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DEVELOPMENT AND CONSTRUCTION OF A INDUSTRIAL SCALE RHEOMETER DEVICE FOR THE CHARACTERIZATION OF COHESIVE BULK MATERIAL.

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Submitted by: Tran Hoang Duy

RUB Student ID: 19218772

VGU Student ID: 14657

Supervisor: Prof. Dr. André Katterfeld

Co-supervisor: MSc. Mohsin Ajmal

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Vietnamese-German University



Vietnamese-German University

Tran Hoang Duy

14657

Main supervisor: Prof. André Katterfeld

Co-supervisor: MSc. Mohsin Ajmal

29 December 2022

Affirmation

Affirmation in lieu of oath

Tran Hoang Duy

Matriculation number: 14657

Title of thesis: DEVELOPMENT AND CONSTRUCTION OF A INDUSTRIAL SCALE RHEOMETER DEVICE FOR THE CHARACTERIZATION OF COHESIVE BULK MATERIAL. I hereby declare in lieu of oath that I have produced the aforementioned thesis independently and without any other means except the aid listed. Any thoughts directly or indirectly taken from somebody else sources are made discernible as such.

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Magdeburg, 29 December 2022

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Abstract

This paper will introduce the process of conceptualizing and developing a Rheometer for measuring the dynamics, bulk and shear properties of such bulk materials as gravel and cohesive material. The thesis will provide essential information about properties of a rheometer, the concept design, selection of component and some analysis about the overall system. Comprehensive knowledge of the material rheological properties can be used for guiding engineering design and reaching requirement in specific task.



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Chapter 1

Introduction

In this section, brief information will be provided for the readers to get the motivation and the existing problem, which will lead to the research for development of industrial scale rheometer devices.

1.1 Background study and motivation

Rheology is the study of the flow of engineering material. Every substance has its rheological properties, which is visible in everyday life. Whenever a material flows or is being deformed, rheology is involved. Rheology is a branch of physics, and it is the science that deals with the relationship between stress (force) and strain (deformation) of matter in such states as solids, liquids and gas.[1]

Rheometer is a laboratory instrument used to measure the way the materials respond to the applied forces. There are two main different types of rheometer:

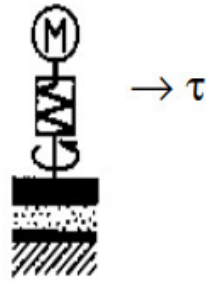
1. *Rotational rheometer*[2]

Rotational rheometers or so called shear rheometers control the applied shear stress or shear strain.

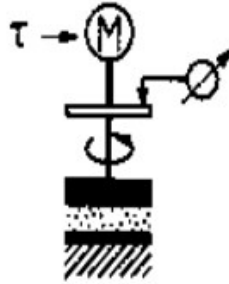
2. *Extensional rheometer*[2]

Extensional rheometers control extensional stress or extensional strain.

The rheometers are usually designed to operate in two ways: **(a.)** strain-controlled (CR-Rheometer) or **(b.)** stress-controlled (CS-Rheometer). With the strain-controlled, users set a defined strain rate and the instrument measuring the result stress during the experiment. The other way is applied for stress controlled, a stress-rate is defined and the resulting shear strain is recorded. Some models have the possibilities to work in both modes.



(a) Strain-control(CR): Shear rate assigned and shear stress is determined



(b) Stress-control(CS): Torque/Shear stress assigned and strain rate is determined

Figure 1.1: Control types of Rheometer

Bulk materials are subjects that are dealt in bulk amounts. Bulk materials can be easily spotted everywhere in human daily lives from food such as grains, flour, gummy snacks and so forth to industrial ingredients for example: gravels, lead shot, fertilizer, soil and so on. The needs of rheometer come about when these materials have to be moved in bulk. Depending on the environment properties such as moisture, material can behave differently such as soil or sand tend to become more cohesive and they are harder to flow.



Figure 1.2: Example of gravels material

In this case, gravel is selected to be experimented on first due to its popularity and availability in the laboratory. Gravel is a popular material that can be found everywhere in daily life. It is widely used in many industries for example construction, agriculture, outdoor-landscaping and erosion control. While being used extensively, they are one of the materials that are difficult to understand because frequent problems appear when dealing with gravel from laboratory to production process.



1.2 Research problems

With the popular and essential usages of gravel, the need for understanding of its rheological properties is rising considerably. While there are many available rheometers for most of the material, there is still a missing one for gravels in general. For example, a rheometer that is designed for concrete can be applied for gravel but its size and the amount of needed testing material is too large. Another one can be used is the powder rheometer and the problem is still there, which is the instrument is small compared to the size of gravel. The need for a gravel rheometer is real and in this project, it is essential to keep the prototype balance between the manufacturing fee and the accuracy of the instrument.

1.3 Purpose and Goal

The rheological properties and flow properties of a bulk are essential for the design of any bulk material handling system as well as discrete element method simulation of many practical industrial scenarios. The testing instrument will run through many desired bulk materials that are cohesive and non cohesive. After that, the result data can be applied and generates a set of material properties that benefits the discrete element method simulation. The purpose of the current work is to prototype a model of rheometer which is suitable for dealing with bulk materials such as gravel, granules and cohesive material such as composite materials in the laboratory. Furthermore, the prototype must be integrated with sensors in order to measure, record and graph the change of force and torque according to time while measuring. The design of the rheometer would be firstly utilized in laboratory and study environments. Then the upgrade and improvement to match the industrial scale usages. The cost of manufacturing must be relevant along with the accuracy provided by the design. The output should be usable and acceptable with many speeds and blades profiles coming with the prototype. The goal of the thesis is to successfully conceptualize and develop a rheometer with the possible available components in the workshop. The concept model must successfully perform either or both rotational and extensional measuring with little flaw as much as possible. Furthermore, the rheometer should come with some following expectations:

- Perform rotational movement of blade in the measuring material.
- Graph the change of torque of blade or shaft whilst measuring.
- Repeat-ability of the rheometer.
- The flexibility of upgrading and improvise when coming to different materials.

1.4 Literature review

The first commercial rheometer is a controlled-strain type which was available up until World War II, produced by Eimer and Amend of New York, USA. This instrument was the MacMichael controlled-strain viscometer Fig.[1.3] which includes a disc of 60 mm diameter and 5 mm thickness suspended in a cylinder rotated at 20 rpm. This device reads the torsion from the twisted wire connected to the disc[3].



Figure 1.3: MacMichael controlled-strain instrument [2003]

The later commercial instruments were introduced, which were the Searle (1912) and Stormer (1909) Fig.[1.4]. These instruments utilized weight and pulleys for operating the devices. The reason for choosing the weight and pulleys was to make the producing process a lot easier and to provide simplicity and economy features. The instrument could provide results in two ways, which were either the stress shear rate according to the controlling factor or shear stress according to the controlling factor. However, there were downsides of the early devices such as friction of the pulleys and bearings, time measuring features. In the next and future improvement of the rheometer, the controlled strain type was focused on developing more than the stress controlled instruments[3].

For over decades there have been many developments in rheometer construction. Top of the range instruments had reached the fully developed technique, where the technical differences are not significant in the practice. The real problem that differ-

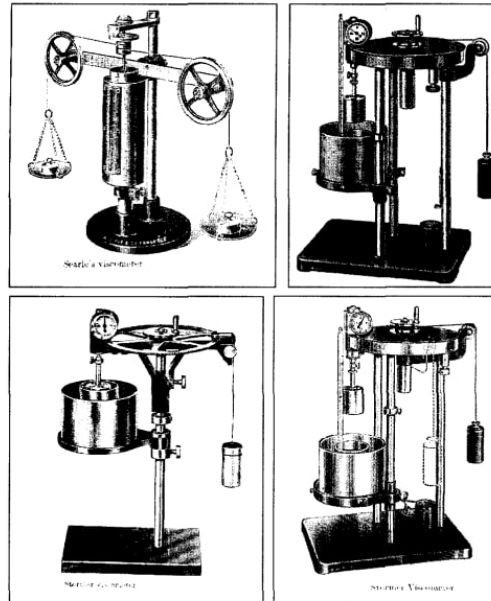


Figure 1.4: Searle, 1912 and Stormer, 1909 commercial versions.

entiate the result and user experiences are software, and service support. Currently, those matured features includes in the rheometer are:

Drag-cup motor



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For making an ideal rheometer, the need of a motor that can provide a torque that does not depend on the rotational speed is satisfied by drag-cup motors. These motors also have no brushes so that there is no friction included.

The position of the rotor can be controlled accurately due a sophisticated control system with a feed-back loop. Therefore, a given strain or steady strain can be achieved and controlled. There are some features of the drag cup motor that are desirable for a rheometer such as smoothness of torque, lightweight and low inertia, which affects the measurement results.

Magnetic Thrust bearing

The so-called magnetic bearing is a special kind of bearing that takes advantage of magnetic levitation to hold the load. The important feature is that it can support moving components without direct contact. In the rheometer, the rotating shafts are levitated and rotated by the thrust bearing with least friction and no mechanical wear.

Optical encoder

Optical encoder will go well with the motor drives for measuring the rotational speed and the position of the rotor at a lower and lower level. Stable devices can analyze and give out the measurement of rotation rates as low as 10^{-8} rad/s.

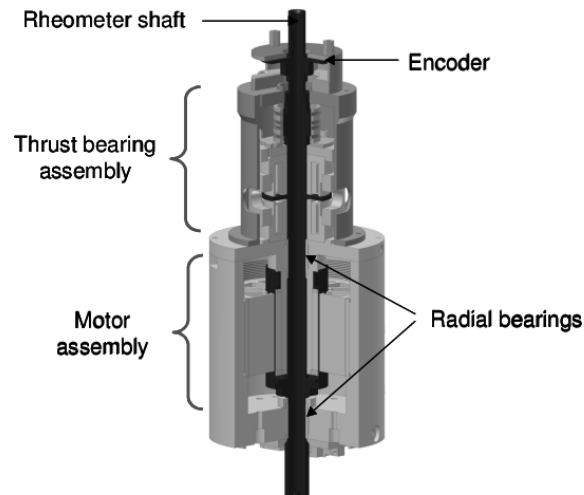


Figure 1.5: A magnetic bearing Rheometer [2005]



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Hybrid and module design

The rheometer nowadays will have a shaft hub integrated in order to change the desired measuring types and methods. Convenience and versatility are the goal when designing the instrument. Many interchangeable accessories can be installed with ease and the system can automatically detect the change and configure itself according to the new accessories for the rheometer operation.

Moreover, there have been some commercial rheometer providing the same expected principle in the thesis. These are some typical product:

-TA Instrument Discovery HR 10, 20 and 30: The rotational shear rheometer are designed for scientist who need better understanding about the rheological data. The device is equipped with the state-of-the-art electronics drag cup motor and can perform both strain controlled or stress controlled experiment. This one inspired the conceptualization process of the thesis.

- FT4 Powder Rheometer: A universal powder tester for measuring powder flow properties and powder behavior. This one was designed for one goal, which is to characterize the rheological properties of powder. However, with the continuous development, the FT4 now has many accessories to perform different methodology and it is considered a universal powder flow tester.



Figure 1.6: Discovery Hybrid Rheometer HR30 [TA Instrument,2022]



Figure 1.7: FT4 Powder Rheometer [Freeman Technology Lt]

- Viskomat XL: A Rheometer for mortar and fresh concrete from Schleibinger. This one can run in both strain controlled and stress controlled mode. The probe or propeller comes with the instrument make it possible for measuring with grain size from 8 mm to 20 mm and the speed may be 0.0001 to 80 rpm in both clockwise and counter clockwise.



Figure 1.8: Viskomat XL for concrete [Schleibinger]

Chapter 2

Mechanical design

After considering the problems and clarifications of the requirements, the next step is to develop a solution to the task. It is necessary to have knowledge of a variety of other engineering fields in order to complete the mechanical design process of any product for measuring device. These fields include mechanical design, structure design and electrical engineering. The mechanical component of the rheometer will be the main focus of this chapter.

2.1 Methodology

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In this rheometer, there will be a stainless steel blade rotated along the vertical axis. It can move up and down through an acrylic or steel container filled with gravel or stone. All of the materials are collected from the laboratory which are the desired working materials. In a typical test, the process will start with an additional step, which requires the blade to traverse downward (2.1a) and upward (2.1b) through the vessel. This additional step will use the blades with a specific helix angle that will help maintain the similarity of the trials. There is a reason for this additional step because of different filing methods and operators. After the conditioning step, the

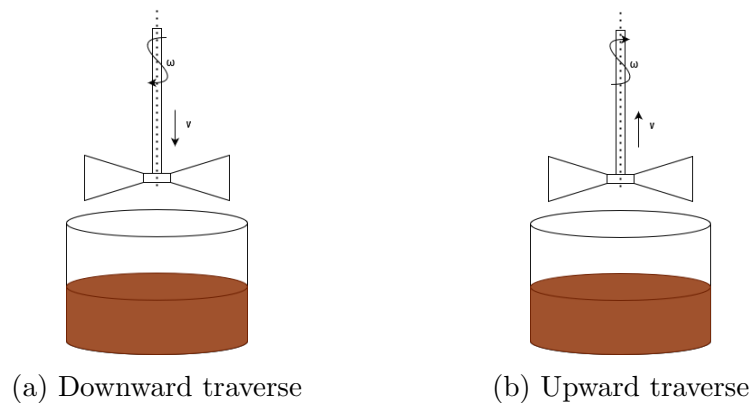


Figure 2.1: Basic operation of the desired rheometer

measuring part begins with the blades going downward and upward with a defined strain rate or velocity. The downward traverse is likely to compact rather than to slice the gravel. After the downward movement, the upward traverse follows after with the opposite rotate direction. During the process, the torque and axial force required to make the blades go through the vessel are recorded and used to calculate the total input energy[4]. During the measuring process, the motors is controlled by an arduino or a PLC for the defined strain rate. Moreover, there will be a torque sensor along the shaft and if possible another sensor at the bottom of the vessel for measuring the force(load). Combining both the data, graphs plotting Force-Torque, Force-Time, Torque-Time and Power-Time can be processed and displayed to monitor.

2.2 Conceptualization

Conceptualization in the general process in which the overall principles and functionality are most important. First of all, the rheometer should be identified and the currently existing mechanism must be considered.



Figure 2.2: Linear actuator types [Teknic]

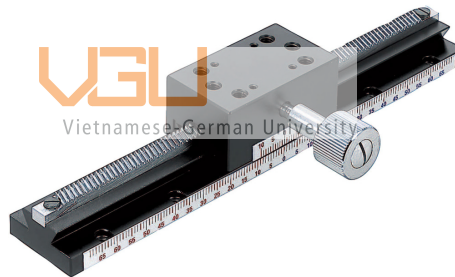
The mechanism of this rheometer is based on 2 movement: vertical translation and rotation. There are many selection for the linear actuator such as screw drive(2.3b), belt drive(2.3a), rack and pinion(2.3c) and linear motor(2.3d).



(a) Belt drive sample (Misumi)



(b) Screw drive sample (Misumi)



(c) Rack and pinion sample (Misumi)



(d) Linear motor sample (Misumi)

Figure 2.3: Example of some possible linear drives for the Rheometer

- **Belt drive[2.3a]**: The belt drive mechanism consists of a number of pulleys and a belt made of a metal material that is wound around the number of pulleys

in a circular direction. A swelling portion is formed to expand outward in a radial direction along the entire circumference of an outer peripheral surface of at least one of the plurality of pulleys. This portion is formed to surround the entire circumference of the pulley. The swelling portion is composed of two parts: a first part with a larger amount of swelling and a second part with a smaller amount of swelling; the first part has a larger linear expansion coefficient than the second part.

- **Screw drive[2.3b]**: Screw drive mechanism is converting rotational motion into linear motions. Its operation is based on the sliding of the screw shaft and nut threads without the use of ball bearings. Because the screw shaft and nut are moving directly against each other over a large contact area, higher energy losses due to friction are produced. However, lead screw thread designs have been developed and improved to reduce friction.

- **Rack and Pinion[2.3c]**: One variety of linear actuator is known as rack and pinion, which consists of a circular gear (known as the pinion) that engages a linear gear (the rack). They change the direction of the rotational motion into a linear one when combined. When the pinion is rotated, this causes the rack to be driven in a straight line. To achieve the reverse direction, linear motion of the rack will cause the rotation of the pinion.

- **Linear Motor[2.3d]**: This motor is a type of electric motor that has its stator and rotor unrolled. As a result, rather than producing rotation, a linear motor generates a linear force that runs the length of the motor. In contrast to the traditional motors, which are designed in the form of a continuous loop, the active section of a linear motor always has beginnings and endings.

Linear actuator	Advantage	Disadvantage
Belt drive	High dynamics performance, long travel distance, easy to maintenance	Accuracy is low, load is low
Screw drive	High precision, high capability of high payload	Limited travel distance, low dynamic performance
Rack Pinion drive	medium dynamic performance, precision, long travel distance, high payload	Overall medium performance and harder maintenance
Linear Motor	High dynamics performance and precision, long travel distance, easy maintenance	No capability of high payload

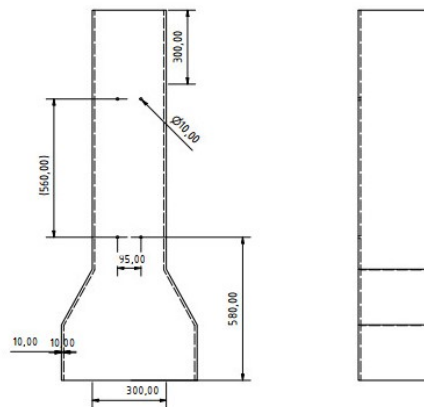
Table 2.1: Advantages and disadvantages of linear actuators.

When all the requirements of the rheometer are examined with all the linear actuators, the most suitable device for the need of constructing the rheometer is the screw drive mechanism. It can provide the precision and ease of controlling as well as the ability to handle heavy load, which comes from the motor and gear combination and variable load when measuring the gravel.

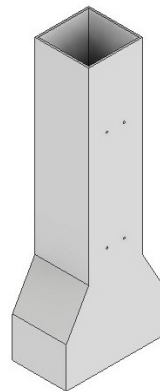
2.3 Parts and components

2.3.1 Stand - Plate

To begin, the prototype is in need of a base that can support the entirety of the system and is stable and robust enough to do so. The base has to be maintained in an upright position, and its surface area has to be large enough, in order to stop the system from leaning forward. In addition, the vibration of the system needs to be taken into consideration whenever the base is being designed.



(a) CAD design of the Base

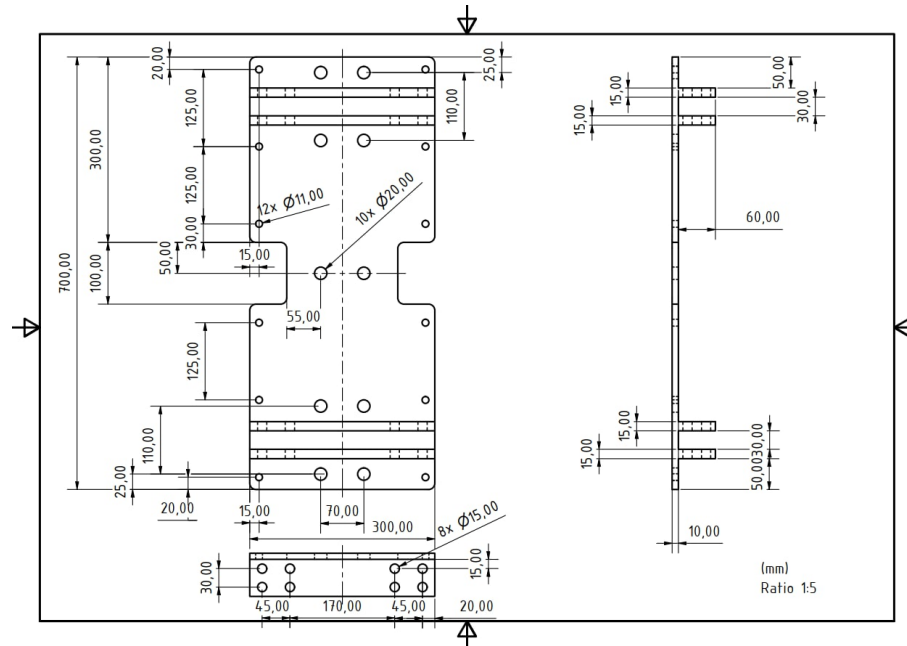


(b) 3D view of the Base

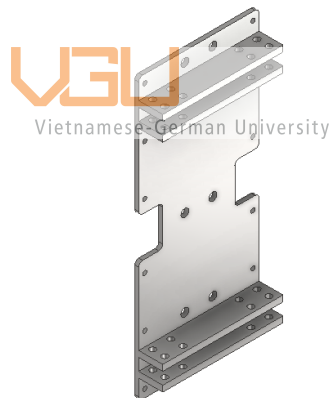
Figure 2.4: Base design

However, when the used area of the bases is taken into account, it is not convenient and it takes up a lot of space in a small laboratory. The structure is provided with a plate that can be used to install the system into a solid wall. The entirety of the system can be fastened securely to the wall with the help of bolts and bolt shield

anchor, but it will not lose the ability to future upgrades and enhancements because of this.



(a) Drawing of the Plate



(b) 3D view of the Plate

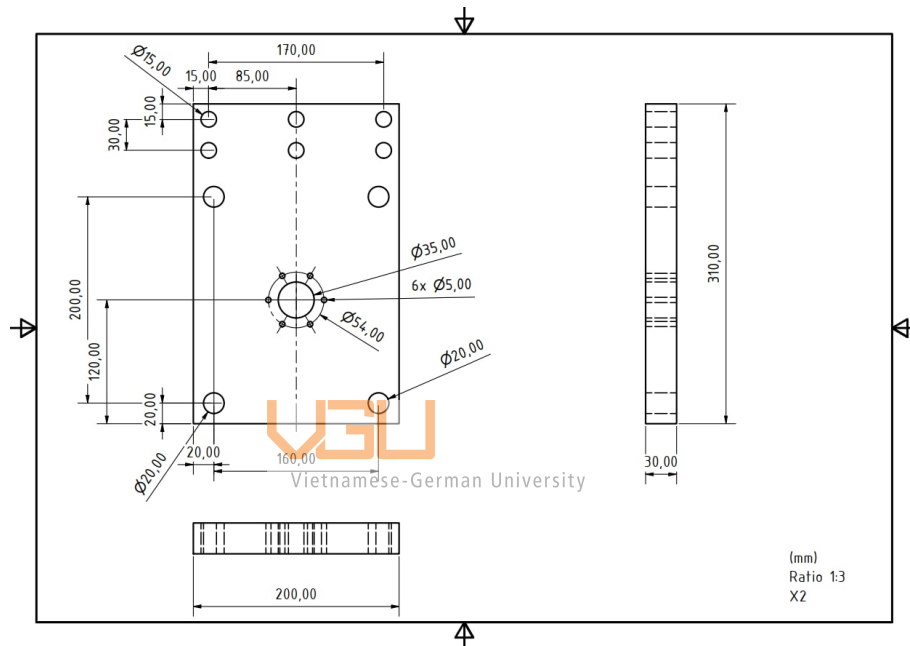
Figure 2.5: Plate design

2.3.2 Linear Actuator

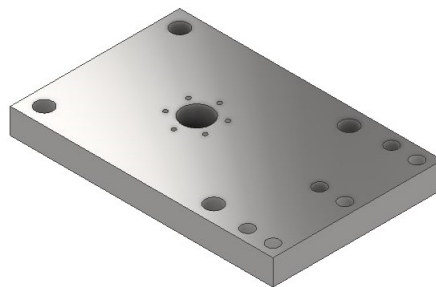
The overall main drive of the system will rely on the operation of the lead screw mechanism.

Mount

One of the so-called mount components will be located at the top of the lead screw, and the other will be located at the end. The mount is responsible for a significant part of the alignment work for both the lead screw and the guiding shaft. Because of this, the vertical motion will be as straight as possible.



(a) CAD design of the Mount

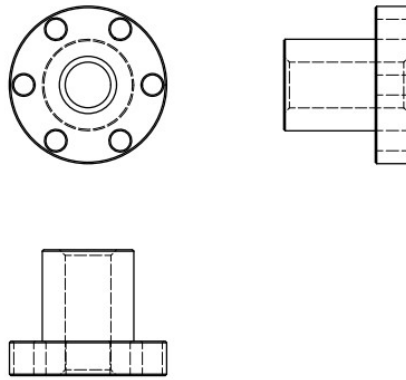


(b) 3D view of the Mount

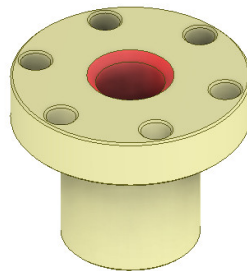
Figure 2.6: Mount design

Lead screw and Lead screw nut

This combination is the most important among the rheometer. The motion is driven based on the relationship between these two components. Because the mounts hold the lead screw in place at both ends, the force that rotates the lead screw from the top acts on the thread. The lead screw can be rotated by a handle bar or a motor. As a result, the lead screw nut will move along the lead screw in combination with the carrier as the lead screw turns. The diameter of the thread is 16 millimeters, and the pitch is 4 millimeters. The thread profile is a trapezoidal right hand.



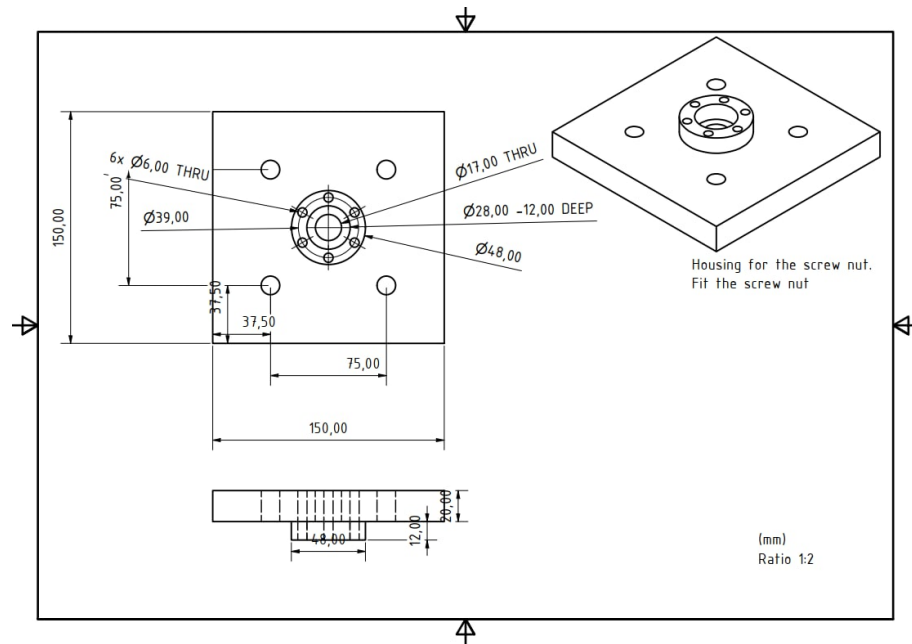
(a) CAD design of the Lead screw nut



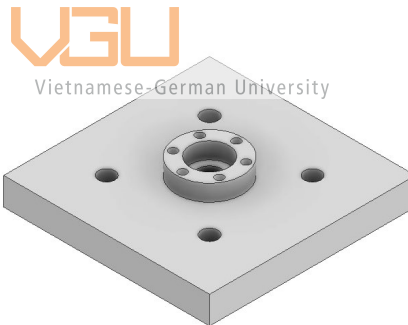
(b) 3D view of the Lead screw nut

Figure 2.7: Lead screw design

Going with this lead screw is a housing, which helps holding the lead screw nut with the carrier. Moreover, there will be room for future installation of the force measuring kit such as load cells or some sensor.



(a) CAD design of the housing for lead screw nut

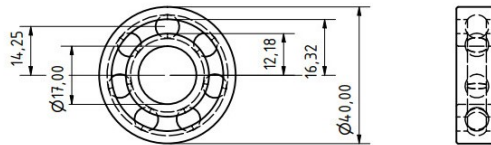


(b) 3D view of the housing for lead screw nut

Figure 2.8: Housing for lead screw nut design

Bearings

Single row deep groove ball bearings with shields are used in the design because they have low friction and are optimized for vibration, allowing for high rotational speed. They can accommodate radial and axial loads in both directions, are simple to install, and provide easy maintenance. The lubricant is kept inside the bearing and away from contaminants. The model of the bearing is SKF-6202 2Z.



(a) CAD design of the Bearing
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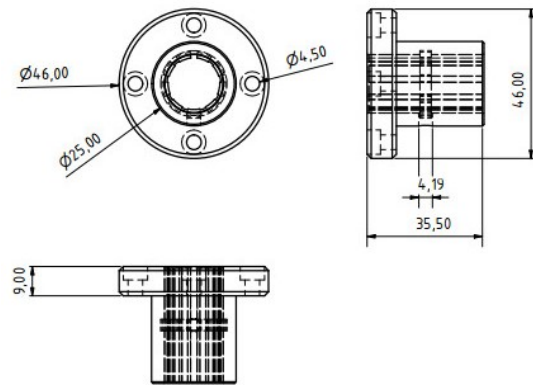


(b) 3D view of the Bearing

Figure 2.9: Bearing design

Guiding bearing

Guiding bearings are added to support the lead screw nut with the load and keep the carrier stable and avoid wobbling when tests are running.



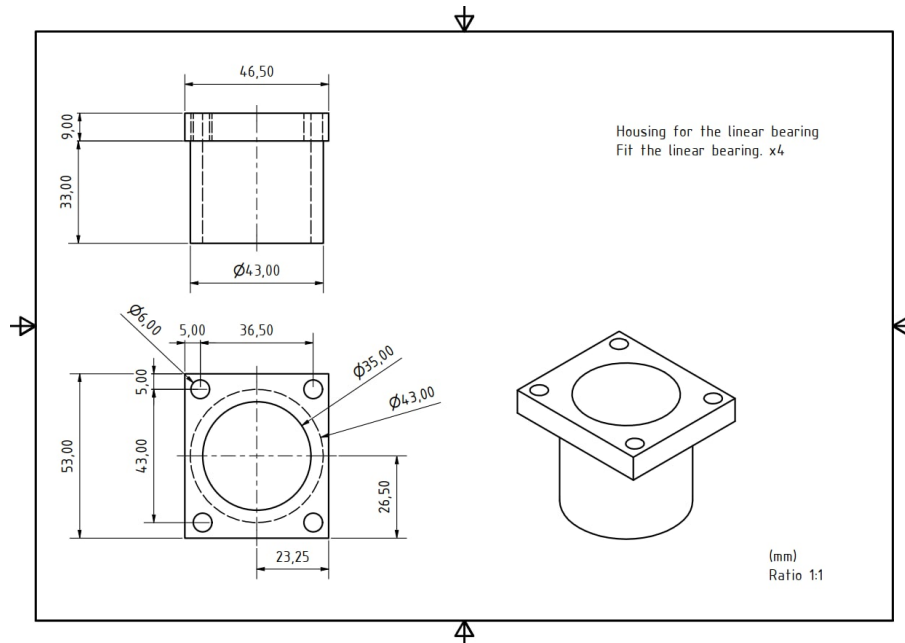
(a) CAD design of the Guiding



(b) 3D view of the Guiding

Figure 2.10: Guiding design

The linear bearing also needs a housing which helps connect the linear bearing with the carrier as well as guiding the movement of the carrier along the guiding shaft.



(a) CAD design of the Linear bearing housing



(b) 3D view of the Linear bearing housing

Figure 2.11: Linear bearing housing design

2.3.3 Motor and gear

For conceptualization, stepper motor is aimed for the purpose of the driving the lead screw as well as rotating the shaft propeller. The feature of the stepper motor makes it suitable for the requirement of low speed high torque. NEMA 34 is the size of the universal stepper motor that is utilized in the rheometer. For operating both the lead screw and the propeller shaft, two motor will have the same size 34 but different power. "34HE31-6004S" is the manufacturer number model of the motor used for turning the lead screw and "34HP44-6004S" is the model for the shaft. Both the motor speed can vary from 0 to 1000 rpm and the output torque will reduce according to the increasing speed of it. However, for the operation of the propeller there will be an additional gearbox paired with the motor in order to slow down the speed and increase the torque.

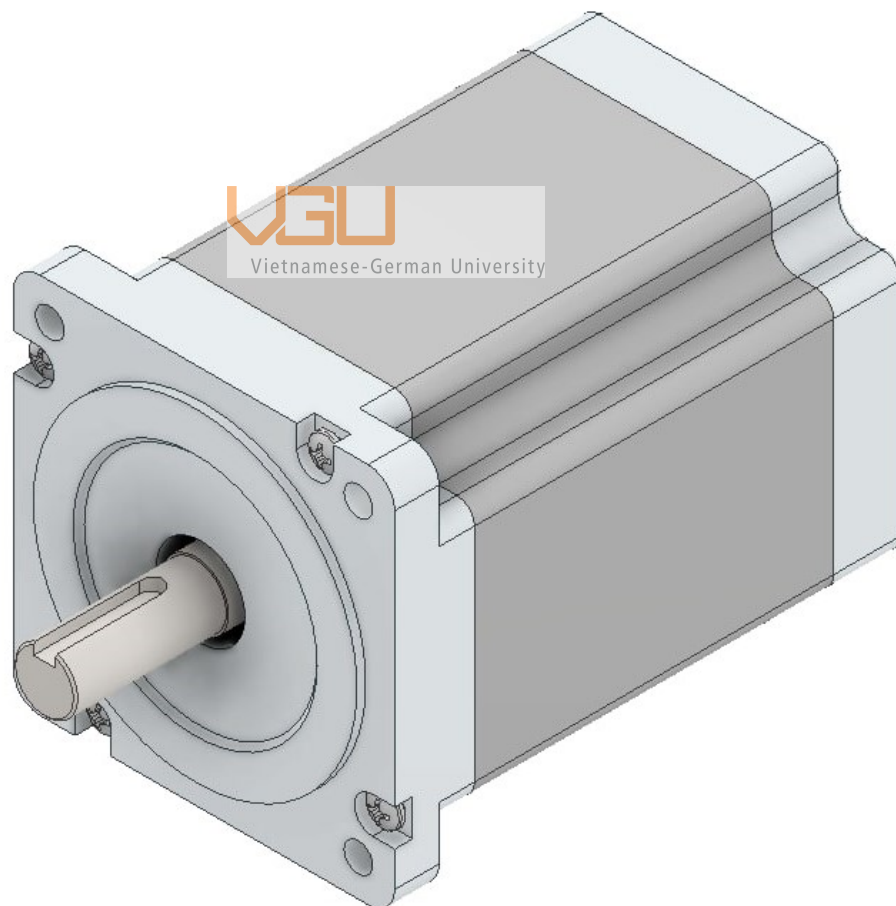
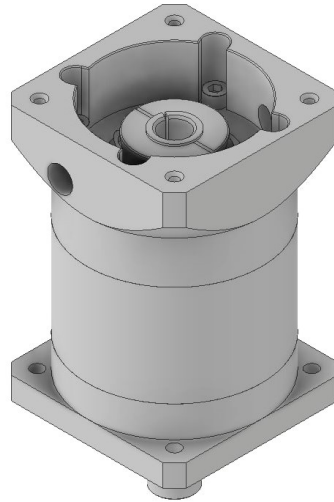


Figure 2.13: CAD model of the stepper motor size 34

The gearbox to go with the stepper motor Nema 34 is a high precision planetary gearbox with ratio 20:1. This has an in-line gearbox making it easy for installation. With a ratio of 20 to 1, the motor can provide sufficient torque at speed around 10 to 20 rpm. The drive shaft will connect to the motor, the driven shaft, blades and sensor vertically.



(a) Gearbox for stepper motor Nema 34



(b) Gearbox for stepper motor Nema 34

Figure 2.14: Planetary gearbox ratio 20:1 for Nema 34 stepper motor

Manufacturer Part Number	34HP44-6004S
Number Of Phase	2
Step Angle	1.8 deg
Holding Torque	8.2 Nm
Rated Current/phase	6.0 A
Inductance	5.0 mH \pm 20%(1KHz)
Weight	3.7 kg
Frame Size	86 x 86 mm

Table 2.2: Specification of Nema 34 Model 34HP44-6004S



Manufacturer Part Number	PLE34-G20
Gearbox Type	Planetary
Gear Ratio	20:01
Efficiency	94%
Max. Permissible Torque	90 Nm
Moment Permissible Torque	180 Nm
Noise	\leq 60dB
Lifetime	20000 hours
Frame Size	90 x 90 mm
Output Shaft	Φ 20 mm x 40mm
Input Shaft	Φ 14 mm x 40m

Table 2.3: Specification of the gearbox PLE34-G20

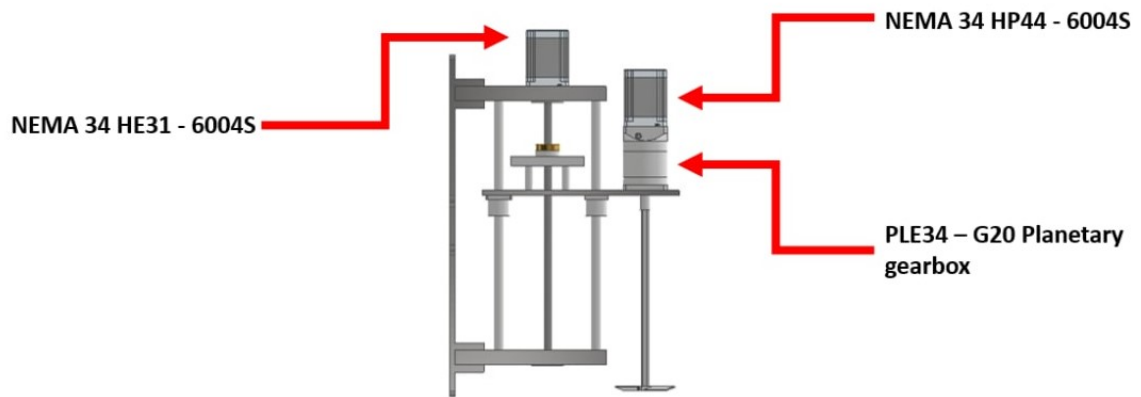
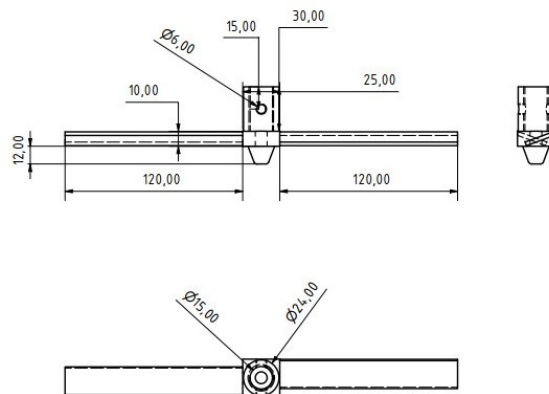


Figure 2.15: Motor and gear set up in the Rheometer.

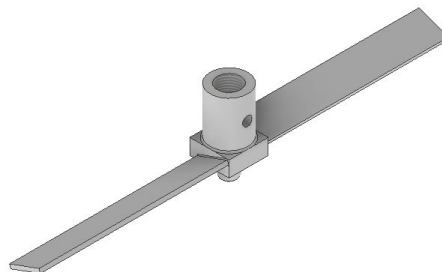
The reason for choosing the motors and gear will be discussed in the later chapter of the document. In conclusion, the two stepper motor will satisfy all the requirements of a Rheometer. One will operate the vertical motion and make sure that all the material along the container height will be included in the measuring process. The other motor will cover the rotation of the shaft and blade during the measuring process. Stepper motor allows the ability to maintain the desired speed of the lead screw and the gearbox enables the low speed of the blade.

2.3.4 Shaft and blades

The blade components play an essential role in the system. It has to be strong enough to stand the force and torque affected by the measuring process. The blades come from the design of the FT4 Rheometer. It has different profiles of the blades angle such as 10-15-20 degrees. The following design of blade will have a angle of 20.



(a) CAD design of the Blade
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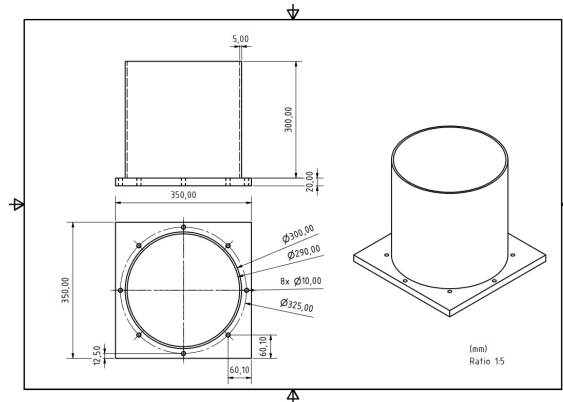


(b) 3D view of the Blade

Figure 2.16: Blade design

2.3.5 Container

The container is the place to store the testing material of the whole system. It needs to be steady and rigid enough to withstand the rotation of the blade, flow of the material inside when tests are running. The bottom will be designed with a plate and hole for grounding into the floor. The container's dimensions are 290 mm diameter, 500 mm height and 5 mm thickness. It provides a maximum volume of 33 liters of material.



(a) CAD design of the Container



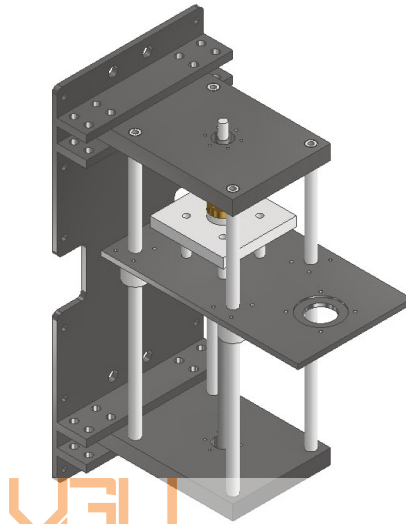
(b) 3D view of the Container

Figure 2.17: Container design

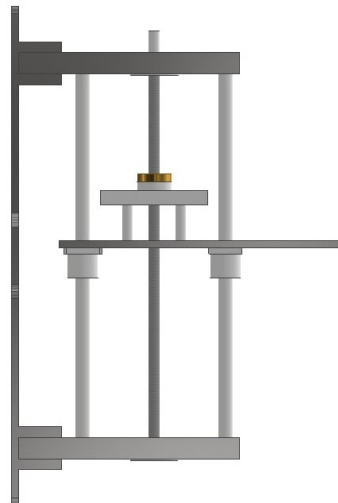
2.4 Mechanical Assembly

All parts of the rheometer will be assembled, installed on the plate which is then attached to the wall. The position of the container is placed depending on the shaft and blades axis. The center of the container must be coaxial with the shaft, it helps maintain the similarity throughout many test runs.

First of all, the whole linear actuator which is the lead screw must be assembled.



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(a) Lead screw drive assembly



(b) Lead screw drive assembly

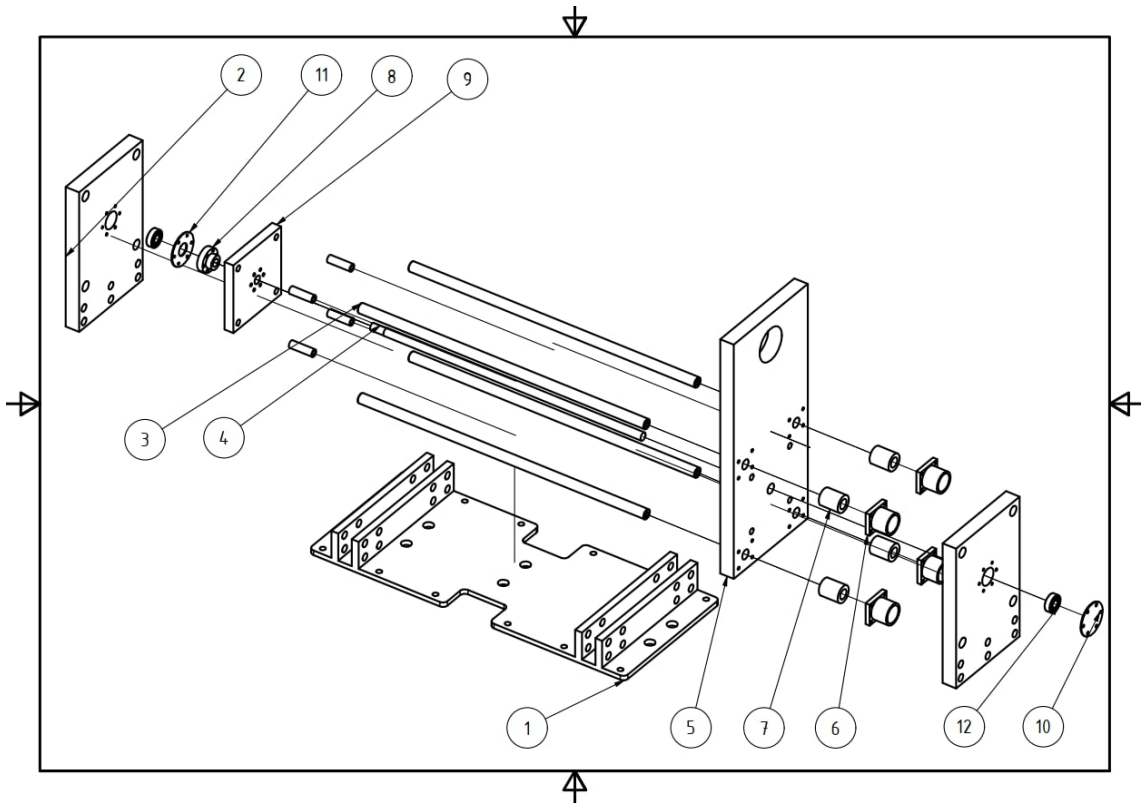
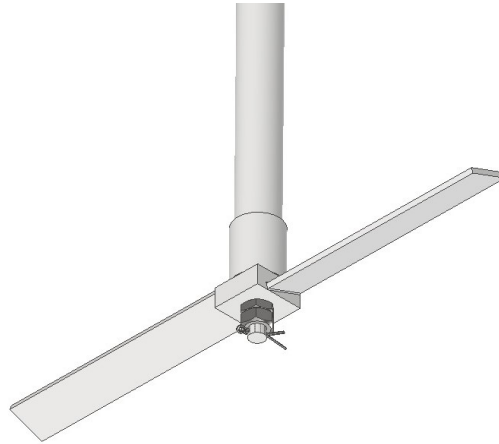


Figure 2.19: Lead screw drive exploded view with components

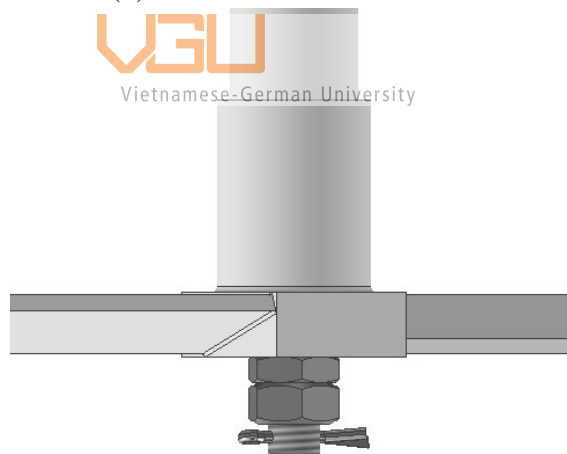
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Plate	
2	2	Mount	
3	4	Plain Guide	
4	1	Lead screw 570mm	
5	1	Carrier	
6	4	Linear bearing housing	
7	4	Linear bearing	
8	1	Spindle	
9	1	Spindle housing	
10	1	Flange cover	
11	1	Flange-hole cover	
12	2	DIN 625 SKF - SKF 6202-2Z	Inner diameter is 16mm
13	4	Connector	

Table 2.4: Part list of Lead screw drive installation.

Moving to installation of the blade. The connection between the shaft and the blade is held by a key and cone, which provide the stability of the blade when the shaft is rotating. At the end of the shaft, the outer part which is not covered by the blade is threaded. the hex jam, hex nut and cotter pin are install respectively as illustration in 2.20b.



(a) Blade and shaft overview



(b) Close up installation of the blade and shaft.

Figure 2.20: Blade and shaft connection

The following figures will demonstrate the whole system when it is installed properly according to the concept.

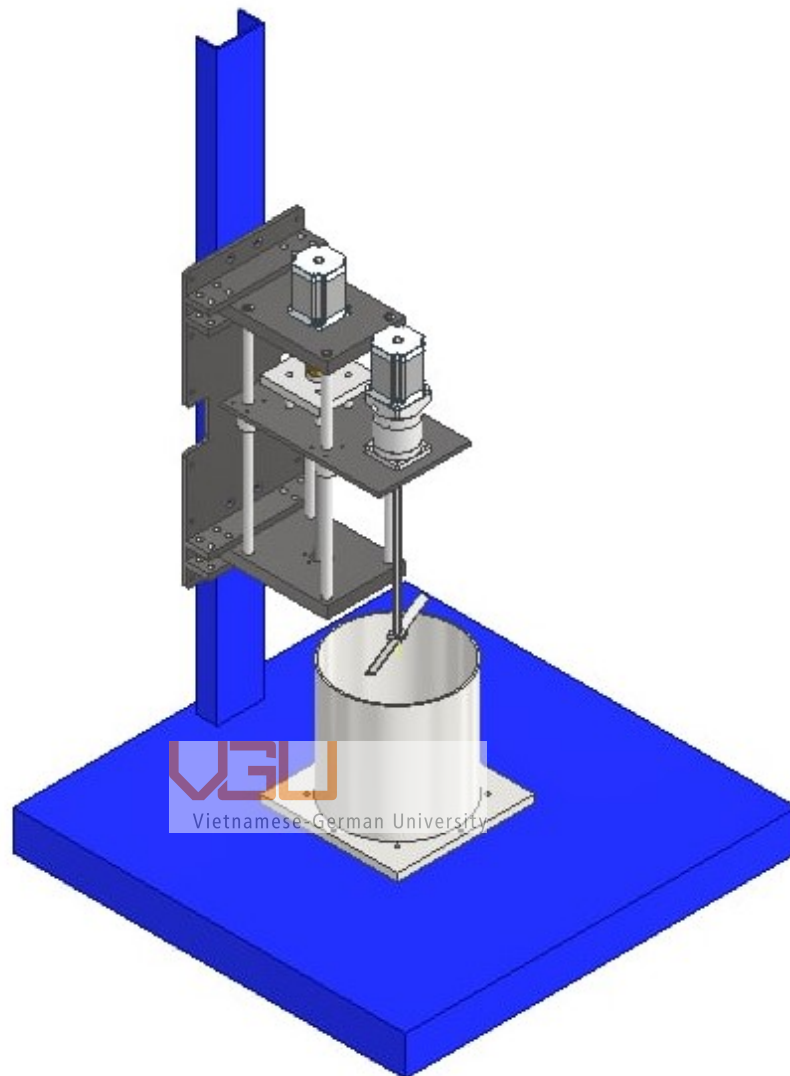
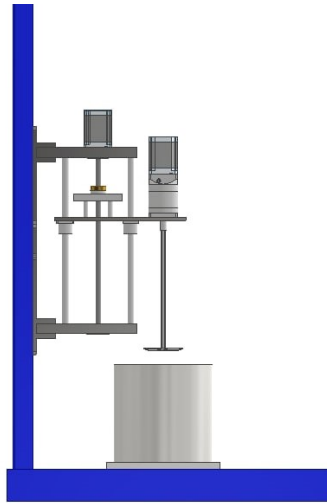


Figure 2.21: Fully assembly of the lead screw drive.



(a) Side view of the full assembly



(b) Front view of the full assembly

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Lead Screw Actuator	
2	1	20:1 Gearbox	
3	2	Nema 34	
4	1	Coupling	
5	1	Vessel	
6	1	Shaft Blade	

Table 2.5: Part list of Fully assembly

Chapter 3

Electrical design

3.1 Measuring Methodology

In principle, when the rheometer operates, the motors are controlled to give a consistent speed of the blade as well as the lead screw linear actuator. During the measuring process, there will be an electrical system recording the change of the torque and force applied of the rotating shaft and blade. Finding and applying a method of measuring both force and torque on the rotating shaft within a small budget is a challenge to overcome.



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3.1.1 Torque measuring methods

When it comes to determining how much torque is being applied to a rotating shaft, there are a few different options available to choose from depending on the specifics of the application. The following suggestions are some common methods to measure on an existing rotating shaft without modification and dis-assembly.

Power meter

Measuring the amount of power that is fed into an electric motor by means of a power meter is one of the more straightforward approaches to calculating the amount of torque that is produced on the shaft that is connected to the motor's output. The power input is determined by the meter by measuring the amount of current and voltage present in the line that is feeding the motor. The amount of electrical power that is inputted is then converted to an estimated amount of torque using the shaft speed (which is typically measured using a tachometer[3.1]) and the efficiency of the motor (usually specified by the motor manufacturer). Because this is not the actual mechanical torque but rather a relation from electrical power measurements to a theoretical torque value, it is referred to as an indirect measurement of torque. This

is due to the fact that it is not the true mechanical torque.



Figure 3.1: Measuring speed of the motor using tachometer.[Bukalapak,2022]



$$P = VI \quad (3.1)$$

$$T = \frac{9550.P}{\omega} \quad (3.2)$$

Where,

V : Voltage of the motor (V).

I : Current of the motor (A).

T : Torque applied (Nm).

P : Power (kW).

ω : Shaft speed (RPM).

Although this method can be easily installed and fairly inexpensive, it fails where accuracy is needed. The accuracy of this method is poor because the speed of the motor as well as the power can vary, which rely on a number of factors such as input voltage, varying load and temperature. Moreover, this method is not suitable for occasions when torque changes quickly, making the power meter not suitable for measuring torque in the rheometer system[5].

In-Line Torque Transducer

In-Line torque transducer or rotary torque sensor are used in many applications that require a torque measurement at a rotating shaft, engine or a stationary motor. In this particular scenario, the transducer is required to rotate in line while it is attached to the shaft. A slip ring or wireless electronics may be installed on a rotary torque transducer so that the torque signal can be transmitted while the device is rotating [5].

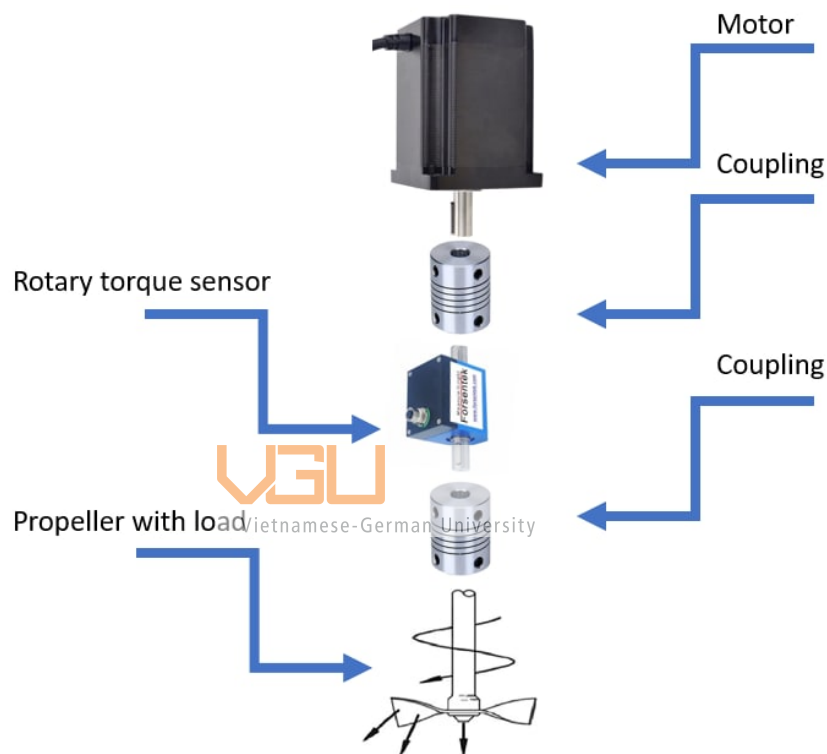


Figure 3.2: Set up for the rotary torque sensor.

This set up come with many advantages. Firstly , is the ability to use many different kin of blades. The propeller can be easily changed due to connection of coupling, different propeller for different materials can be utilized in torque measuring method. Some in-line rotary sensors along the shaft from different manufacturers can be used. The following are some available torque transducers that can be found online and come with supports.

-Forsentek: a Chinese manufacturer provides a measuring solution. The model FYTE-100-A and FYTE-200-A are considered suitable for the torque measuring of this system.

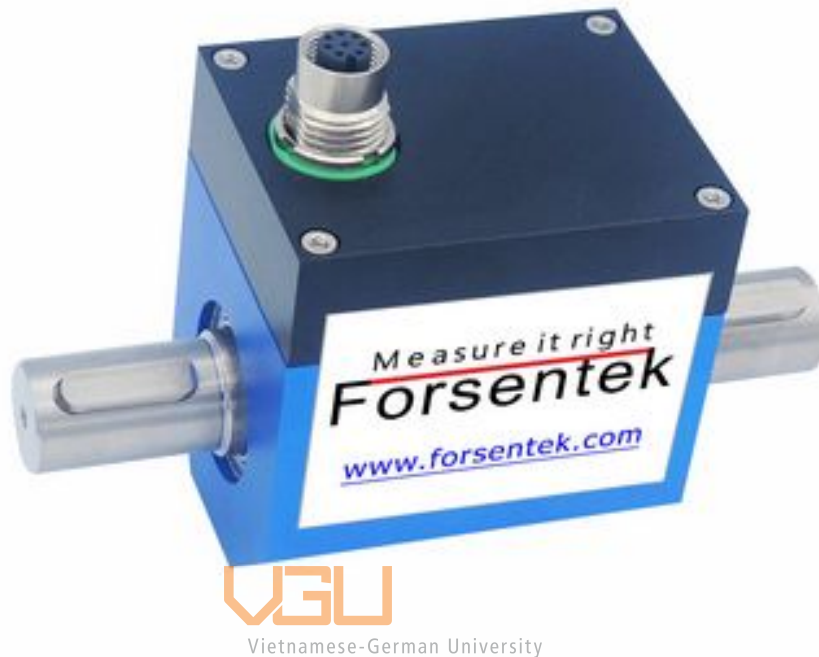


Figure 3.3: Forsentek rotary torque transducer Model FYTE [Forsentek, 2022]

Model	FYTE
Type	Rotary torque sensor
Structure	Shaft to shaft
Load direction	Clockwise & CCW
Rated output	$\pm 5V$ / $\pm 10V$ / 4-20mA
Excitation	24V / 12V
Capacity	0-500Nm
Price	900 Euro/pc

Table 3.1: Specification of Forsentek rotary torque sensor

-Futek: Measuring devices manufacturer provides rotary torque sensor with the model TRS605 which are suitable for the concept of the rheomete.



Figure 3.4: Futek rotatry torque transducer TRS605 series [Futek, 2022]

Model	FSH02059
Type	Rotary torquese sensor
Structure	Shaft to shaft
Load direction	Clockwise & CCW
Rated output	± 5 Vdc
Excitation	24V
Capacity	0-200Nm
Price	2000 Euro/pc

-Lorenz: Another manufacturer that provides precision torque measurement which can be applied in research. The model DR-2 is selected for the concept of the Rheometer.



Figure 3.5: Lorenz torque transducer DR-2 series [Lorenz-messtechnik gmbh, 2022]

Model	DR-2
Type	Rotary torquise sensor
Structure	Shaft to shaft
Load direction	Clockwise & CCW
Rated output	± 5 Vdc
Excitation	12V
Capacity	0-500Nm
Price	Unknown

Although this method is perfectly fit for the application, but the the price for each sensor is expensive and the the follow up accessories are costly as well. This will be remain as a proposal for further improvement or solution as well as proper investment with a careful process and set up team.

Surface mount using strain gauge

If budget is a big problem or a proper sensor can not be bought and used, there is a solution to overcome this challenge. That is the direct surface mount for torque measuring, which is based on strain gauges installed around the propeller shaft.

When the shaft rotates, the gauges will send the signal to the microcontroller. Then the signal will be processed to give out the measuring result.

3.1.2 Hardware component for surface mount method using strain gauge.

In this section, the component used for torque measurement of the rheometer system is introduced.

Strain gauges

Strain gauge is a kind of sensor installed on the surface of measurement, which measures the change of electrical resistance due to the relative variation of strain. This strain is the result of deformation or translation of the material under the impact of applied stress. Force applied to the materials divided by the cross sectional area is the stress. In general, force, torque, pressure etc. cause strain in the material, which is then measured by the strain gauge and converted into electrical signal [6].

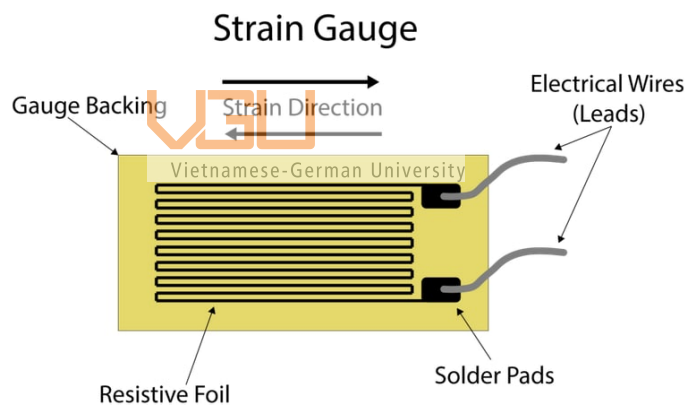


Figure 3.6: Strain gauge [MichSci,2020]

In order to create electrical signals for measuring, the strain gauges require a voltage source or known as excitation voltage typically 5 V. When deformation happens in the strain gauge, its resistance changes according to the strain and creates voltage difference.

ADC amplifier board

Due to the fact that the change of resistance of the strain gauge is relatively small, the signal is pushed into an amplifier and changed to readable and more powerful such as 0-10 VDC, 4-20 mA, +- 10 VDC, RS485 , RS232 and USB. For this rheometer electrical set-up, the amplifier board HX711 is selected for playing a role of measuring the signal from the strain gauge and converted to electrical signal for

the microcontroller.

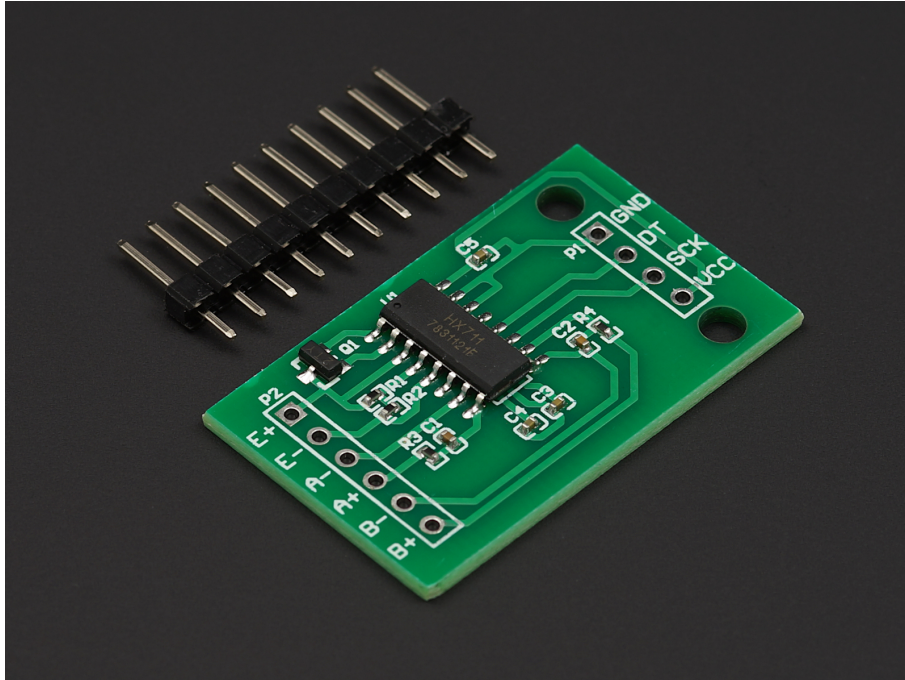


Figure 3.7: HX711 amplifier board [Sparkfun]

HX711 is a precision 24-bit analog-to-digital converter (ADC) designed for application of bridge sensors. The board can go well with the microcontroller with the available pin outs using data and clock pins. This has input voltage from 2.7V to 5V, enabling the ability to pair with 3.3V or 5V micro controller operations. This board is widely applied in recording signals from strain gauge bridges of load cells, which have the same working principle.

Excitation voltage	5-10V
Differential input channel	2
Low noise PGA gain	32, 64, 128.
Output data rate	10SPS / 80SPS
Operation temperature range	from -40 to 85 degree Celcius

Micro controller

The chosen micro controller for controlling the measuring system is Arduino Uno, which is based on the ATmega328P. Arduino Uno is developed by Arduino.cc and is marked as the first Arduino board (UNO means "one" Italian). Coming with the Arduino Uno is the Integrated Development Environment (IDE) software, which is used to draft, compile programs and load code for the microcontroller[[7]].



Figure 3.8: Arduino Uno R3

This board is among one of the most popular open source microcontroller used for electrical projects buildings. The board can be programmed from the personal computer through a type B USB cable which also power the whole board. Or it can be powered from a 9 V battery.

Controller	ATmega328P
Operating Voltage	5V - 9V
Analog pins	6
Digital pins	14
Frequency	16 Mhz
Flash memory	32 Kb

The Arduino is not only easy to use but also it can drive the amplifier and provide the essential excitation voltage. Therefore, the Uno is one of the most suitable micro controllers to pair with the whole system.

3.1.3 Torque measuring using surface mount method

This part will focus more deeply into the methodology of using the surface mount. For this shaft measuring, two pieces of two-element 90 degree rosette aluminum CEA-13-062UV-350 from Micro Measurement VPG (Fig. 3.9) or equivalent specification will be utilized to form a full bridge strain gauge. In this grid, there will be 2 strain gauges parallel and 2 angled 90 degrees for each other.

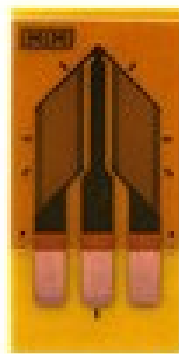


Figure 3.9: Half bridge torsion strain gauge CEA-13-062UV-350 [Micro Measurement]

This full bridge configuration will be installed along the shaft and blade of the rheometer, each of the aluminum strain gauge is located on the two opposite sides

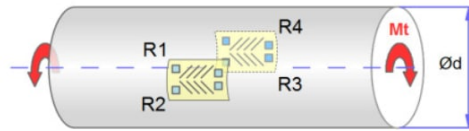


Figure 3.10: Wiring diagram of the Wheatstone bridge circuit for torque measurement [ME-meßsysteme,2022]

of the shaft according to Fig. [3.10].

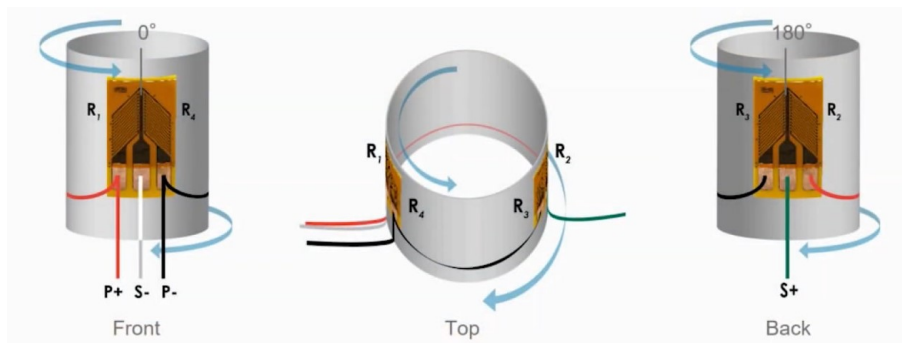


Figure 3.11: Wiring and orientation of the two strain gauges on shaft [Micro measurement,2022]



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The purpose of using two pieces of this type of strain gauge is to create a Wheatstone Bridge (Fig. 3.12) grid with each resistance is 350 ohms. This configuration provides linear outputs and compensates well with temperature. With this popular design, the measurement can cancel the effects of bending and axial load. However, it requires careful and precision gauge orientation and placement for the best result.

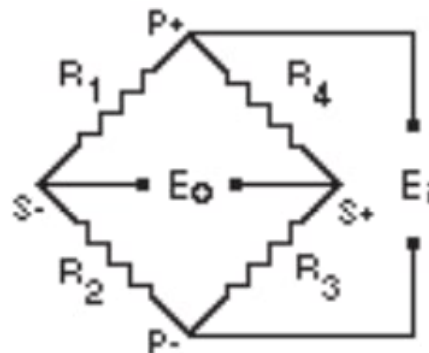


Figure 3.12: Wheatstone bridge used for torque measurement of the rheometer [Micro measurement, 2022]

The output of the bridge can be written as:

$$\frac{E_o}{E_i} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \quad (3.3)$$

Where E_o represent the output voltage of the bridge and E_i is the excitation voltage of the bridge. R_1, R_2, R_3 and R_5 are the resistances of the gauges. When there is no load, the bridge is considered balanced and no output is produced then:

$$\frac{R_1}{R_1 + R_2} = \frac{R_4}{R_3 + R_4} \quad (3.4)$$

or

$$\frac{R_2}{R_1 + R_2} = \frac{R_3}{R_3 + R_4} \quad (3.5)$$

During the measuring process of the rheometer, there will be an increasing load acting on the shaft when the shaft and blade hit the material. Under the effect of the material, the change of the resistances of the gauges will make the bridge unbalanced which lead to the variation of the output voltage. By using a 5 V excitation voltage from the Arduino Uno microcontroller, the HX711 can convert the analog signals which are the change of the gauge resistances into digital signals by measuring the output voltage of the bridge. The output signal from equation [3.3] is recorded continuously during the measuring time of the rheometer. After completing the rheometer measuring cycle, the set of collected data needs an additional step to get the desired result of torque. The relation between the voltage output and the strain caused by torque is:

$$\frac{E_o}{E_i} = \frac{F\gamma}{2} \quad (3.6)$$

$$\gamma = 2\varepsilon = \frac{4T}{\pi R R^3} (1 + \nu) \quad (3.7)$$

Where,

F : Gauge factor usually equals 2 for thin metal gauge.

R : Radius of the measured shaft.

E : Young modulus of the shaft.

ν : Poisson ratio of the shaft.

T : torque acting on the shaft.

From the two equation (3.6) and (3.7), the result of the acting torque on the shaft

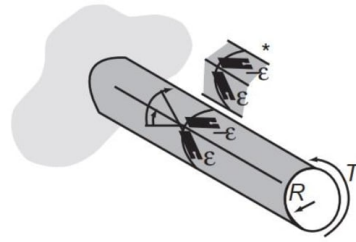


Figure 3.13: Torque acting on a rotating shaft.

can be achieved:

$$T = \frac{E_o}{E_i} \frac{\pi ER^3}{2F(1 + \nu)} \quad (3.8)$$

Assume that the temperature does not change drastically during the measuring cycle, the constant such as the gauge factor F and properties of the shaft are not affected, the result of torque is changed linearly according to $\frac{E_o}{E_i}$. The result of torque acted on the shaft can be measure and used from the equation [3.8].

3.1.4 Wiring Block

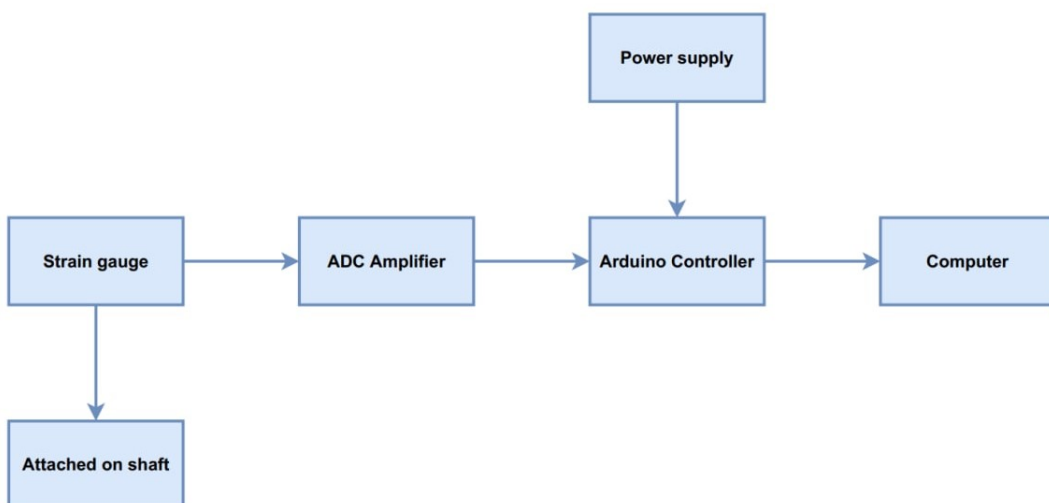


Figure 3.14: Block diagram of surface mount measure with strain gauges.

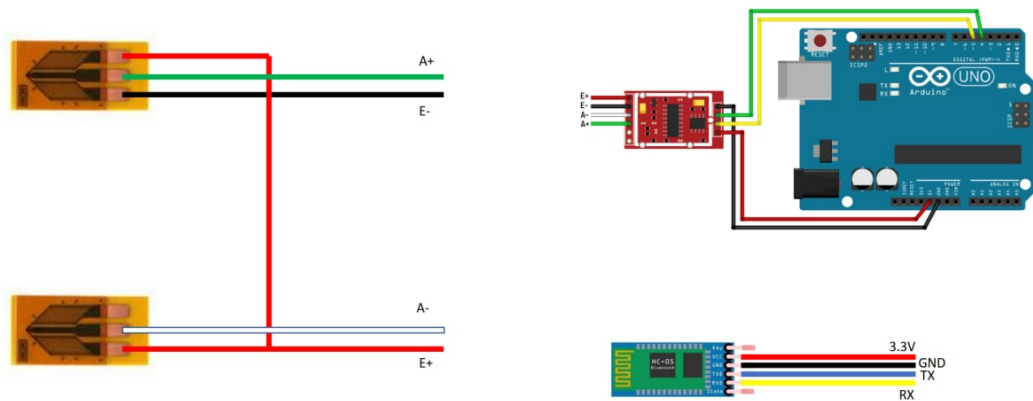


Figure 3.15: Wiring diagram of surface mount measure with strain gauges.

In [3.15], it shows the way to setup the strain gauge and connection between the strain gauges and ADC amplifier and microcontroller. With physical properties of the rotating shaft, additional wireless connection such as Bluetooth is needed if the controller lacks memory write capability.

3.1.5 Force measuring methodology

In the rheometer, the force needed to push down the propeller through the container is the main force to be measured. In the concept, the screw nut is covered inside a housing, which is attached to the carrier plate. Raising force or lowering force mainly appear in the lead screw rod and then convert through the screw nut, the carrier plate and the propeller respectively.

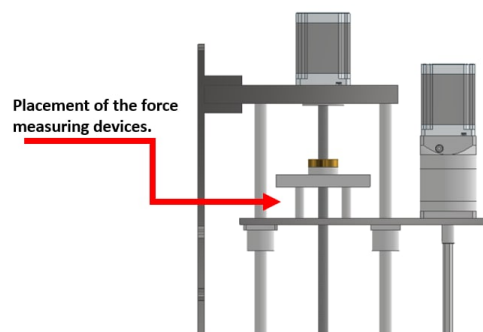


Figure 3.16: Possible placement of force measuring instrument

The idea of measuring the force needed for the measuring process is to measure the

force between the lead screw nut and the carrier plate. In Fig [3.16], it can be seen that there is room left for the installation of a possible force sensor between the lead screw nut and the carrier plate. When the lead screw is lowering the plate, it is the compression of the screw nut into the carrier plate. When lifting the plate, it is where the tension happens. The lead screw nut lift the plate up. To measuring both the compression and tension, it is suitable to use load cell as the force measuring device in this application.

The most suitable type of force measuring device is the compression and tension column load cell. The load cell will be installed between the lead screw nut housing and the carrier plate. It is secured to the plate by using screws.

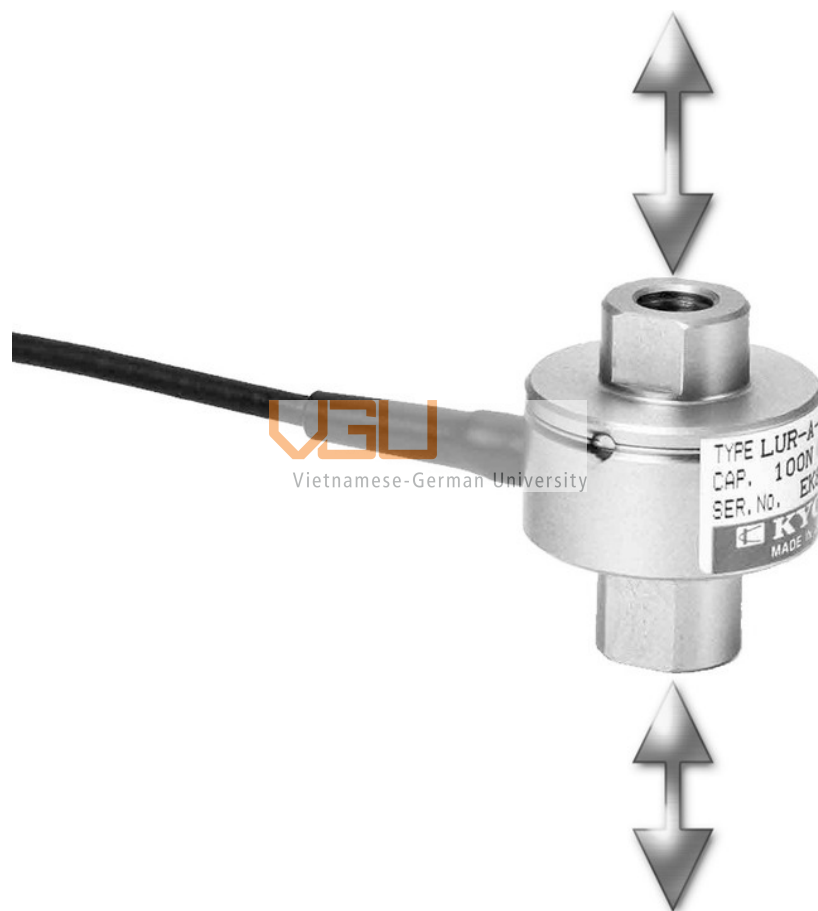


Figure 3.17: Direction of force acting on compression and tension load cell [ZSE GMBH, 2022]

The following are some available compression and tension load cell that can be found online and come with customer support:

-Bransensor: A column type compression and tension load cell (B317) made of stainless steel. This model can fit to the tight and limited space design of the rheometer concept. This model has the capacity ranging from 20 N to 2000 N.



Figure 3.18: Bransensor compression and tension column load cell [Bransensor, 2022]

Forsentek: S beam load cell FSH04470 tension and compression load cell is suitable for larger space and the gap between two plates is spacious. The connection of this model is thread for holding plates together.

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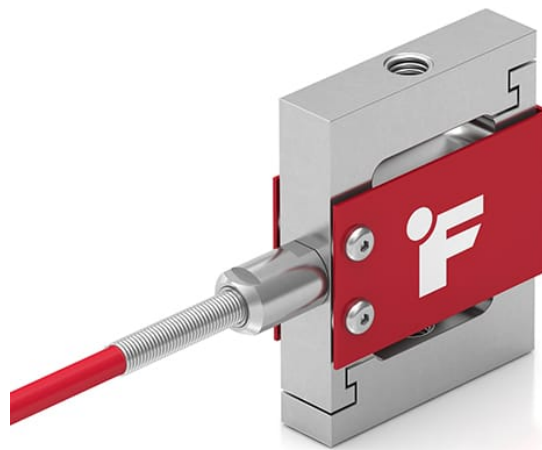


Figure 3.19: Futek compression and tension S beam load cell [Futek, 2022]

3.2 Driving methodology

In the operation of Rheometer, it is important to maintain the motor at a constant while the load is varying. The motor must provide the a required rotation speed for converting to other type of motion speed.

For the control of the stepper motor, a driver module is needed to drive the motor. In this concept, two separate drivers will be used for two motors independently.

3.2.1 Stepper motor driver DM860I

The DM860I is a DSP based digital stepper driver which can provide smooth motion control technology. It can also operate at low noise while driving a large stepper motor, which makes it suitable for this specific rheometer concept. The driver has many configuration input steps ranging from 400 to 40000. Having multiple choices of step allows a low step resolution, which provides smoother motor movement.



Figure 3.20: DM860I digital stepper driver [Stepperonline, 2022]

Model	DM860I
Output Peak Current	2.47.2A
Input Voltage	2080VDC
Logic Signal Current	716mA
Pulse Input Frequency	0200kHz
Pulse Width	2.5 μ S
Weight	550g

Table 3.2: Specification of DM860I digital driver.

3.2.2 Power supply

This suggested power supply can be used in this rheometer concept for providing power for the motors. Its high efficiency while being low cost makes it suitable for the concept.



Figure 3.21: 24V Power Supply Stepper Motor [Stepperonline, 2022]

Output	24V DC 16.7A
Input	93 $\tilde{}$ 132V/176 $\tilde{}$ 264VAC
Switch selection	115V/230V AC
Cooling	Built-in DC fan

Table 3.3: Specification of the 24V power supply.

3.2.3 Wiring diagram

This is an example of wiring a stepper motor set up using micro controller and driver module.

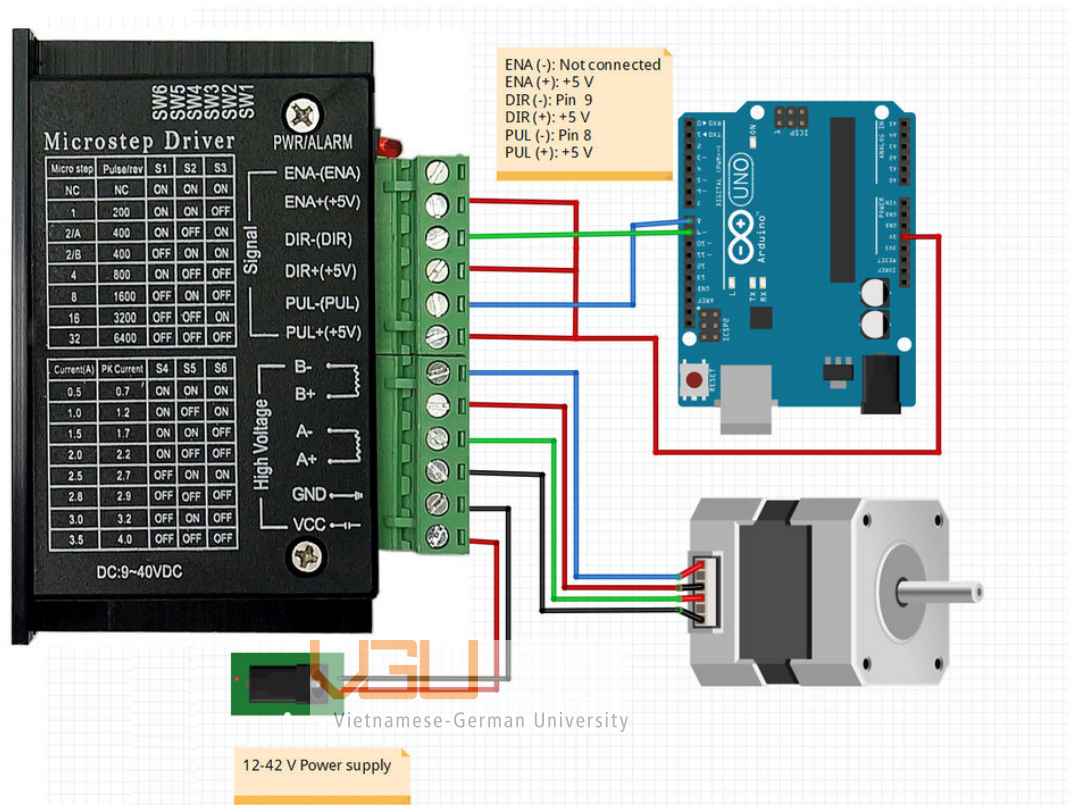


Figure 3.22: Wiring scheme for the driving methodology [Curiousscientist, 2020]

Chapter 4

Analysis and Prototyping

4.1 Analysis

This part is focusing on breaking down the detailed technical information about the whole system. The torque needed to raise and lower the carrier, motor as well as the shaft blade system through the testing container. The torque needed and speed for the motor to achieve desired motion of the Rheometer.

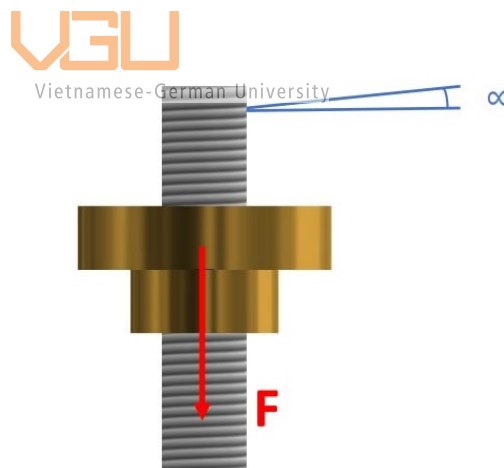
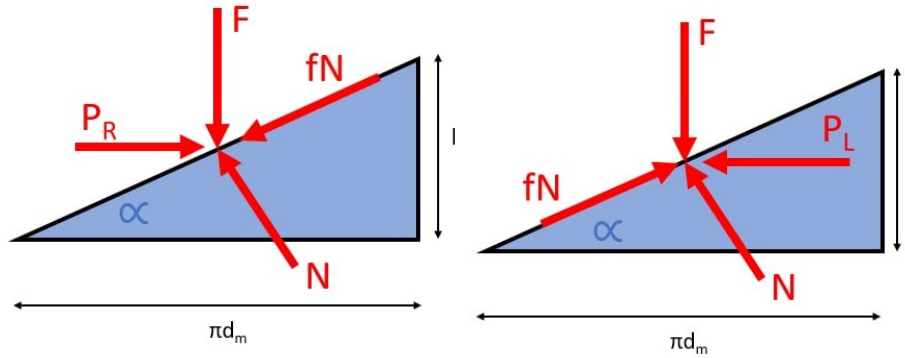


Figure 4.1: Portion of a lead screw and lead screw nut.

In the system, a lead screw which is provided from the workshop has mean diameter d_m , a pitch p , a lead angle α and the lead screw is under load by the axial force from the carrier. The mean diameter is the average of maximum outer diameter and minimum inner diameter. The pitch of the lead screw can be known as the vertical displacement of the nut when the lead screw performs a complete revolution. Compressive force F coming from the rheometer acting on lead screw and the lead angle are illustrated in fig[4.1].



(a) Raising the lead screw nut. (b) Lowering the lead screw nut.

Figure 4.2: Force diagram.

First, an exact single turn or a revolution is carried on and the thread of the screw is unwrapped and developed. A triangle is formed with the hypotenuse edge is the thread of the lead screw, the base is the circumference of a circle with the diameter d_m and the height of the triangle is the pitch of the lead screw ($l = p$).

In Fig[4.2a] and Fig[4.2b], the friction force (fN) is the product of the normal force N and the coefficient of friction of the lead screw whose direction is opposite the direction of the lead screw. Fig[4.2a] shows when raising the lead screw a force P_R acting to the right side, and Fig[4.2b] shows when lowering the lead screw a force P_L acting to the left side. All the force are acted on the diagram, the system is in equilibrium state so that for raising the lead screw nut there are:

$$\begin{aligned}\sum F_x &= P_R - N \sin \alpha - fN \cos \alpha = 0 \\ \sum F_y &= -F - fN \sin \alpha + N \cos \alpha = 0\end{aligned}$$

Similarly, for lowering the lead screw nut there are

$$\begin{aligned}\sum F_x &= -P_L - N \sin \alpha + fN \cos \alpha = 0 \\ \sum F_y &= -F + fN \sin \alpha + N \cos \alpha = 0\end{aligned}$$

Although there is normal force N , but it is not the main consideration so it is eliminate from each other of the equation. And the force for raising the load is

$$P_R = \frac{F(\sin \alpha + f \cos \alpha)}{\cos \alpha - f \sin \alpha} \quad (4.1)$$

and for lowering the lead screw, the force is

$$P_L = \frac{F(f \cos \alpha - \sin \alpha)}{\cos \alpha + f \sin \alpha} \quad (4.2)$$

After that, using the relation of trigonometry $\tan \alpha = l/d_m \pi$ and the torque is the product of the force and the lever arm $d_m/2$. Therefore, the torque required to raise and lower the lead screw are resulted respectively[8],

$$T_R = \frac{F d_m}{2} \left(\frac{l + \pi f d_m \sec \alpha}{\pi d_m - f l \sec \alpha} \right) \quad (4.3)$$

$$T_L = \frac{F d_m}{2} \left(\frac{\pi f d_m \sec \alpha - l}{\pi d_m + f l \sec \alpha} \right) \quad (4.4)$$

Where the T_R is the torque to overcome the friction and raise the lead screw nut. More over there is one condition which is called self-locking. The condition for self locking is

$$f > \tan \alpha \quad (4.5)$$



The results are applied for the Acme lead screw or trapezoidal lead screw. And now all the parameters of the lead screw used for the rheometer are taken into account for the calculation.

The parameters are,

$$d_m = 15 \text{ (mm)}$$

$$l = 4 \text{ (mm)}$$

$$\alpha = 5 \circ 16'$$

$$f = 0.2$$

$$F = 700 \text{ (N)}$$

The given lead screw from the workshop has the maximum outer diameter of 16 mm, the lower inner diameter of 14 mm, which result in the mean diameter $d_m = 15$ mm. Its pitch or lead step is 4 mm. The coefficient of friction is obtain from the two material steel (lead screw) and brass (nut), which are $f = 0.2$ [8]. The estimated maximum load can be up to 700 N for many range of the material that can be applied in the future testing run. From the all available parameter combined with the equation[4.4]. The result for torque need to raise the lead screw and lower the

lead screw are respectively,

$$T_R = 1.525(Nm)$$

$$T_L = 0.598(Nm)$$

and the self locking condition are satisfied ($0.2 > 0.09$) so the the rheometer will not lower by its weight.

Next, the speed of the motor should be taken into consideration, because the velocity of the vertical movement is directly dependent on the speed of the motor. It is known before, 1 revolution of the motor shaft will result in 1 revolution of the lead screw and the lead screw nut will be lifted or lowered by its lead 4 mm. The relation of the velocity of the nut, the lead step and motor speed can be explained as:

$$V = l \frac{N}{60} \quad (4.6)$$

Where,

V : Vertical velocity of the nut.

l : Lead step of the lead screw.

N : speed of the motor (RPM)

Due the limited length of the given lead screw, the possible travel length of the nut is around 300 mm. The desired measurement vertical speed of the nut or blade can be control according to the table[4.1]

Motor speed (RPM)	150	225	300	375	450
V(mm/s)	10	15	20	25	30
Time 1 way (s)	30	20	15	12	10
Time cycle (s)	60	40	30	24	20

Table 4.1: Table of relation between motor speed, velocity and time cycle for lead step of 4 mm.

Overall, the suitable motor for controlling the vertical movement of the rheometer can be narrowed down. The possible motor for this application is the NEMA 34 (34HE31-6004S), which can provide the maximum torque up to 4.8 Nm.

From the [4.3], relation of the motor speed, screw nut translation, and torque can be found:

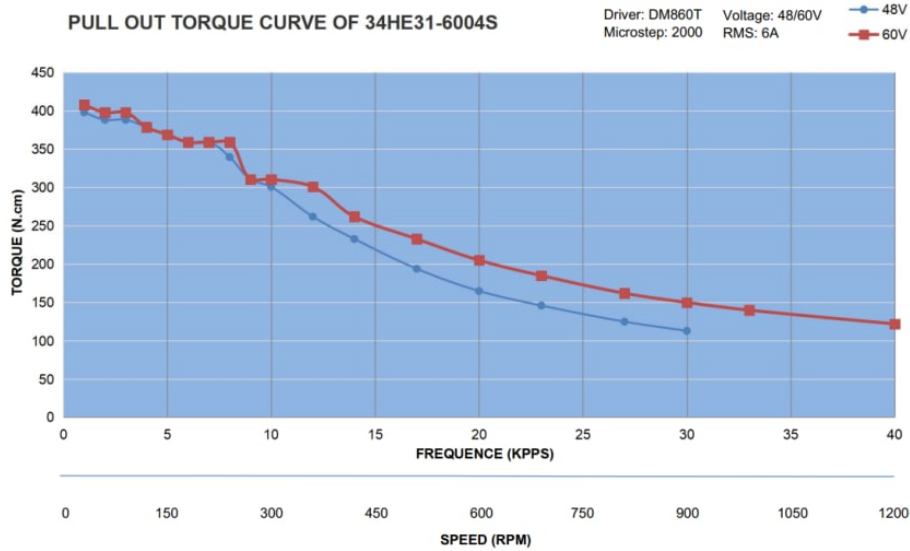


Figure 4.3: Torque curve of the Nema 34 34HE31-6004S at 1/2000 micro step.[Stepperonline, 2022]

Speed (RPM)	Torque (Nm)	Screw nut speed (mm/s)
450 (60V)	2.5	30
375	2.7	25
300	3	20
225	3.5	15
150	3.7	10

Table 4.2: Motor speed, torque and screw nut speed relation.

4.2 Prototyping and Simulation

Up to now, there is not enough information about the many concepts or similar documents for prototyping the Rheometer. This concept will be built from scratch, assumption and simulation.

For the motor which is used for rotates the shaft and blade, a power tool Fig [4.4] borrowed from the workshop with the specification of 60Nm and speed from 0-600 RPM are use for getting requirements for the motor.



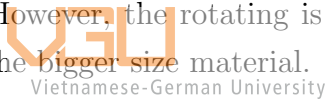
Figure 4.4: Power tool Bosch Professional GSR 18V 60 Nm [Bosch, 2022]

Firstly, the shaft and blade are made from steel and connected to the power tool. The power has many different rotational speeds combined with the propeller. After that, a bucket with 25 cm diameter and 30 cm height is filled with sand and gravel. The power tool set up is then pushed down by hand simulating the vertical translation motion of the rheometer. The process is repeated with the same power and different speed for each material. By this way, the basic amount of torque can be retrieved from the simple test.

Power tool speed (RPM)	Depth of trial 1 (cm)	Depth of trial 2 (cm)	Depth of trial 3 (cm)
30	16.5	18	16
60	23	21	22.5
120	25	25	25

Table 4.3: Trials tested on sand and small stone (1 mm to 5 mm).

From table [4.3], it can be seen that with constant 60 Nm, the higher the rotating speed of the power tool the less effort it took to get the propeller through the container. With 30 RPM, the propeller will work as expected according to the concept of the rheometer but it will not make it to the bottom of the container by hand. At the speed of 60 RPM and 120 RPM, the propeller will make it to the end of the container with ease. However, the rotating is too high that it will dig up the material as well as crush the bigger size material.



Power tool speed (RPM)	Depth of trial 1 (cm)	Depth of trial 2 (cm)	Depth of trial 3 (cm)
30	8	7.5	8.5
60	14.5	15	15.5
120	25	25	25

Table 4.4: Trials tested on gravel(1 cm to 3 cm)

In table [4.4], It is harder to dig in the container when the particle size of the material is bigger. With 60 RPM, the depth that the propeller can go through with hand is around 8 cm. For the high speed of 60 RPM and 120 RPM, the result is similar to the one of sand, although the blade can reach to the bottom, the propeller will damage the testing material and create non uniformity for the later test.

In conclusion, the rheometer will need more than 60 Nm for the propeller to rotate constantly lower than 30 RPM such as 10 RPM or 15 RPM. Torque around 120 Nm is predicted to be sufficient for the operation of the propeller at low speed.

The lead screw nut is responsible for the linear motion of the rheometer through the screw and the motor. It has to carry the weight of the carrier, motor, shaft and blades as well as bearing the load from the screw to drive the blades through the testing material. The assumed total weight applied on the screw nut is around 700 N when the rheometer is at stationary state. The simulation is roughly conducted on Autodesk Inventor 2019 software, the material assigned to the screw nut is brass.

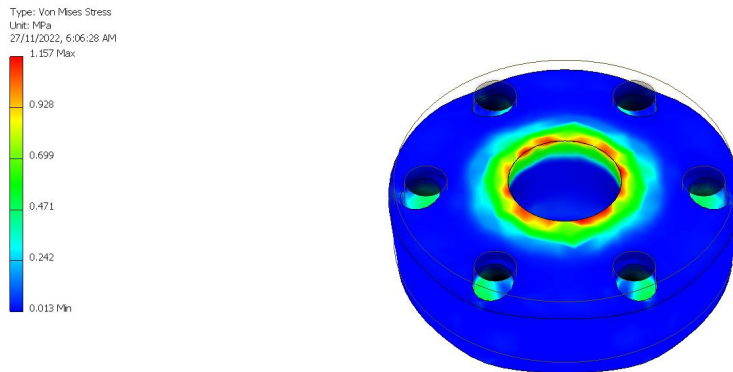


Figure 4.5: Stress distribution on the screw nut.

In the simulation the force acts along the screw nut inner diameter, where there is the connection between the nut and the lead screw. The Fig [4.5] shows that the maximum stress is on the top edge of the screw nut flange and it is 1.157 MPa. The simulation from Autodesk Inventor 2019 with its built-in library for brass material, it can be believed that the provided screw nut can withstand the load of the rheometer as well as the force needed to move the rheometer throughout the measuring process.

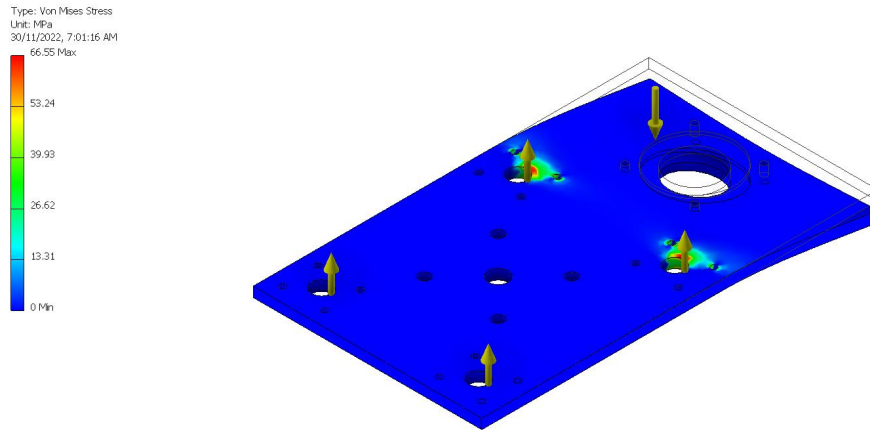


Figure 4.6: Simulation on the carrier plate.

Moving to the carrier, the plate is simulated to hold the weight of the motor as well as the acting force when running the test. The thickness of the plate is 10 mm and the result from Autodesk Inventor 2019 shows that the plate will not fail with the load. Beside with the support from four linear bearing housing, the carrier plate will be strengthened and become more stable and durable.

Chapter 5

Conclusion and Future Work

5.1 Conclusions

After all the working process, the concept of the instrument have already meet up with the requirement needed of a rheometer:

- Perform constant rotation movement inside the testing material.
- Perform constant vertical translation of the blades through all the testing material inside the material container.
- Methodology for measuring force and torque acting on the propeller.
- Achieving a module design which means the set up of the rheometer is flexible, components of the concept can be easily change according to the usage.

By looking through the concept, the instrument will fulfill the properties of a rheometer. However the cost needed to construct a proper rheometer that can fit the industrial scale and provide data for research and working applications is expensive. As a result, this remains as a proposal for constructing a rheometer. In case if there is someone interested in the concept and has the sponsor and equipment, that person can follow the proposed concept and can guarantee a successful working rheometer. The key point of the rheometer for cohesive bulk material and granules has been solved and that is the two motions during the test. The constant rotation of a propeller is carried on by a stepper motor and the constant vertical translation of the propeller is operated by a lead screw drive. Although the construction part was not successfully conducted, the prototyping and experiments had formed a basic foundation of constructing a rheometer as well as the selection of the whole system components such as motors, sensors etc.

During the making of the thesis, I have utilized all the knowledge I have learned in academic years. Furthermore, extra skills such as microcontroller programming skill and simulation have been achieved during the conceptualization process of the rheometer.

5.2 Further work

During the development and construction process, there are many remaining problems and flaws that need to be improved in the future construction.

5.2.1 Mechanical aspect

On the side of mechanical design, the overall shape of the rheometer is formed but the whole system is still bulky and not optimized. Some thickness of the components part can be recalculated in order to reduce the thickness as well as the total weight of the system. The Rheometer has achieved the module design but still not optimized.

5.2.2 Electrical and control aspect


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In terms of electrical components, besides the disadvantages of the measuring sensors such as expensive installation service and so on, the alternative solution of using strain gauge still needs some improvement in the future. In case of accuracy and the quality of the torque measurement, the strain gauge installation process needs careful chemical treatment and proper angle placement to give out the best result. Since the torque measurement takes place while the shaft is rotating, direct connection between the microcontroller and personal computer is not possible. Therefore, a wireless connection method or data storage is needed in the measuring process. Moreover, the rheometer can be optimized by program a automatic process, where the system perform a cycle of measurement without the the help of human.

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