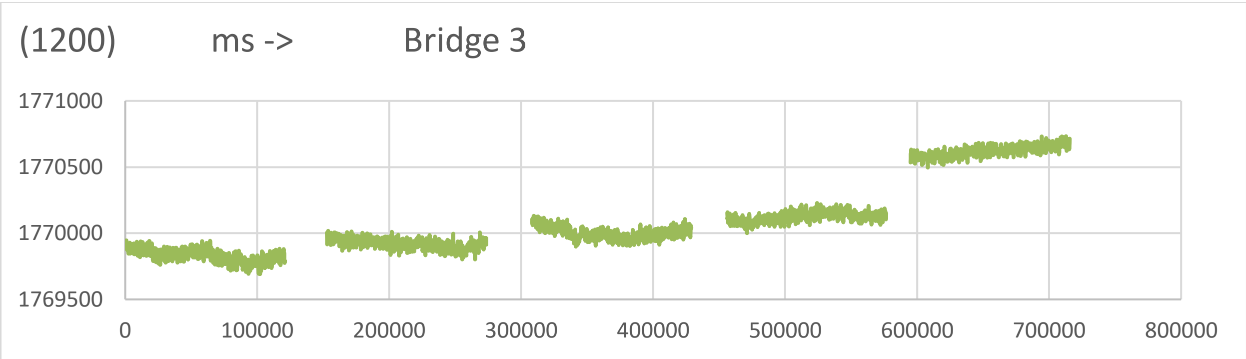


Figure 19. Bridge 3 reading in the lathe with 0 load, with vibrations in between intervals of 2 minutes

The measurement changes noticeable after the vibration cycles. For the dynamic test there must be measured a 0-load calibration in between each cut, to see if drift or vibrations is causing a higher-than-expected error.

7.3 OPERATION TEST

An insert will be used to machine with constant parameters until failure. Initially the surface is turned with another insert, to ensure that it is cylindrical. Each pass is made gradually shorter, to conserve the surface finish. As seen on the figure 20.

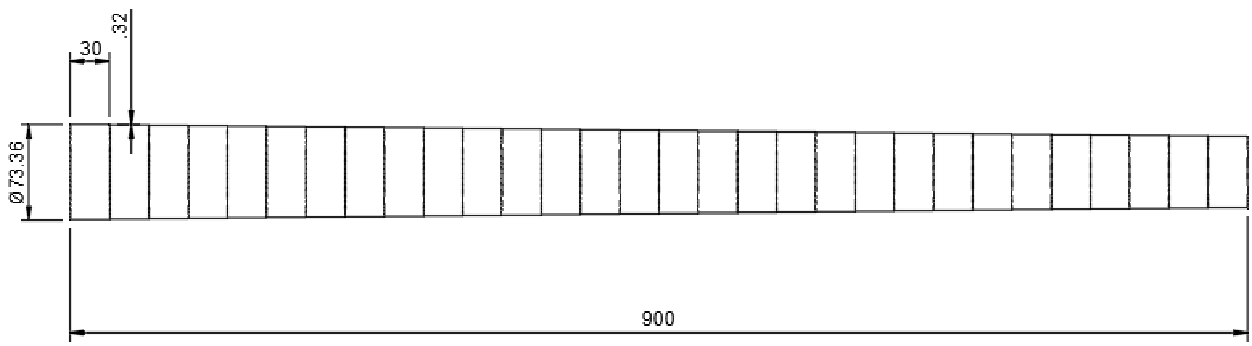


Figure 20. Drawing of how the finished part will be after cutting test.

Inserts and Cutting parameters are chosen for early wear compared to material removed. Still in the recommended range.

- Depth of cut 0,32mm
- Feed 0,1mm/r
- Speed 555m/min (Later increased to 700m/min)

Figure 21. Inserts used in the lathe test.

7.4 DYNAMIC TEST WITH COOLING FLUID

The test of the stepped toolpath is proceeded with cooling fluid. The data is normalized by setting zero load to the average of the first 100 points (ca. 10.000ms). The 30 steps are expected to look similar, with approximately 10.000ms 0 load, followed by a constant load.

The results are not as expected when concluding on the trends of the test. The calibration phase is stable followed by a significant change of load when initializing the cut. The graph during the cut resembles exponential decay, associated with thermal change.

Despite our estimation of critical wear happening before the operation was finished this didn't happen. Even if any increase in cutting forces were to happen, it would be impossible to detect due to the inconsistency of the data.

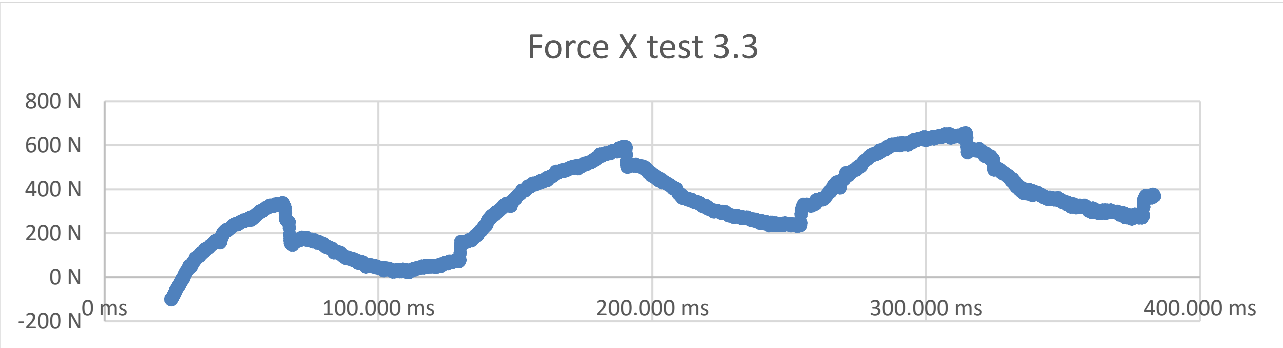
It is worth noting that not every irregularity can be traced to thermal change. Some of the changes happen too fast, and don't look gradual as temperature would. The causes of inaccuracy deemed most likely and most severe are listed:

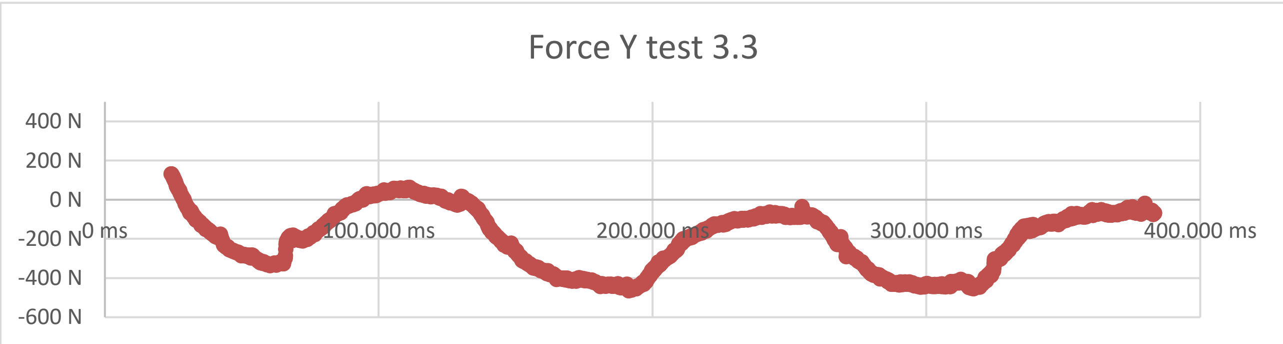
- Thermal
- Strain gauge adhesion faults from vibrations
- Interference from motors of axis.

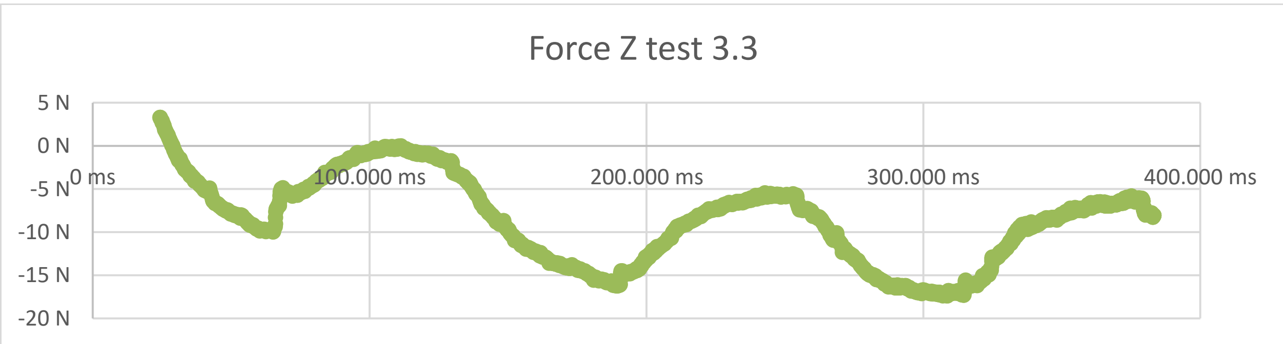
Later it was found that the most detrimental cause was cooling fluid entering the electronics box.

TEST WITHOUT COOLING

Another test without cooling has been made, to be more certain of thermal influence being a problem. The lathe is run on and off in 60 second intervals, with the hypothesis of seeing exponential trends of heating and cooling. The hammer test shows that there is a likely problem with vibrations, although we can't be sure that the cause is the strain gauges and their adhesion, there won't be further investigations of it.







Had heat not been a source of error, the output should have been a stepped graph. Instead, it clearly shows exponential curves, with strongly indicate a thermal sensitivity. It is so severe that the immediate engagement and relief of cutting is only slightly noticeable. All dynamic-tests'-3 have the same results. When the heat is this critical, it is likely to also have a lot of effect when using cooling fluid.

7.5 RETEST WITH COOLING FLUID

As written in the diary (in appendix), the electronics box was found to be full of cooling fluid during cleanup of the project. A quick test showed that dripping cooling fluid on the analog side of the circuit board, made the same abnormal jumps as in the dynamic test with cooling fluid. This gives reason for a retest with cooling fluid, with emphasis on waterproofing the electronics.

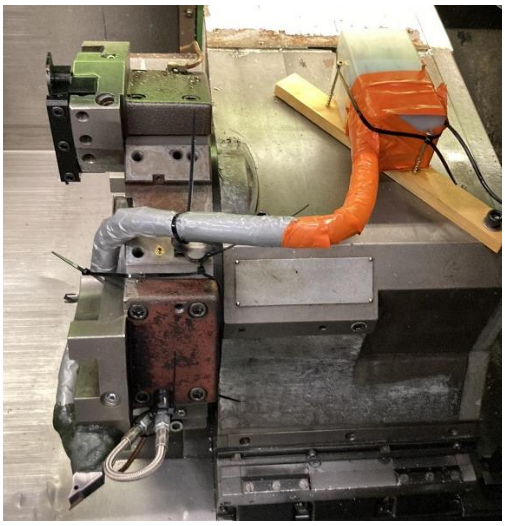


Figure 22. New mount with better waterproof electronics box

The test will not be run for so long to see wear change of the insert, due to the limited time left of the project. A variation of cutting force will instead be made with two different depths of cut.

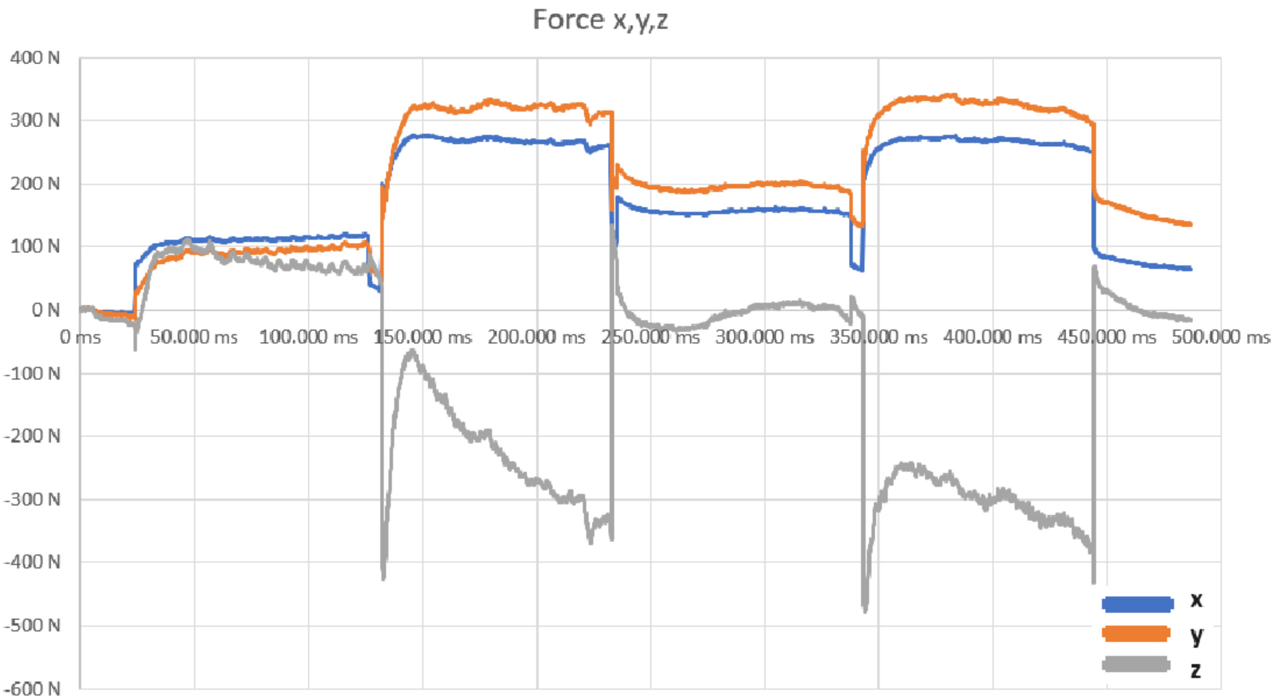


Figure 23. X,y,z forces for depth of cut in steps of 0,3 and 0,6mm.

It seems that the waterproofing has worked, as there is no longer unexplained jumps in the graph. The thermal effect is still visible but at much lower impact compared to the tests without coolant. The graph doesn't immediately return to zero in between cuts, this can both be due to the static drift, but also heat build-up during the operation. The force in the z direction is initially in the right direction, but then is negative, even though the load on the insert should be positive. The uncertainty even during static load was shown to be unreliable, so it was to be expected that the measurement of the z-force was unreliable.

8 DISCUSSION OF METHOD AND RESULTS

The price of the hardware without VAT is approximately 800 dkk + insert holder. The labour of adhering the strain gauges, doing QC and calibration the sensor accounts for 20 – 30 hours in a low production volume.

An optimized toolholder will probably have to be fitted with custom strain gauges, for ease of assembly. The price of such strain gauges may not be in the acceptable price range.

PRECISION AND ACCURACY

It has not been investigated whether the accuracy demand of 15% is sufficient for the hypothesis' first argument.

1. *It is possible to measure cutting forces with strain gauges and inexpensive DAQ with greater detail than what's integrated in industrial lathes.*

This is critical, as most machines measure current draw, which correlates with cutting forces and therefore wear-state. The accuracy of this, while not known, should serve as a benchmark.

With knowledge of cutting forces, there may be set foot on some of these use cases.

- Optimizing insert run time
- Minimizing tool wear related risk of machine crash
- Enabling more control for "balance cutting" for long workpieces
- Calculating real-time and compensating for workpiece deflection
- Probing workpiece
- A tool for analysing surface of chips forming problems
- Realtime stability (Chatter) evaluation

The use cases have different requirements, of precision, accuracy, and sampling rate. To better analyse the requirements of the sensor, there would have to be considered what it can accomplish for the cases.

The 15% requirement is for accuracy while the uncertainties in table 6 is for repeatability (accuracy). The test has not been made with sufficient time in between, to denote it as reproducibility. To quantify the accuracy it will have to be combined with the uncertainty of the calibration setup and equipment.

The calibration accuracy has been estimated to be 0,066% with careful use of DAMRCs equipment. (Jakob Jan and Lynge, 2023) However, the actual handling of the calibration was not as methodical. Despite this, given that the calibration uncertainty can be made so low, it is plausible that the accuracy of sensor is within 15%

It has been deprioritized due to most use cases being more dependent on precision.

DESIGN COMPROMISES

The current sensor state significantly hinders machining capabilities, necessitating an additional 40mm overhang. The most challenging aspect is the use of wires; unless routed through the centre with sliprings, the revolver may occasionally need to unwind them. They are also exposed for breakage. Wireless tool communication is considered essential for commercial adoption. This also simplifies tool changes.

Since the strain gauges are attached to the insert holder, they are limited to that particular type of insert. If a company chooses to equip their machine with sensors, they will gain greater advantages from the ability to use various tools with the same hardware. Such a design will need to accommodate varying tool overhang lengths and therefore should not directly link stress of the strain gauge to load.

The use of strain gauges means it becomes thermally sensitive, especially when placed close to the point of contact. This issue also supports the idea of a tool holder, where strain gauges aren't directly placed onto. The research shows a high certainty of ruining the measurements. Although multiple causes also can play a part, such as impacts and vibrations. The later test with cooling fluid, resolved some of the thermal issues, and can probably be improved upon further by using a tool with internal cooling.

Previous cutting force projects have been done at DAMRC, which may have led to a too narrow scope of solutions. Different sensing methods have thus not been given sufficient consideration but have higher cost.

9 CONCLUSION

The objective of the project was to design and test a low-cost strain gauge based cutting force measurement system with aim to identify tool defects, wear, and other features in machining. Pure material cost is at the estimated 800kr below the price requirement of 1500kr. This is quite low cost for a sensor and data acquisition system and in the intended price range. Mounting and calibration are likely to be a bit laborious though.

The precision of the cutting force can be expected to be within 1,9%, for static repeatability. Heat and possibly impacts from the operation means the sensor is significantly less precise in the lathe but still within the stated 15%. The tool design was expected to undergo some changes, but the standard tool holder was usable as of the shelves directly. There are only small changes to do, to improve the design.

The time and competencies needed to install and calibrate the strain gauge system may turn out to be an obstacle for the technology to get more widespread in industry. Therefore, other technologies may still be interesting to research in terms of easier installation at the machining centre.

10 PROPOSALS OF FUTURE ACTIVITIES

GEOMETRIC OPTIMIZATION

The placement of strain gauges is crucial for their sensitivity of loads. It also impacts the tools spatial and structural limitations for machining.

In the report of AU Mechanical engineering students: (Jakob, Jan and Lynge 2023), a method is proposed to simulate a strain gauges sensitivity when used on both flat and curved surfaces. If the method is shown to have acceptable predictability, it can be used for geometrically optimizing the insert-holder sensing unit.

It has through this rapport been shown that geometric optimization with regards to thermals also should be considered.

WEAR AND ERROR DETECTION TESTING

A well-defined procedure or algorithm must be developed to consistently process the data. It is imperative to identify reliable indicators of critical wear, as these serve as the basis for altering machining parameters or pausing the machine. The margin for error is extremely narrow, as any false sense of security could lead to potentially hazardous consequences.

SENDING G-CODES FROM THE MICROCONTROLLER TO THE CNC-LATHE

For automating machining processes, the microcontroller must possess the capability to modify the machining program in real-time. This also offers the advantage of quicker response times when manual intermediary actions are eliminated.

TESTING STANDARD DEVIATION OF INSERT WEAR RESISTANCE

Insert changes can’t be optimized solely from time under load if the wear resistance differs within the same model of inserts. This activity will analyse how much is to gain from continues monitoring, rather than optimizing runtime.

11 DISSEMINATION

The project has been presented at various events internally at DAMRC, Techdays, several visits from companies and DI and externally at VTM ’23 at Odense Congress Centre.

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13 Appendix (Diary)

As of 03-08-2023 all strain gauges have been adhered and have the specified 120 Ohm resistance. There is no short circuit between them. The gauges used have three wires, where two of them are connected in the end of the strain gauge. For these experiments they will not be used, as all circuits are full bridges. They will either be isolated in the ends or put in the same terminal as their already connected wire. (LYJ)

04-08-2023: The wires to a strain gauge have been ripped off during cable management on the toolholder. (LYJ)

07-08-2023: The damaged wire has been manually soldered and the gauge shows 121 Ohm. It is not alarming as its expected not to have changed the gauge factor meaningfully. (LYJ)

08-08-2023: The cables have been routed to the DAQ assembly. All three bridges show signs of working from loading the tool by hand. As it is more noticeable than the signal noise. (LYJ)

11-08-2023: The first stair-test have been made. (LYJ)

14-08-2023: The last three stair test have all been made today do to the setup taking up machining space for other projects. Although it was meant for different days, this was not of much priority, as climatic variance such as thermal, may have varied just as much though the day. I made a mistake during the first test of the y-axis (2-2.1). As I loaded the from 1000N - 1500N before the recording period of 1000N had finished. (LYJ)

17-08-2023: Although the 500N and 1500N tests for 2-2.1 are valid, they have been too troublesome to include though the python extraction software because of the missing data. Therefor only three repetitive tests have been made for the y-axis. (LYJ)

21-08-2023: The tool has been inserted into the lathe. The wires have been wrapped in foam and duct-tape to protect them from chips and other sharp objects. The electronics box has also been fitted to the revolver, so the strain gauge cables don't break if the revolver rotates.

During the fitting of the tool there occurred a minor machine crash. The tool had a longer than usual overhang and the adapter-insert was not removed prior to installation. The rotation of the revolver caused the adapter-insert to crash into the machine. Although unfortunate, it has not shown signs of impacting the device or measurement. (LYJ)

29-08-2023: There has been made a roughing cut on the first piece. From the simultaneously collected data, it has become clear that it is highly sensitive to heat. It is so severe that it greatly masks any continues change of cutting forces. The process was made without cooling fluid, for the next test we will attempt to have a more stable temperature by using cooling fluid on the insert.

04-09-2023: The first dynamic step test had problems during data acquisition. There didn't accumulate enough wear as expected. The cutting speed of test 2 will be increased to 800m/min. (LYJ)

07-09-2023: We have noticed that the maximum spindle speed is 3000RPM instead of 3500RPM which the lathe specifies. This means the dynamic test of 800m/min only is done with initially 700m/min and decreasing throughout the test. (LYJ)

12-09-2023: The electronics box had been mounted upside down, which made it take in coolant. This may have been the reason of some of the unresolved results of the dynamic tests. Due to this it was decided to do the operation test with coolant again.