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RUHR-UNIVERSITÄT BOCHUM

MechEng
Mechanical Engineering



Vietnamese-German University

DESIGN, FABRICATION AND TESTING OF MAGNETORHEOLOGICAL DAMPER FOR PROSTHETIC LEG

BACHELOR THESIS



Vietnamese-German University

HO CHI MINH 2023

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DESIGN, FABRICATION AND TESTING OF PROSTHETIC LEG

A Thesis presented

By
NGUYEN ANH VU

Submitted to the department of Mechanical Engineering of the

RUHR-UNIVERSITÄT BOCHUM and VIETNAMESE-GERMAN UNIVERSITY



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DESIGN, FABRICATION AND TESTING OF
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Approve by :
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Abstract

This thesis was produced to fulfill the requirements for the Mechanical Engineering Bachelor's Degree at the Vietnamese-German University. The goal of this project is to design, fabricate and testing of a MR damper for prosthetic leg applications,

In a period of continuous technological development with the development of all kinds of technologies that support smooth operation of mechanical mechanisms. With an interest in human augmentation industry, which focus on replicate and improve human body function regards to both physical and cognitive function. With the invention of many advance augmented body parts that perform better compared to our body parts available at birth such as high precision surgeon robot that can assist the surgeon to perform surgery in specifically high risk part of our body. Prosthetic running amputees can run back to their full strength and get the same speed as due to the leg lightweight and flexible feature of the material allowing them to run effortlessly. And in the robot industry, many humanoid robots have been researched and designed so that they can stand on their two legs with an integrated control system so that they can provide self-stability by controlling the stiffness of the limb so that it can detect the change in center of gravity and adjust the positioning accordingly. In which the MR damper pose as the suitable mechanism to achieve variable stiffness control

This highlights a potential opportunity to improve health and daily function of leg amputated patients. However, there are companies out there that already provide such products but the cost ranges between 20,000 USD and 80,000 USD making it difficult to purchase.

This study will emphasize the integration of MR Damper on a cheaper prosthetic design and focus on study the effect of MR Damper compared to prosthetics with no MR Damper. The polycentric knee was initially built for a past research, then we integrated the mechanical design of the damper, the integration design of the MR damper was made using Inventor Professional, followed by optimization in Topology Study. Finally testing for change in damping efficiency is going to be conducted for assessing the optimal setting for the MR damper.

The results of this study are based on the compatibility of the compatibility between the positioning of the knee and the frequency setting of the damper with velocity control features for the knee. The findings are expected to help patients have a quality affordable product with a price that could help the patients to get back with their normal life.

AUTHORSHIP STATEMENT

This project was accomplished by two MEN2017 students of Vietnamese-German University Nguyen Thai Binh and Nguyen Anh Vu and is being used as a thesis project for the degree of Bachelor in Mechanical Engineering program. Each team member contributes to various parts of all components of the project.

I hereby certify my authorship of the bachelor thesis submitted today entitled:

" DESIGN, FABRICATION AND TESTING OF MAGNETORHEOLOGICAL DAMPER FOR PROSTHETIC LEG ".

The result of my own research, except where otherwise acknowledged, and that this thesis has not been submitted for a higher degree at any other institutions. To the best of my comprehension. The thesis contains no information previously or published by other individuals except when the reference is given in the thesis itself.

Author's signature\



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CHAPTER 1: INTRODUCTION

1.1 Motivation

With the growing trend on prosthetic knee development, many papers work on the optimization based on the existing design have been made. With all parameters of each component in a polycentric knee is defined so that it can achieve fully the purpose of the prosthetic knee while safety is ensured, we decide to research about physical and biological of a healthy human body to understand the different to a polycentric mechanism and turn out the muscle in our body not only work as actuator (flexion and extension of muscle) but it also works as suspension due to the elastic properties of muscle and tendon (1).

With the MR Damper known for the smart suspension feature (3), we can utilize this to analyze and replicate the suspension cycle of a normal human leg. In order to tailor fit for the prosthetic leg, many working type and structure design concepts of the damper are compared and finalized.

We decided to apply it to the knee joint to create a product that is both capable of accurate damping while keeping the price affordable for consumers in Vietnam. This can be done by applying MR technology on a prosthetic design specifically designed to reduce costs while maintaining safety for the prosthetic wearer.



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1.2 Aim

The aim for our thesis is to determine the most suitable design for the structural design of the MR Damper that create ease for both the patients and the technicians while maintain quality operation.

CHAPTER 2: LITERATURE REVIEW

2.1 HUMAN KNEE MOVEMENT

2.1.1 Front view knee structure :

The knee consists of 3 main bone femur and tibia and patella. The 3 bone is connected by the tendon and ligaments system illustrated in Figure 2.1. Patella structures : The lateral condyle of the 2 main bones create a natural curve for the positioning of the patella bone, when the knee bends or extends the patella slide along the lateral condyle. The upper patella tendon is connected to the quadriceps muscle and the lower patella tendon is connected to the tibia bone. The tendon and ligament act as a suspension when the leg is walking.

2.1.2 Controlling extension

The mechanism that controls the flexion of the knee joint is done by the hamstring muscle. With the patella acting as a lever for flexing the knee, the patella is trapped between the 2 condyles between the tibia and femur bones. Whenever the person wants to flex the knee straight the quadriceps muscle pulls the patella upward then the patella will pull the tibia upward and make the knee flex. When the muscle stop pulling, the natural resistance of the patella tendon will pull the patella back to the original position. The tendon and muscle act as a damper for the flexion-extension movement of the knee, controlling the speed when walking.

2.1.3 Back view knee structure:

The main mechanism that controls the flexion of the knee joint is done by the hamstring muscle. The hamstring muscle is connected directly to the tibia and fibula bone through a tendon.



Figure 2.1: Anatomy of front knee [2]



Figure 2.2: Anatomy of back knee [2]

2.1.4 Controlling flexion

To curl the leg, the hamstring muscle will contract and pull the tibia bone with the hamstring tendon connected directly to the tibia bone. When the muscle stops contracting, the tibia is back to its original position. Similar to knee extension movement, the tendon, and muscle act as a damper for the flexion-extension movement of the knee, controlling the speed when walking.

2.1.5 Gait Cycle

The gait cycle is one of many indexes to determine the walking cycle of leg movement. The gait cycle is described to consist of 2 predominant phase: the stance phase and the swing phase. However, if we take in detail, a total of 6 micro phases is determined in the gait cycle: heel contact (HC), foot flat (FF), mid-stance (MST), heel-off (HO), toe-off (TO) and mid-swing (MSW) as shown in the figure. In our case, we are most interested in analyzing the swing phase since it is where the damper is actively switching between different damping forces to precisely control the walking speed. In the stance phase, the damping force is constant for stability.

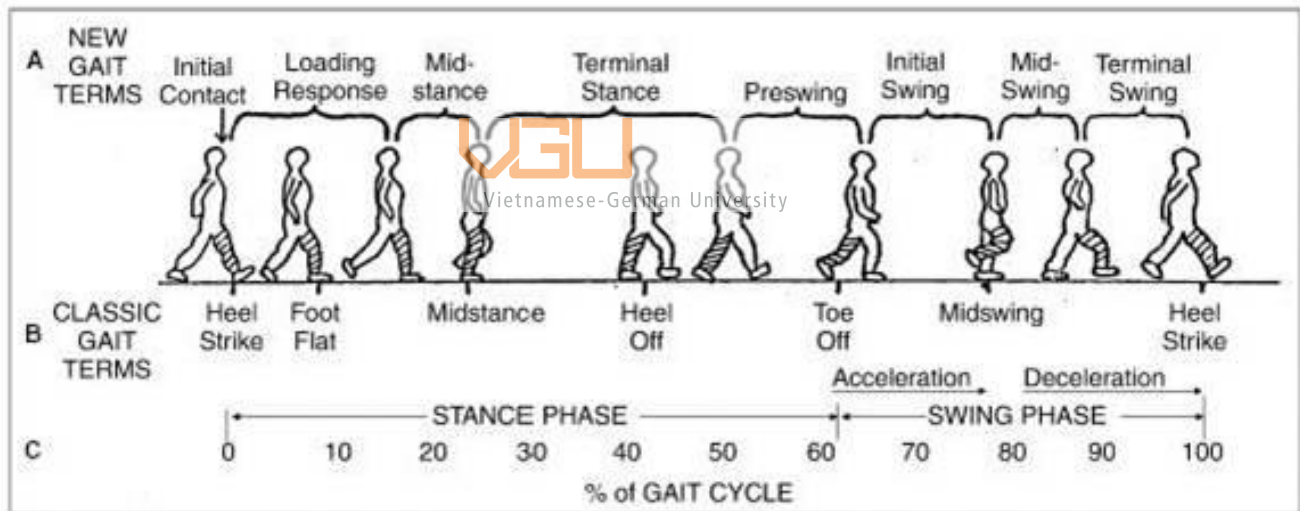


Figure 2.3: Human gait Flow chart [4]

2.2 MR DAMPER

2.2.1 The need of MR Damper in Prosthetic leg

In the Vietnam market nowadays, the most commonly used type is the single-axis knee, this type of knee doesn't allow the patients to bend their knee. As dysvascularity is related to age, elderly patients account for 50% of amputations while patients older than 54 took up 25% of the total amputees [5]. With underlying medical conditions due to old age making the use of prostheses increasingly difficult for the elderly, using single-axis knees pose a strain on their body. This

data speaks to the need for the development of prostheses in older patients to perform well without affecting their health.

With our previous design for the prosthetic knee, we apply a control method to adjust the stiffness of the leg leading to a controlled walking speed suitable for different age groups instead of relying on the existing rotating motion of the 4 bar polycentric knee mechanism, ensuring safety to the patients

2.2.2 MR Damper

MR Damper has been widely researched in many industries from manufacturing, and automotive to medical. The damper first appeared on a smart suspension system called “MagneRide”, which is commonly used for car applications, the system controlled the suspension to make the ride stiffer or smoother.

MR damper works on the principle that a damper containing MR fluid is controlled by a magnetic field controlled by an electromagnet, in most cases, the electromagnet takes the form of a copper coil, which is illustrated in **Figure 2.5** below. The damper fits perfectly to our need for the damper with the capability to precisely adjust the stiffness to replicate the leg muscular system.

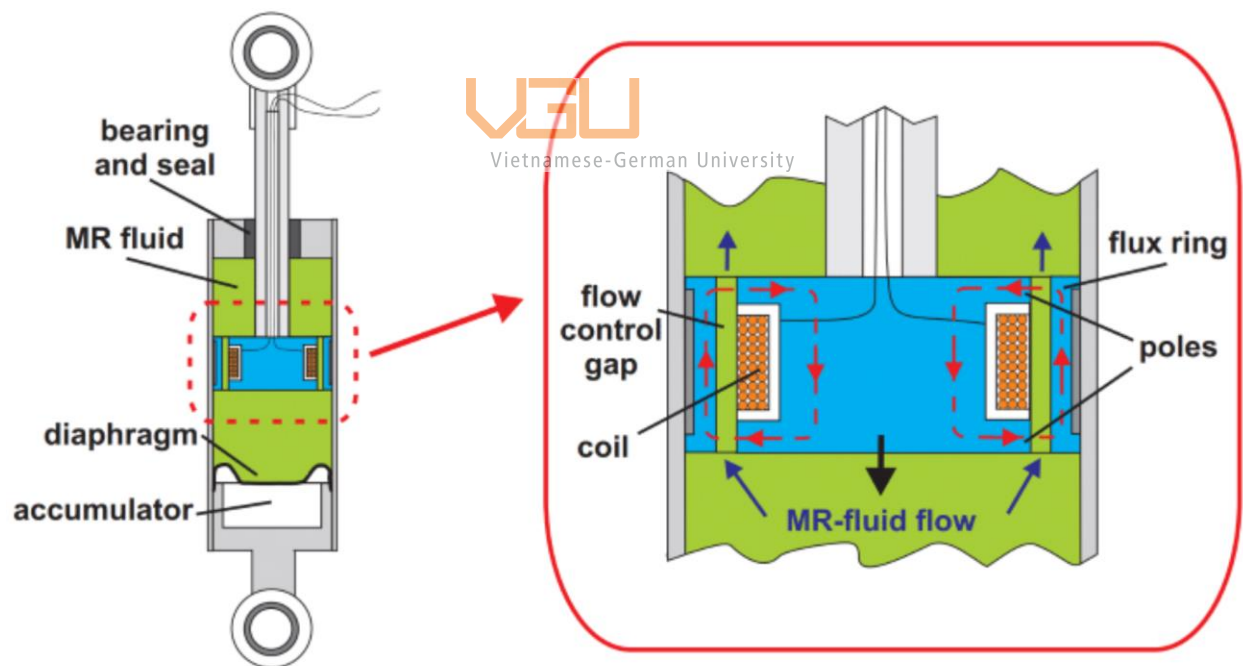


Figure 2.4: Basic Structure of a MR Damper [6]

2.2.3 MRF Characteristics

The MR Fluid is the main component of the MR damper, the fluid is made of a combination of a magnetic material that is distributed evenly within a synthetic carrier oil. The MR fluid has the properties of Bingham plastic fluids, meaning that the fluid has a constant viscosity according to Newtonian fluids. The characteristic difference between these two fluids is shown in the figure, the change in viscosity as the rate of shear strain increases indicating the potential in applications in smart damper application.

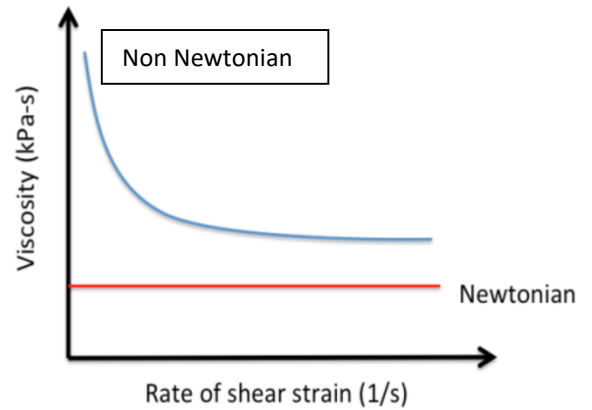


Figure 2.5: Viscosity and shear rate of Newtonian and Non-Newtonian fluid [7]

One of the ways to show the difference between Newton and Bing fluids ham plastic solid is with the correlation of the shear stress τ and Shear rate $\dot{\gamma}$, displayed as a linear function in **Figure 2.6**. For the Newtonian function, the linear function starts at origin O, displayed by the equation:

$$\tau = \mu \cdot \dot{\gamma}$$

While with Bingham plastic fluid, the function line starts at initial shear stress, which states that initial shear stress must be met before the fluid can begin to move on the shear rate axis and the larger the magnetic strength H, the greater the initial shear stress force, for MR damper this value affect directly to the change of viscosity of MRF. This phenomenon is expressed by the Formula :

$$\tau = \tau_y + \mu \cdot \dot{\gamma}$$

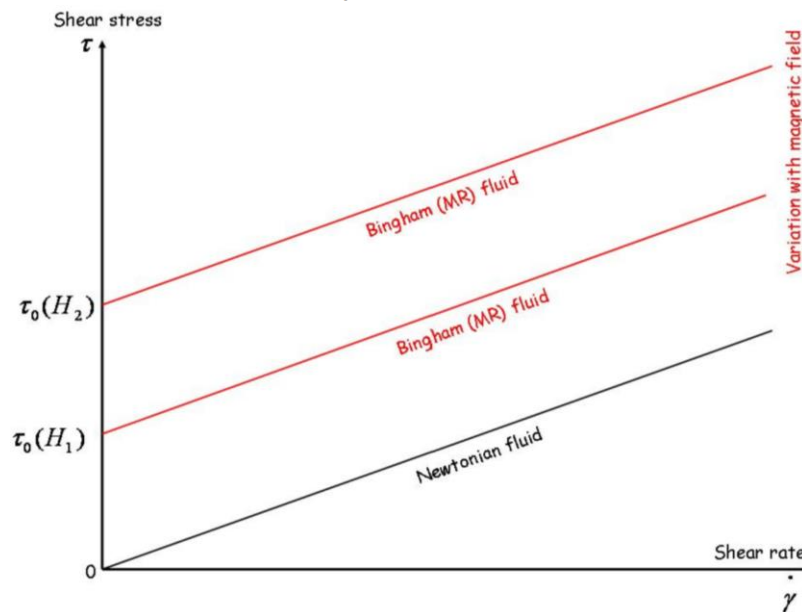


Figure 2.6: Shear stress vs shear rate for Newtonian and Bingham fluid [8]

The fluid when placed between 2 stationary plates has the property of laminar flow since no turbulence can occur inside the damper. The MR fluid's natural state is similar to a laminar flow between 2 stationary plates (figure 2.8)

For laminar flows, the shear rate formula is expressed as follows, the shear rate is the division of $d(u)$ and $d(n)$, which represents the velocity of the flow in a direction perpendicular to which the formula direction to represent the velocity difference in the y direction (Figure), displayed by the formula:

$$\dot{\gamma} = \frac{du}{dn}$$

With magnetic particles inside, the liquid can change its viscosity by adjusting the effect of the magnetic field on these particles. When the MR particles are acted upon under a magnetic force, these particles will arrange along the magnetic flux and exert a force created by the bonding between these particles, shown in figure 2.9. At this point, the particles do not move as easily as before, leading to an increase in the viscosity and shear stress of the fluid.

Depending on the nature of each type of MR Fluid, The ratio of fluid shear stress to the magnetic field strength is shown in an example is shown in a different type of MR Fluid in figure 2.10, with greater magnetic field force H , the particles are more tightly bound together and the yield stress increases up to a saturation point at the right side of the chart.

MR Fluid are classified by the percentage of magnetic particles, for example, the MRF-122ED have 22% of MR Fluid in the carrier oil and the MRF-241ES have 41% MR particle in the carrier oil, the higher percentage of MR particle the higher the maximum shear stress the fluid can generate, depending on the maximum load engineer select the suitable type of MRF for their specific use

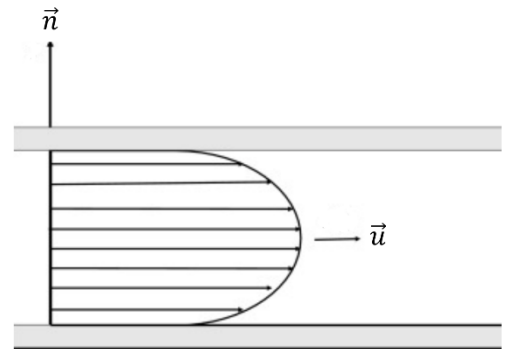
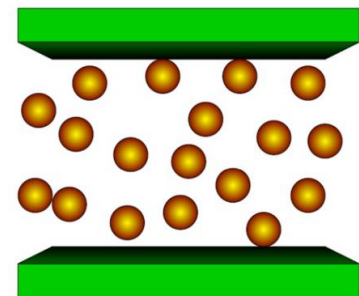
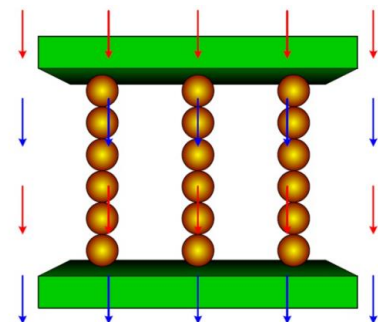


Figure 2.7: Laminar flow between 2 stationary plate [source: internet]



(a) Without Magnetic Field



(b) With Magnetic Field

Figure 2.8: MR particle behavior
 (a) without magnetic field
 (b) with magnetic field
 [9]

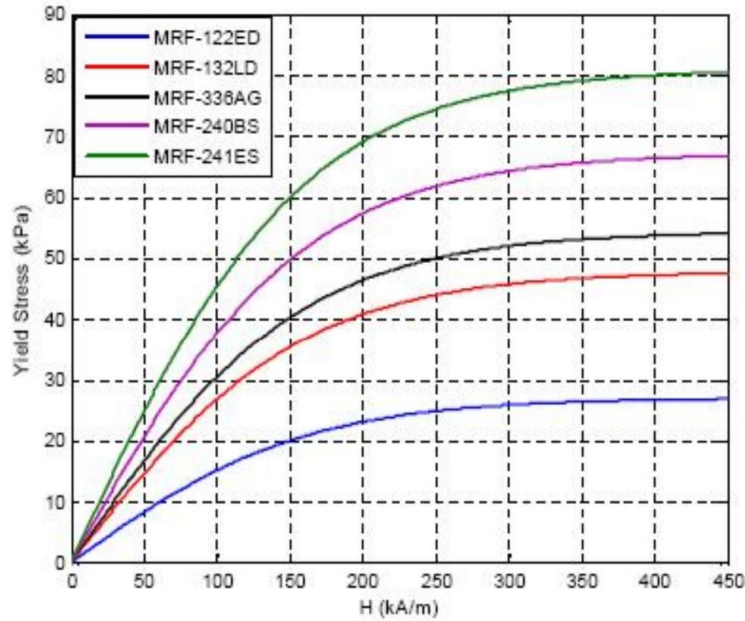


Figure 2.9 : Yield stress vs magnetic strength of 5 different MRF [source: internet]

2.2.4 Electromagnet



To be able to control the magnetic field to be able to control the MR damper, we need a magnet, and an electromagnet to complete this job. An electromagnet is a type of magnet in which the magnetic field is produced by an electric current. Electromagnets usually consist of wire wound into a coil. In figure 3.2, a current through the wire creates a magnetic field that is concentrated in the center of the coil. The biggest advantage of an electric pin is its ability to rapidly change over a wide amperage range by controlling the strength of the current.

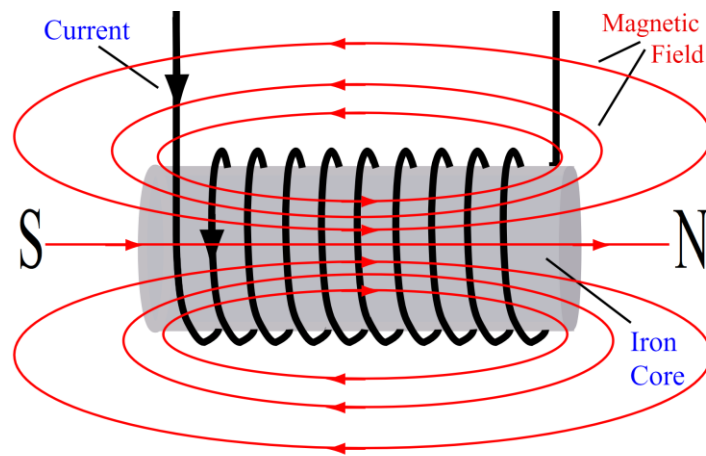


Figure 2.10: Electromagnet Diagram [10]

Copper is chosen for *coil material* for 3 main reason:

1. Copper is classified as a non-magnetic material, which means that during operation, the damper frame will not be affected by the magnetic field of the coil.
2. Unlike copper, Magnetic material like steel tends to magnetized when the coil is working, which may interfere with the coil magnetic field and can cause the magnetic field to phase out each other.
3. Copper have high electrical conductivity. Copper conductivity enhances the electrical energy efficiency. Resistivity of copper is $1,68 \times 10^{-8}$ when comparing to other wire material like aluminum and gold, with corresponding conductivity is 2.65×10^{-8} and is 2.44×10^{-8}

2.2.5 Operation Principle

The MR Damper consist of 3 main component :

- MR Fluid : The MR Fluid is the main component of the MR damper, the fluid is made of a combination of a magnetic material that is distributed evenly with in a synthetic carrier oil. The magnetic material have size range from microscale to nanoscale. (Shown in **Figure 2.9**).
- Damper Piston Shell : A piston design with a compartment for storing MR fluid that contacts directly with the moving parts of the damper, integrate with a gap to winding the electromagnetic coil. (Shown in **Figure 2.5**)
- Electromagnet Coil : Act as a source for the magnetic field for controlling the density of MR damper. When the coil is off, magnetic particles is spread evenly in the carrier oil (**Figure 2.9**), however, when there is a magnetic field active, the particles align in the direction of the magnetic flux, creating a quasi-solid state that create friction when the 2 plates are moving.

A main advantage of using MR Fluid is that the MR damper doesn't require mechanical valve control, laying the foundation for the design of a compact, lightweight, and mobile damper system for prostheses,

In addition to that, the MR damper also demonstrates superiority in the range of force of the damper, with the force generated from the conventional passive damper (oil and gas damper).

The MRF damper, with the ability to adjust the magnetic intensity to change shear stress, the damper can adapt to a wider range of force and velocity.

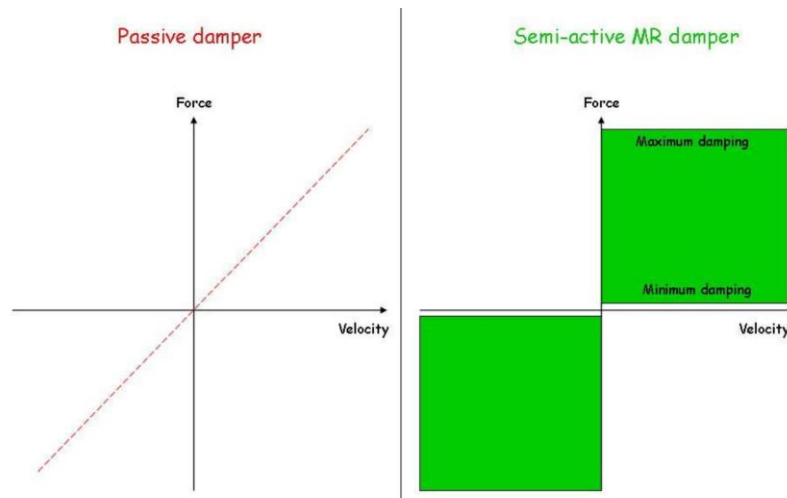


Figure 2.11: Passive damper vs Semi-active damper characteristic [11]

2.2.6 Operation Modes:

There 3 basic operation modes of MR damper (shown in **Figure 2.4**): Flow mode, Shear Mode, and Squeeze mode. In the figure below, the Shear mode is involved with a displacement motion of the two plates that move relative to each other. Most useful in damping and brake mechanism. Flow mode involves the moving of the fluid flow between 2 stationary plates, utilize commonly in brake and damper structures. The squeeze mode involved a force that pushes the flow perpendicularly away from the 2 plates, this mode is not widely utilized except for a few models in the anti-vibration system. However, to increase damping capacity there are designed to integrate 2 or more working modes to a single system, which is called mixed mode dampers, usually they combine flow and shear modes to create a design with a significant greater damping force.

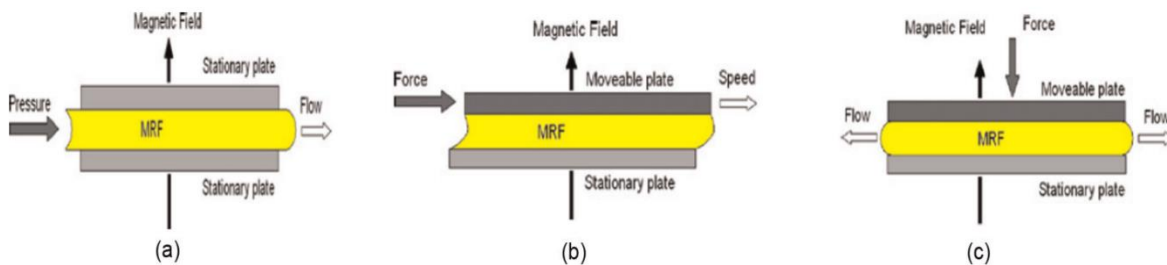


Figure 2.12 Design and application of magneto-rheological fluid [12]

Then general structures of Flow mode and Shear mode is compared to better understand the advantage and disadvantage of each type, we will take some point into consideration size, maximum damper force, and MR fluid amount. Note that we only discuss general structure design, after this phase, 2 examples of flow mode and 2 examples of shear mode are taken into consideration for further detail analysis to choose the final structure.

2.2.6.1 Flow mode :

The MR Fluid is contained in the MR fluid chamber. The name flow mode specifies that the moving compartment of the damper is the MR fluid itself. When the piston is compressed aka the piston rod pushing down, the MR fluid will flow from the chamber through a small gap with a coil to controlled magnetic fluid, the damping force can be precisely adjusted

Especially in this design, the flow slot is small so that the fluid can be more compressed and create a much greater damping force. Due to a large amount of MR Fluid, the design required an additional gas chamber for pressure balancing to prevent the occasion when the MR is maximum compressed and cannot make a return to the equilibrium position due to lack of pressure to return to the equilibrium position.

Unfortunately, this makes the damper heavier and more complex due to more compartments to be assembled. The sufficient amount of MR fluid is also larger than other types of MR damper and the traveling distance is longer compared to the other types. In general, this configuration allows more damping force but consumes more MRF.

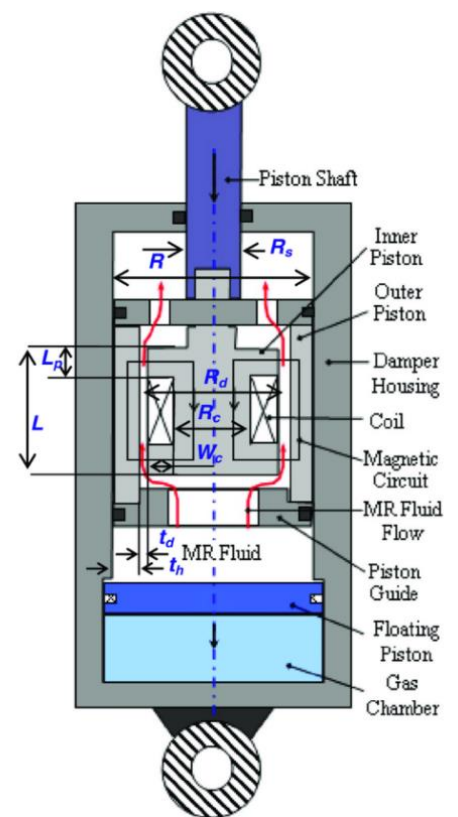
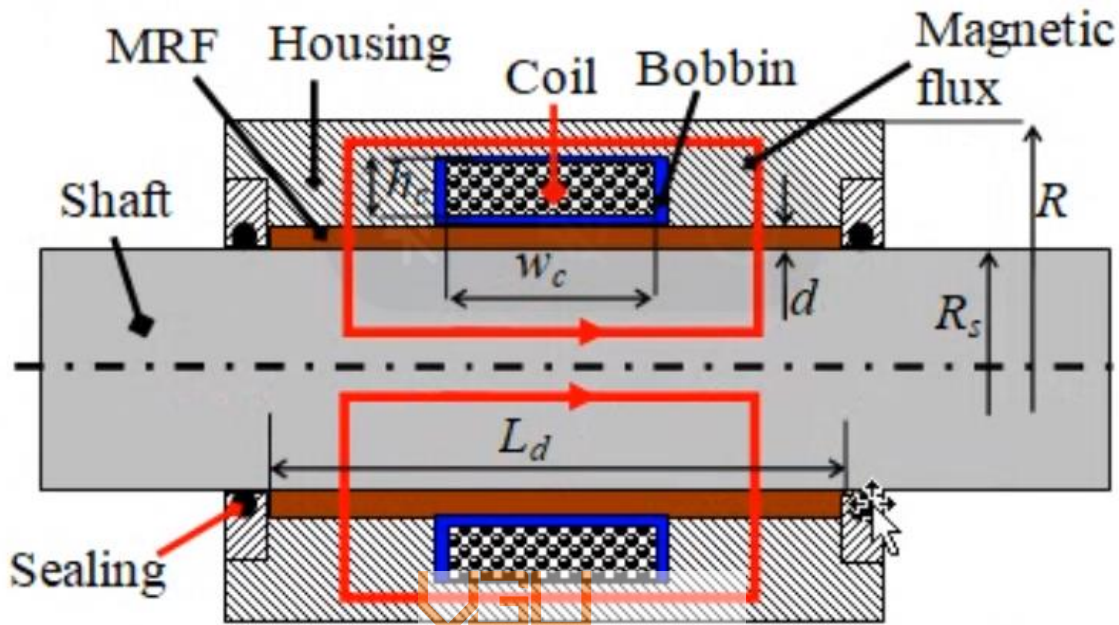


Figure 2.13 : Schematic configuration of a flow mode damper

2.2.6.2 Direct Shear Mode

This schematic, unlike the one above, doesn't have a reservoir for MR fluid due to the small amount of the MR Fluid, which, is contained in a small gap between the coil and the outside

cover of the Piston. Due to the low amount of MRF needed, the design is simplified much simple, the reservoir is limited leading to no Gas chamber which makes it much lighter with a simpler design However, the travel distance is limited which makes it more suitable for light-damping needs.



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Figure 2.14 : Schematic configuration of a flow mode Damper [13]

2.3 PROTOTYPE WITHOUT MR DAMPER

To understand the design and choose the best mechanism for applying MR Damper, we review the existing design in 4 bar polycentric knees [14] (Shown in Figure). Polycentric knee utilized the 4 bar mechanism.

The design follows the parameter requirement of the 4 bar 3R20 prosthetics from India [15] and the new design has performed weight reduction to achieve a sturdy yet lightweight prosthetic leg. It also shows that the polycentric leg itself can perform rotation up to 90 degrees, allowing the user to sit comfortably on the chair as shown in Figure below.

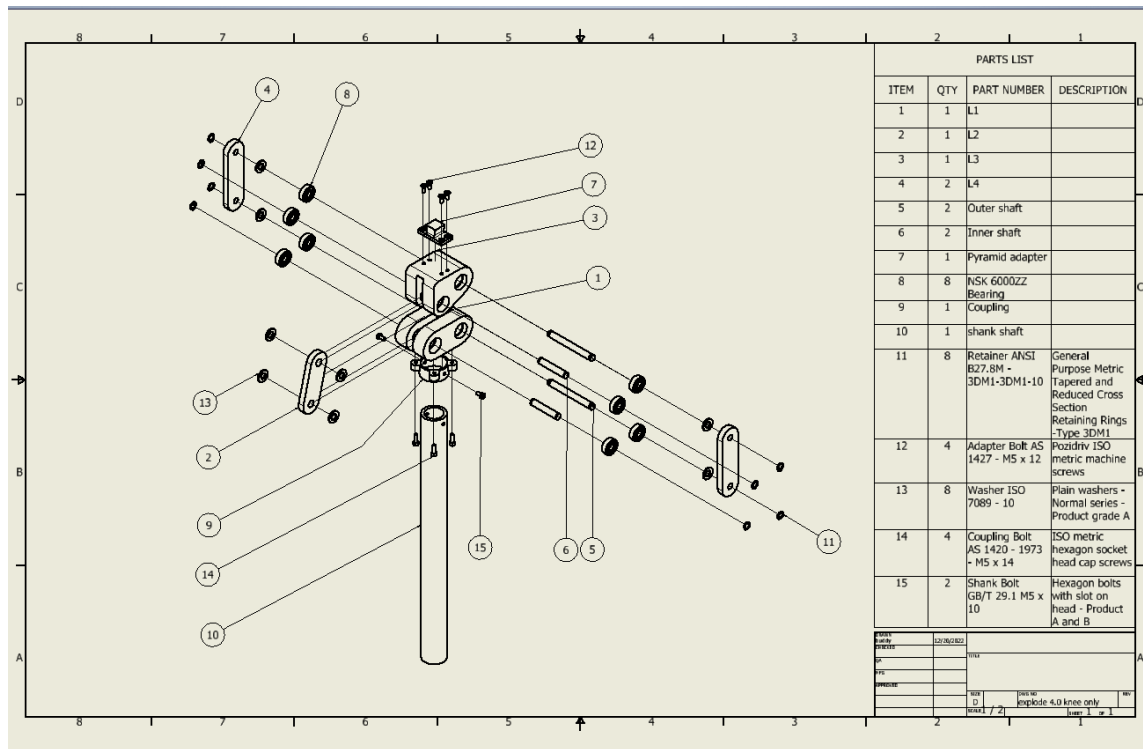


Figure 2.15 : Exploded view drawing of the prosthetic knee frame [14]



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The design above only depict the suitable walking speed requirement for walking for the tested age group in the testing of the product, to optimize for all age group, a walking speed control mechanism is required when applied for all users group, the MR damper is used, with the construction of a basic piston with multivariable damping, it becomes easier to control the walking speed of the prosthesis, for the convenience of assembly, some requirements need to be defined:

- Damping force required : As research from 3 paper (16) (17) (18) that research the application of MR damper for Prosthetic knee, average damping force obtained from design parameters is 140N.
- Damper dimension must fit to the existing frame, without restraining leg movement.
- Damper size (Outer Shell diameter, Shaft size, MR fluid gap size)

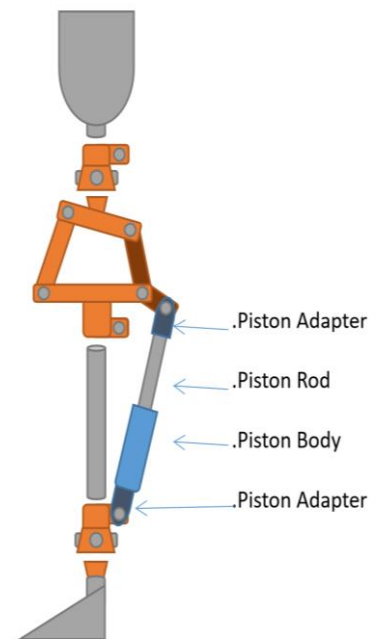


Figure 2.16: Optimize schematic

The design above only depict the suitable walking speed requirement for walking for the tested age group in the testing of the product, to optimize for all age group, a walking speed control mechanism is required when applied for all users group, and the MR damper is used, with the construction of a basic piston with multivariable damping, it becomes easier to control the walking speed of the prosthesis, for the convenience of assembly, some requirements need to be defined.

2.4 CONFIGURATION SELECTION

To determine the best structural design and working model for the damper, we decide to take into consideration of the 4 designs, of which, 2 are working based on Flow mode and 2 are working with Shear Mode. We perform concept selection for the 4 designs based on 4 basic requirements: weight, size, damping force, and structure complexity.

Structure 1: Twin Tube Flow mode MR Damper for a motorized knee [16]

- *Damper length : 350 mm*
- *Maximum Damping Force: 489 N*
- *Working mode: Flow mode*

This MR Damper is applied on an electrical motor-actuated prosthetic knee. The EC motor controls the knee joint angle in the swing phase while the MR damper will create a reaction force when in contact with the terrain. The Damper Structure consists of 2 compartments: stationary and moving parts. The stationary consists of a simple cylindrical shell with an O-ring for oil sealing ability while the moving part consists of a coil winding frame connected to the 2 ends of the piston. When the damper is working, the oscillating movement of the damper shaft causes the MR fluid to travel between the 2 chambers A and B through the MRF Gap as the system is classified as Flow mode.

In conclusion, the design shows that it requires a large amount of MRF to operate but is capable of generating a correspondingly large force of up nearly to 400N. However, 1 major flaw in this design is that the MR fluid contact directly with the magnetic which may cause an error in the output magnetic force of the coil.

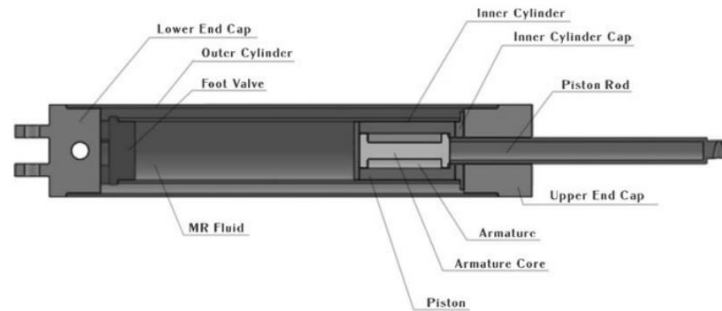


Figure 2.17 : Structural design of a Twin Tube Flow mode MR Damper [16]

Structure 2: MR Damper Application for Motor Actuated Knee joint [17]

- *Damper Length : 400 mm*
- *Damper Width : 35 mm*
- *Maximum Force 150N*
- *Working mode: Flow mode*

The MR damper with EC motorized prosthetic support for knee angle control, and the MR damper responsible for creating a reaction force when the leg contacts the ground, creating a shock suspension feature. This damper is designed with a total length of 400mm however the moving damper part is only 100mm long which makes this parameter more freely to design. But due to it being a flow mode design, the amount of MR used is relatively high and this design also does not isolate the MRF part from the copper coil. But with the flow mode, it will ensure to achieve of a larger damping force and as Tested in **the paper** the damper can generate a maximum damping force up to 150N.

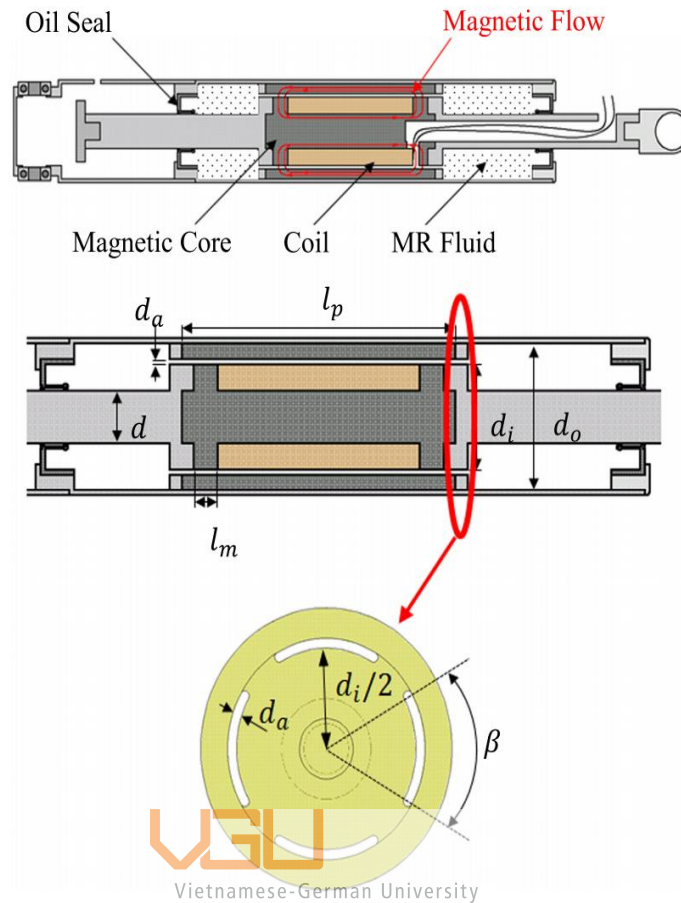


Figure 2.18 : Structural design of a mono tube flow mode MR Damper [17]

Structure 3: MR Damper Application for Washing Machine Anti-vibration system [18]

- ***Damper length : 80mm***
- ***Damper Width: 36 mm***
- ***Damping force : 80N***
- ***Working mode: Slide mode***

MR Damper is designed as an anti-vibration system for washing machines with a damping force range from 80 to 120 N. MR damper is utilized to combine with a control system to reduce the vibration caused by the washing machine cage.

This range suits perfectly to our prosthetic damping and stiffness control needs. It also exhibits high bearing capacity when installed at the base of the washing machine, with its small size,

which ensures easy installation, reduces production costs and does not affect the overall structure of the system. The Damper structure is a basic slide working mode, with a small space between the inner and outer casing of the damper in order to contain the MR Fluid, saving MR fluid. This structure consists of 11 parts, with 2 main compartments: stationary and moving. The damper consists of many parts with a basic thread connection, in addition, there is a part guide bush and additional O-ring which ensures MR fluid sealing, making sure no MR fluid can be leaked, affecting the working condition. The additional guide bush, which function is to direct the horizontal direction of the damper cylinder, protects the damper shell from wear and tear. However, difficulty can be faced when disassembling the damper for maintenance and fixing since there are no MR Fluid reservoirs for easy storing and collecting MR Fluid, however, this disadvantage can be leveled off due to the small amount of MR Fluid in use.

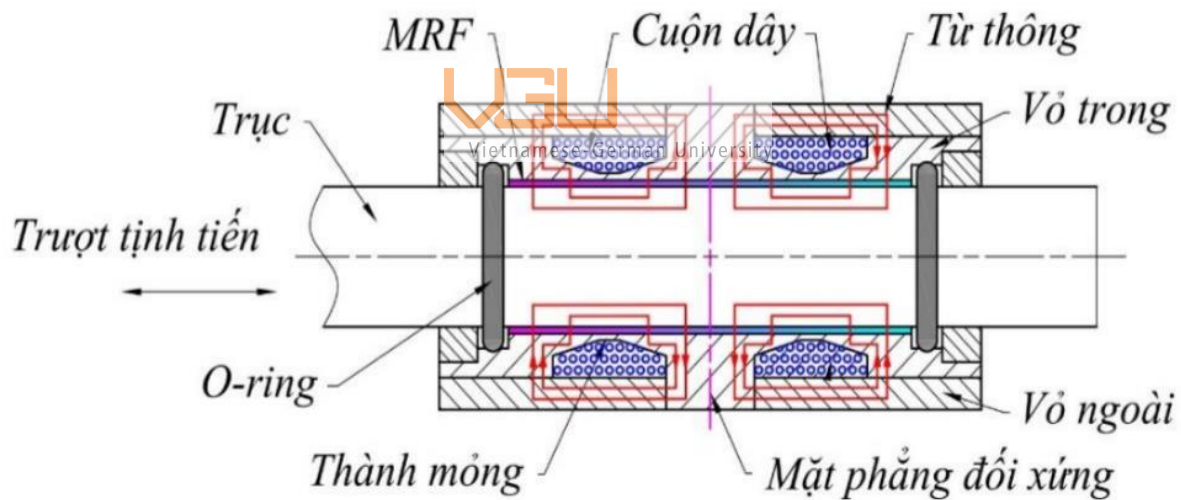


Figure 2.19 : Structural design of a mono tube slide mode MR Damper for washing machine anti-vibration system [18]

Structure 4: MR Damper for Single-Axis Knee joint [19]

- **Damper length: 227mm**
- **Max damping force: 147.7 N**
- **Working mode: Flow mode**

In this design, the damper is applied to create support and control for the torque in the knee joint, to create an optimization to improve gait quality for the amputee.

The design for the damper has 2 main components: a stationary part and a moving part. The stationary part is the damper body, consisting of (3) end cover, (4) cylinder body, (8) lower lifting lug. (3) and (4) are connected by a basic flange type connection where the holding compartment is the bolt and nut, Part 4 and (5) are assembled similarly. The moving part consists of (2), (5), (6) and (7). With parts (2) and (7) connected by a thread connection and the coil winding frame is clamped between the 2 parts, ensure the location of the coil, however, there is one defect is that the MR Fluid is in direct contact with the coil, create an error in the resistance of the coil leads to the value of the magnetic field being deviated from the calculated value, leading to an error when damping, affecting the gait quality of the user. Another disadvantage is the damper has not yet clearly shown its water-resistance feature, which may cause inaccurate damping, and create an unnecessary loss of MR Damping force. The position of the MR Damper is similar to our design idea, based on the positioning of the hamstrings. This damper is tested on 6 different currents: 0, 0.4 , 0.8 , 1.2 , 1.6 , 2.0 and achieves maximum damping force (estimated from 105N to 147N) at 2.0A.

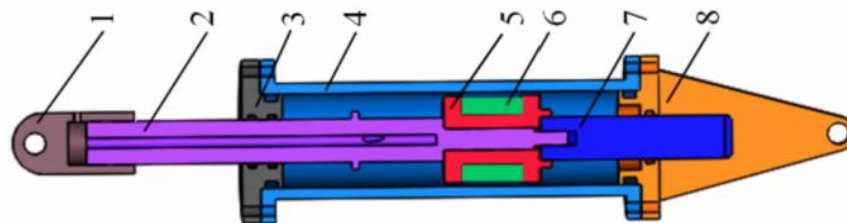


Figure 2.20 : Structural design of a mono tube mixed mode MR Damper for a single-axis knee joint. (1) Upper lifting lug, (2) piston rod, (3) end cover, (4) cylinder body, (5) coil frame, (6) excitation coil (7) piston rod (8) lower lifting lug [19]

After evaluating 4 design structure for different application for MR Damper, we choose the most suitable configuration based on the following design criteria

1. **Size** : The size of the MR Damper should be of the right length to fit on the prosthesis frame, in addition, the thickness should be designed so as not to affect the space for joints and range of motion.
2. **Weight** : Damper should have a lightweight design to be suitable for application on prostheses without making the whole system heavy in order to meet the criteria of a lightweight leg.
3. **Simple Design** : The design should be simple based on the number of parts and simple connections, no special tools are required for assembly and maintenance.
4. **Damping force** : The design should have a Damping Force between 80-150N, which proves to be enough to support the prosthesis
5. **Amount of MR Fluid** : The amount of MR Damper should be minimized to reduce costs.
6. **Safety** : The coil should be well insulated from the MR Fluid to be able to generate the correct calculated magnitude.



All criteria are scored on a scale of 1 to 5 then the total score is summed and compared to get the most suitable design.

Looking at the comparison table, we can see that damper 3 has the highest score. Design 3 has a compacted size that meets the size and weight criteria, and saves MR Fluid more than other designs since it doesn't need for the additional gas chamber and MRF reservoir. Furthermore, it has the ability to isolate the coil so that it does not come into direct contact with the MRF. The only drawback is that design 3 has the lowest damping force compared to other designs, fortunately, this can be completely adjusted through parameter optimization to ensure increased damping force but kept a small size, without affecting the range of motion of the leg.

The damping force of damper LATS when testing is only 1A to meet the requirement for the washing machine, to reach the damping force of 150N we will increase the amperage for the coil to determine the appropriate damping force for prosthetic knee needs.

After we have the structural design, we need to modify the damper's parameters to suit our needs through calculation in parametric design.

Concept Scoring				
<i>Selection Criteria</i>	Concepts			
	<i>Flow mode</i>		<i>Slide mode</i>	
	1	2	3	4
	Twin tube damper for Motorized knee	Mono tube damper for Motorized Knee	Damper for washing machine anti-vibration system	Damper for Motorized Knee
Size	3	3	5	4
Weight	3	3	4	4
Complexity	3	3	4	5
Damping force	5	4	3	4
Amount of MRF	2	4	5	3
Safety	2	2	4	2
Net Score	18	19	25	22

Table 2.1 : Concept selection for 4 different MR damper design

CHAPTER 3: PARAMETRIC DESIGN

3.1 Damper Design and calculation preparation

3.1.1 Mechanical formulas:

Structural design of the damper developed by is recalled in Figure 3.1, with the cross-section of the damper with the parameter included.

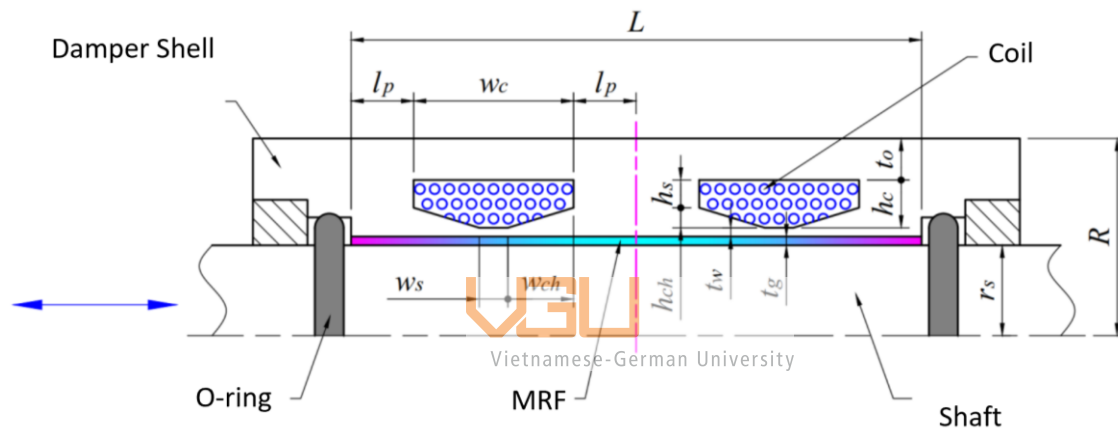


Figure 3.1 : Structure configuration of double coil MR damper developed by [18]

Based on The design decided to follow the design flow from the paper, the process starts with damper force analysis, it can be seen that the total damping force F_d is the summation of 3 forces F_{torque} is the force caused by yield the stress of the MRF on the two contact surfaces, F_n is the damping force due to the density of the oil, F_f is the force acting on the moving surfaces in contact with each other, in this case, the MRF is in direct contact with the two adjacent surfaces.

$$F_d = F_\tau + F_\eta + F_f \quad (1)$$

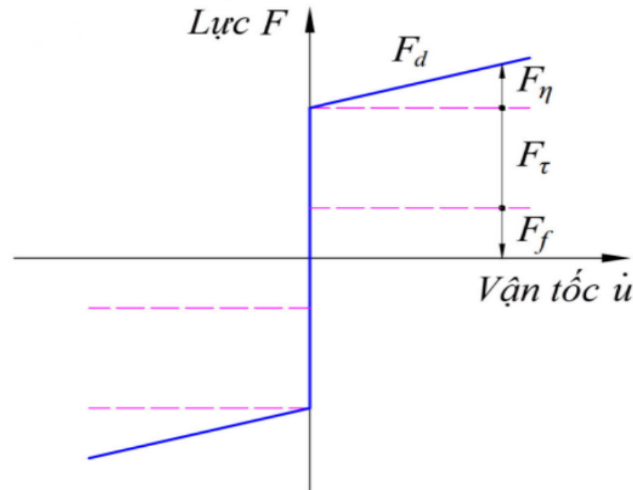


Figure 3.2: Force profile of damper [18]

The fluid when placed between 2 stationary plates has the property of laminar flow since no turbulence can occur inside the damper. The MR fluid's natural state is similar to a laminar flow between 2 stationary plates. For laminar flows, the shear rate formula is expressed as follows, the shear rate is the division of the change in velocity $\mathbf{d}(\mathbf{u})$ and change in the direction perpendicular to the velocity $\mathbf{d}(\mathbf{n})$, which represents the velocity of the flow in a direction perpendicular to which the formula direction to represent the velocity difference in the y direction (Figure 3.3), displayed by the formula:

$$\dot{\gamma} = \frac{du}{dn}$$

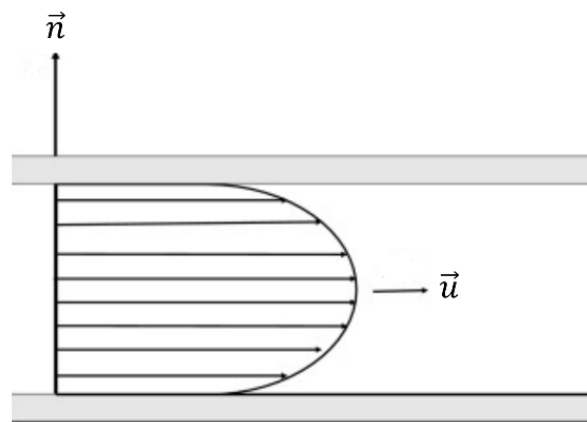


Figure 3.3: Flow profile of fluid between 2 moving plates [source internet]

Due to the very small t_g thickness of only 2mm, at this very small size, the parabola (Figure3.4) is seen as a diagonal line (Figure 3.5), and when this is the case, the laminar flow expression formula is formatted.

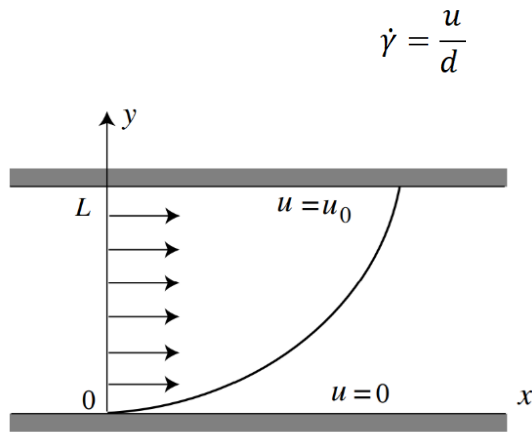


Figure 3.4: Flow profile of fluid between 2 moving plates

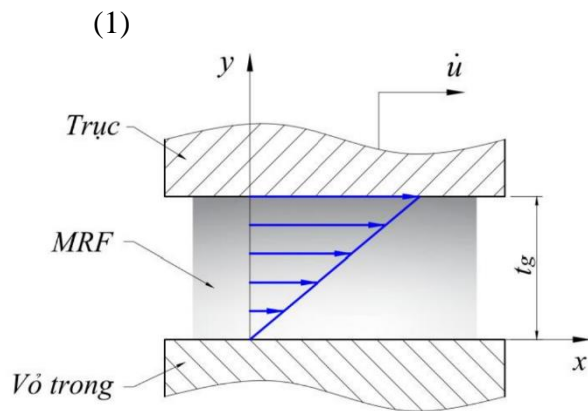


Figure 3.5: Flow profile of fluid between 2 moving plates when t_g is very small [18]

The
n

we have the relative velocity $\dot{u}(y)$ between shaft and shell:

$$\dot{u}(y) = \frac{\dot{u}}{t_g} \cdot y \quad (2)$$

Sliding speed formula for y direction :

$$a\dot{\gamma} = \frac{d\dot{u}(y)}{d(y)} = \frac{\dot{u}}{t_g} \quad (3)$$

With t_g is the thickness of the MR gap. The viscous shear stress is determined by the formula:

$$\tau_{xy} = \eta \cdot \frac{\dot{u}}{t_g} \quad (4)$$

F_τ, F_η, F_f are calculated with corresponding formula

$$F_\tau = A_l \cdot \tau_y \quad (5)$$

With A_l is the damping area which have the highest shock absorbtion under the effect of magnetic field.

$$F_\eta = A_l \cdot \tau_{xy} = \eta \cdot \frac{\dot{u}}{t_g} \quad (6)$$

From the above formulas, we have the general formula of active damping force and non-active damping force as follows:

$$F_d = A_{l,on} \cdot \tau_y \cdot \left(\eta \cdot \frac{\dot{u}}{t_g} \right) + A_{l,off} \cdot \tau_0 \cdot \left(\eta_0 \cdot \frac{\dot{u}}{t_g} \right) + 2 \cdot F_{or} \quad (7)$$

$$F_0 = A_l \cdot \tau_0 \cdot \left(\eta_0 \cdot \frac{\dot{u}}{t_g} \right) + 2 \cdot F_{or} \quad (8)$$

With :

- τ and η are yield stress and viscosity of the MRF :
- \dot{u} is relative velocity between shaft and shell
- t_g is the thickness of MRF Gap
- A_l là the area of part in contact with the MRF

$A_{l,on}$ và **$A_{l,off}$** consecutively is the area of the shaft exposed to the activated and non-activated section of the MRF with length **L** is the length of the MR gap, which consist of activated length **L_{on}** on and non activated length **L_{off}** . For this structure design, $L_{on} = L$ since all area in the MR gap is activated by the magnetic coil, thus making $L_{off} = 0$. :

$$\circ A_l = 2 \cdot \pi \cdot r_s \cdot L \quad (9)$$

$$\circ A_{l,on} = 2 \cdot \pi \cdot r_s \cdot L_{on} = 2 \cdot \pi \cdot r_s \cdot L \quad (10)$$

$$\circ A_{l,off} = 2 \cdot \pi \cdot r_s \cdot L_{off} = 0 \quad (11)$$

F_{or} là lực ma sát Coulomb giữa trục và mỗi O-ring, được tính toán bởi [21] :

$$F_{or} = f_h \cdot A_r + f_c \cdot l_r = f_c \cdot l_r \quad (12)$$

In which,

- L_r is the circumference of the damper shaft,
- f_c is the friction force cause by O-ring which can be attained using the Friction force-compression rate chart in Figure

- A_r is the cross-section area of O-ring.
- f_h is the friction force caused by MRF acting on a unit cross-section

Noted that specifically for the slide mode, there are no MRF reservoir for the damper design, there are no mass of fluid pressing directly to the O ring, the f_h are considered very small thus make $f_h \approx 0$.

A non-reactive force occurs even when the coil is not powered since in this phase the MR Fluid is still considered an oil suspension. This force will help the patient to stabilize better when the foot makes contact with the ground in the HC phase (Figure 2.4). O-rings need to be compressed enough to be watertight while ensuring non-reactive forces are small enough for the patient to walk comfortably. In this project, NBR-70- durometer are assembled at 15% compression rate, with such data we can get from the chart below to find $f_c = 175 \text{ N/m}$.

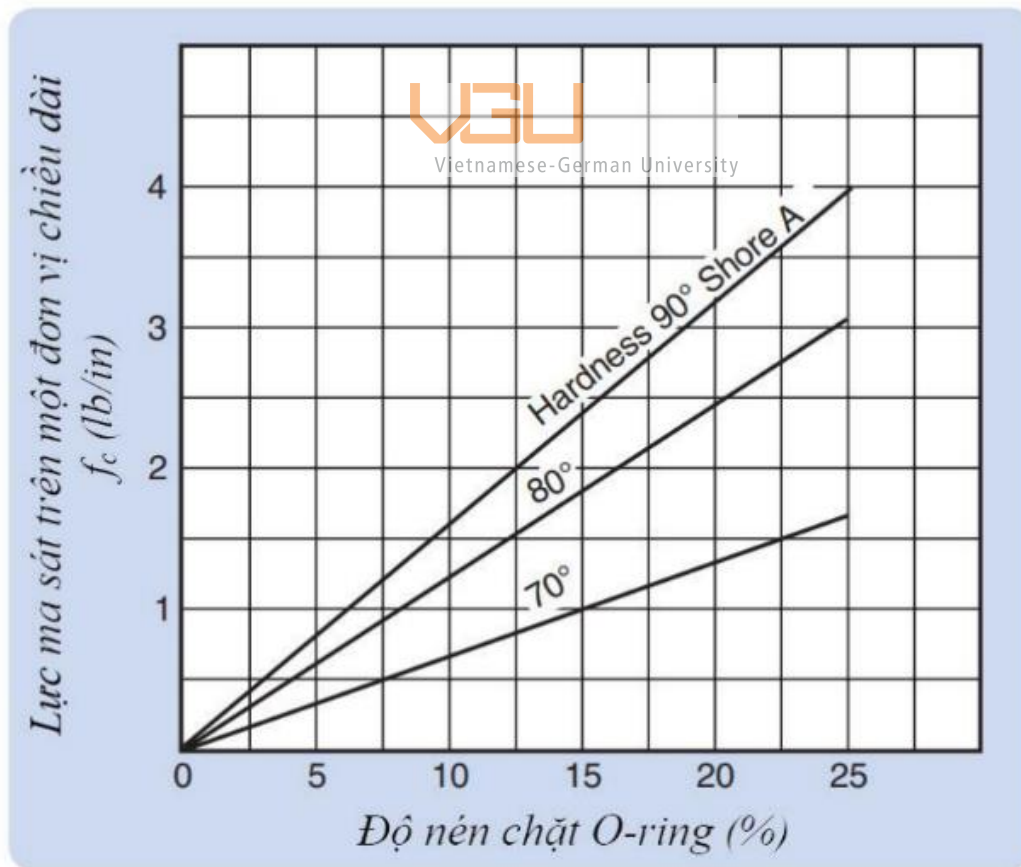


Figure 3.6: O-ring force and Compression rate chart [20]

We got a generalize function for damping force :

$$F_d = A_{lon} \cdot \tau_y \cdot \left(\eta \cdot \frac{\dot{u}}{t_g} \right) + 0 + 2 \cdot F_{or} \quad (13)$$

$$F_d = 2 \cdot \pi \cdot r_s \cdot L \cdot \tau_0 \cdot \left(\eta \cdot \frac{\dot{u}}{t_g} \right) + 2 \cdot f_c \cdot l_r \quad (14)$$

With this the formula still lack index τ_y and τ_0 , which can be determined after calculating for the electrical values.

3.1.2 Electrical formulas:

First, the shape of the winding frame needs to be discussed, the shape is trapezoidal because of the direction of the magnetic field flux. If defined as a rectangle, the next MR gap will receive very little traversing magnetic field lines. But when using a trapezoidal shape, the number of magnetic field lines going across the gap increases significantly, because the outline of the wrap shape can affect the magnetic field line perception, in the case of MRF, the shear force is applied perpendicular to the direction of piston movement, the MR particles relocated so that the arrangement can impede the flow, thereby increasing the shear stress on the wall and increasing the damping force many times, in **Figure 3.7**. With the resistivity of copper is and the area of the wire, the formula for the area of the wire calculated as follows

$$A_c = \pi \cdot r_{wire}^2 \quad (15)$$

With resistivity of copper is $\rho = 1,68 \cdot 10^{-8} \Omega \cdot m$. Resistivity for the wire can be calculated as followed :

$$r_{rc} = \frac{\rho}{A_c} \quad (16)$$

The cross section area of the coil is shown in Figure, the total area for winding coil is calculated with formula:

$$S_{coil} = (h_s + h_{ch}) \cdot (W_s + 2 \cdot W_{ch}) - 2 \cdot \frac{1}{2} \cdot W_{ch} \cdot h_{ch} \quad (17)$$

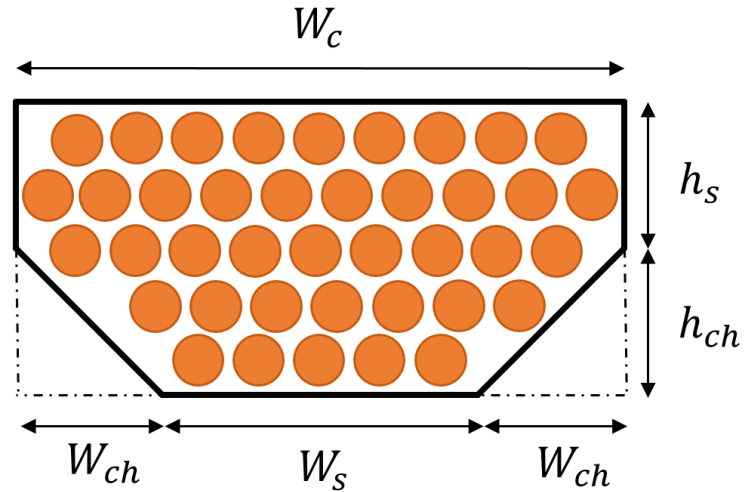


Figure 3.7: Coil cross-section

The number of winding round N_{turn} is determined by the amount of cross-section of wire that can fit the wire winding frame, with winding coefficient $c=0.7$, the number of turn N is formulated as:

$$N_{turn} = c \cdot \frac{S_{coil}}{A_c} \quad (18)$$

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With r_0 is the inner radius of the coil and h_{ch} is the projection of chamfer edge to vertical direction, the resistance of the winding R_c has the following formula:

$$R_c = rrc \cdot N_{turn} \cdot 2\pi \cdot (R_o + \frac{1}{2}hc) \quad (19)$$

3.2 Simulation Process

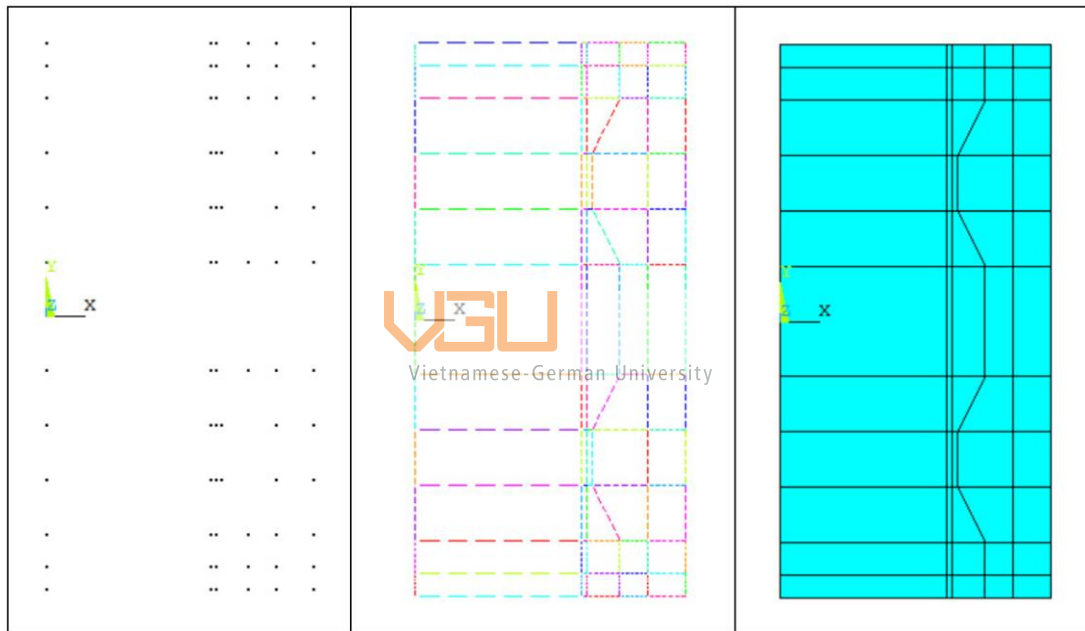
After having all formulations and requirements regarding the damper design, we begin the *simulation process* to calculate the parameter. First, to start the simulation, *plane 13* is assigned in the simulation, this signalizes to the system that a simulation regarding magnetic field is going to be conducted, then the program can prepare the correct simulation module for this design.

The simulation have 3 main step:

3.2.1 Pre-processing :

The first step is to build a 2D model for simulation by creating the dot representing every point in the x and y direction, each point is input manually one by one (Figure 3.8a). Then, structure lines are defined by connecting the dot, recreate the design for the damper (Figure 3.8b)

The next step is to define the area on the design, each area is formed by connecting 3 to 4 lines, as illustrated in figure 3.8c, every line has been declared in the step above Finally, a material is added to each area, create a complete 2D modeling for the damper.



a) Define dots

b) Define lines

c) Define areas and materials

Figure 3.8: Step for building model of MR damper in ANSYS

3.2.2 Show solution:

A crucial part of this step is to input the parameter and calculation formula. All formulas mentioned in Formula Preparation are recalled for the code.

The formula consists of 2 parts: Mechanical formula and electrical formula. In mechanical formula consist of calculation for Dimension, the damping force of the damper, and the Shear stress of the MR Fluid. The electrical formula consists of calculations for the requirement for the

copper wire such as the number of turns and the magnetic intensity. All of the formula and parameter is input into the program, illustrated in Figure 3.9.

```

Ratio_C=0.8 ! Winding Ratio
Ratio_M=0.9 ! Energy loss ratio
pi=3.1416
dc=0.00051      ! diameter of copper wire

res=0.01726e-6  ! resistivity of Copper
Ac=pi*dc*dc/4   ! cross-section area of wire
rrc=res/Ac      ! resistivity on a unit of area

tfo=4.8e-3      ! Lp
tfoo=tfo        ! Lp

to=3.7e-3       !thickness above coil
tfi=tfoo        !Lp
Rs=15e-3        ! shaft radius
tg=0.5e-3       !MR gap thickness
ch1=5e-3        !Chamfer corner projected on y-direction
ch=2.5e-3       !Chamfer corner projected on x-direction
wc=5e-3         ! Ws

L=2*(tfi+2*ch1+wc+tfoo) ! Total Length

dch=2.5e-3      ! coil height without chamfer part
hc=ch+dch       ! total coil height
ti=0.5e-3      !thin wall thickness

Rd=Rs+tg        ! Outer radius of MRF gap
Ro=Rd+ti        ! Inner radius of MRF gap

R=Ro+hc+to      ! Total Radius

Scoil=(hc*(wc+2*ch1)-ch1*ch) ! Cross-section area of coil winding frame
nturn=Ratio_C*Scoil/Ac        ! Number of winding turn

Rc=rrc*nturn*2*pi*(Ro+0.5*hc) ! Resistivity of coil

I=2
JJ=I*nturn/Scoil ! Current density
PP=2*I*I*Rc      ! Power Consumption

```

Figure 3.9: Code for the calculation for Fd and Fo

3.2.3 Post-processing:

The main task of this step is to display the simulated calculation on to graph for easy visualization. First, the magnetic flux simulation is shown in Figure, we can see that the magnetic field intensity most at the 2 positions noted in the graph 3.10b. Then the intensity starts to fade down as we move further from that point. As can be seen in the figure, as predicted the MRF located next to the thin wall has very few magnetic field lines passing across it according to graph 3.10c, however, the other areas are provided with an effective magnetic field, making it visually plausible.

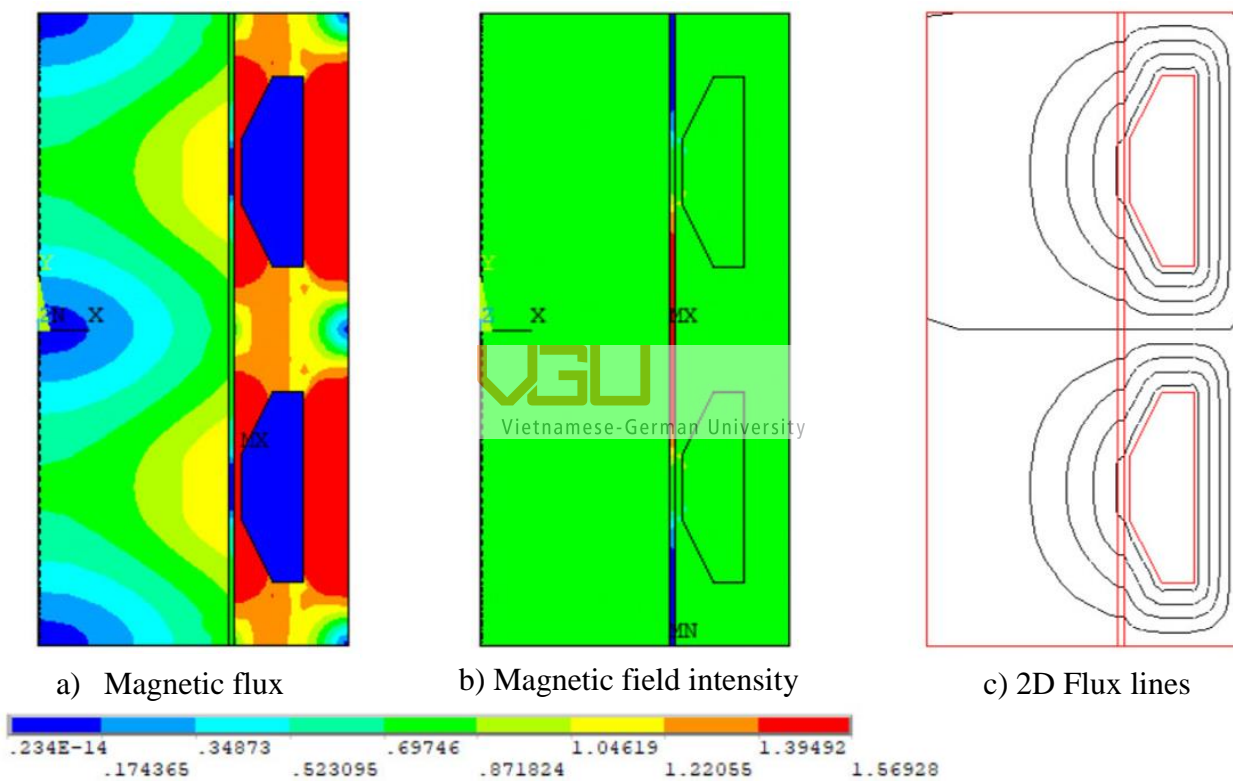


Figure 3.10 : Simulation result of MR damper behavior

For other mechanical results, we access the “Scalar parameters table”. Figure 3.10. As we can see, the maximum force has qualified the stated requirement for our damper. However, the design could be further optimized for attaining a more compact design with the equivalent damping force since the result for damper active force is **120N**.

This number is below our required number (150N). For that reason, an optimization code is applied to find the most optimal design for weight while increasing the damping force to 150N. The optimization is done in ANSYS Workbench.

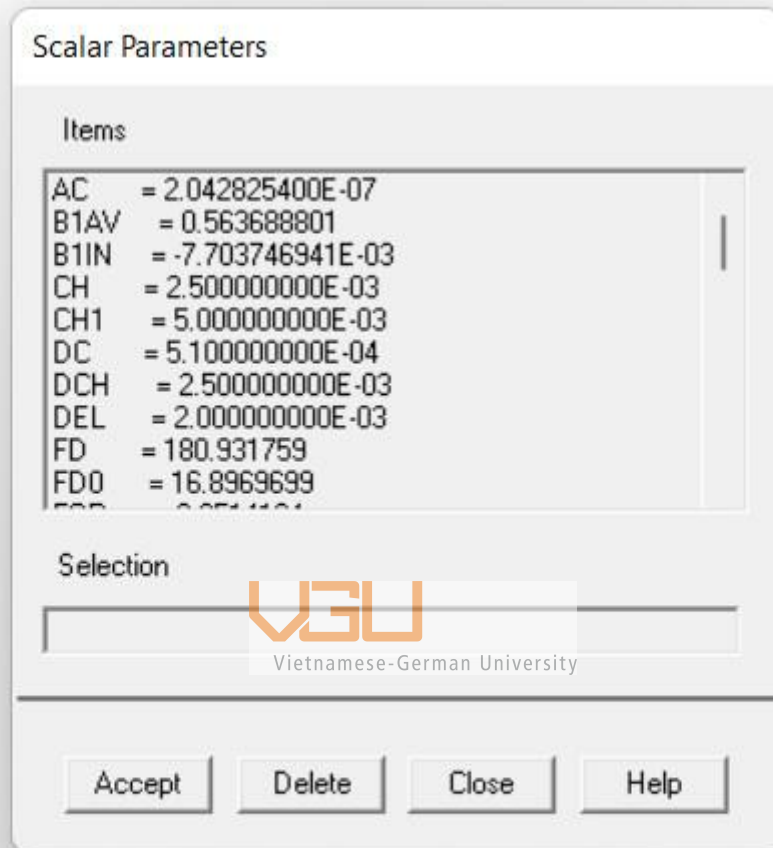


Figure 3.11 : Table of simulation result

3.3 Optimization Process

The simulation will work with the given formula to calculate and predict for the most suitable result for a given condition. Input parameters and Output parameters are determined first.

3.3.1 Input parameters:

The variable that the program can change to find the output according to the user's conditions. These specifications is then simulated within a safe range for modification, we have choose the $\pm 25\%$ margin for each parameter in figure above, since the premise is to find an optimal design with in this size range.

3.3.2 Output parameter:

Parameter that we want to find. In this case, the damper is simulated to find a design that has a large damping force while having a low mass. Therefore this are also declared in Figure (3.11) .

Table of Schematic B2: Optimization				
	A	B	C	D
1	[-] Input Parameters			
2	Name	Lower Bound	Upper Bound	
3	P1 - DCH	0.0024	0.00275	
4	P2 - CH	0.0025	0.00275	
5	P3 - CH1	0.005	0.0055	
6	P4 - TG	0.00045	0.00055	
7	P5 - WC	0.0045	0.0055	
8	P6 - TFO	0.0027	0.0033	
9	P7 - TO	0.00315	0.00385	
10	[-] Parameter Relationships			
11	Name	Left Expression	Operator	Right Expression
*	<i>New Parameter Relationship</i>	<i>New Expression</i>	<=	<i>New Expression</i>

Figure 3.12: Table of *input parameter* and deviation range

In this simulation we focus on finding the smallest weight of the damper while still ensure damping force. Then we can choose the most suitable dimension for our frame design.

3.3.3 Result and conclusion

After the simulation is finished the program list out the most highlighted result, shown in **figure** (3.12). The program evaluates the designs with 2 input conditions: maximize damping force F_d and minimize mass m . All 3 design surpass the required maximum damping force of 150N by exceed to 180N, which make the only argument left is to minimize the weight of the

damper. For the mass feature the program took the heaviest design – design #3 as a reference, design #2 is seen as the most optimal due to being the lightest.

We then collect the dimension data from **the figure**, The design parameters are collected from Figure 3.13 then rounded up and consolidated in **Table 3.1** to ensure realistic measurements for machining parts

Table of Schematic B2: Optimization , Candidate Points						
	A	B	J	K	L	M
1	Reference	Name	P8 - MASS		P9 - FD	
2			Parameter Value	Variation from Reference	Parameter Value	Variation from Reference
3	<input type="radio"/>	Candidate Point 1	0.75048	-3.57%	★★ 185.09	-2.31%
4	<input type="radio"/>	Candidate Point 2	0.73716	-5.29%	★ 181.59	-4.15%
5	<input checked="" type="radio"/>	Candidate Point 3	✖✖ 0.7783	0.00%	★★★ 189.47	0.00%
*		<i>New Custom Candidate Point</i>				

Figure 3.13: Concept scoring by damping force Fd and mass of 3 most optimal design

Table of Schematic B2: Optimization , Candidate Points									
	A	B	C	D	E	F	G	H	I
1	Reference	Name	P1 - DC1	P2 - CT	P3 - CH	P4 - TG	P5 - WC	P6 - TFO	P7 - TO
2									
3	<input type="radio"/>	Candidate Point 1	0.0024438	0.0025481	0.0050766	0.0004985	0.0052397	0.0027625	0.0037997
4	<input type="radio"/>	Candidate Point 2	0.0025278	0.0025364	0.0050272	0.0004793	0.0047499	0.0028815	0.0037002
5	<input checked="" type="radio"/>	Candidate Point 3	0.0027168	0.0025891	0.0050231	0.0004649	0.0054671	0.0028518	0.0038245
*		<i>New Custom Candidate Point</i>	0.002575	0.002625	0.00525	0.0005	0.005	0.003	0.0035

Figure 3.14: input specification of the 3 most optimal designs

After this step, the dimension is put into the ANSYS APDL to re-calculating for the damper mechanical and electrical specification, which is then consolidated in **Table 3.2**. The design parameter chosen with the dimension shown in figure resulted 0.7gr in weight and 181.59N in maximum damping force.

Design parameter				
Total height of coil	$h_c (mm)$	5	Thin wall thickness	$t_w (mm)$ 1
Total width of coil	$w_c (mm)$	20	Sliding shell thickness	$T_o (mm)$ 3.7
Height of chamfer	$h_{ch} (mm)$	2.5	Shaft Radius	$R_s (mm)$ 15
Width of chamfer	$w_{ch} (mm)$	1.5	Total Radius	$R (mm)$ 25
Distance between coil	$l_p (mm)$	4.8	Electrical current	$I (A)$ 2
MRF Length	$L (mm)$	49	Max damping force	$F_d (N)$ 180
MRF gap thickness	$t_g (mm)$	0.5	Non-active damping force	$F_0 (N)$ 17

Table 3.1: Design parameter for the optimized damper

Damper Specification				
Maximum damping force	$F_d (N)$	180	Total radius	$R(mm)$ 25
Non-active damping force	$F_0 (N)$	17	Total MRF length	$L(mm)$ 49
Amperage	$I (A)$	2	Winding Coefficient	C 0.8
Number of winding turns	N_{turn}	244,75	Energy loss coefficient	M 0.9
Coil Resistivity	$R_c (\Omega)$		Magnetic Intensity	$JJ (A/mm^2)$ $7,8 \cdot 10^6$
Mass	$m (kg)$	0.735	PP Power Consumption	$PP(W)$ 19,23

Table 3.2: Damper mechanical and electrical specifications

CHAPTER 4: DETAIL DESIGN

4.1 Assembly Drawing

The Damper body consist of The inner shell, 2 outer shell Damper, piston Cap, piston adapter, O-ring and Piston Guide Bush (Figure 4.1)

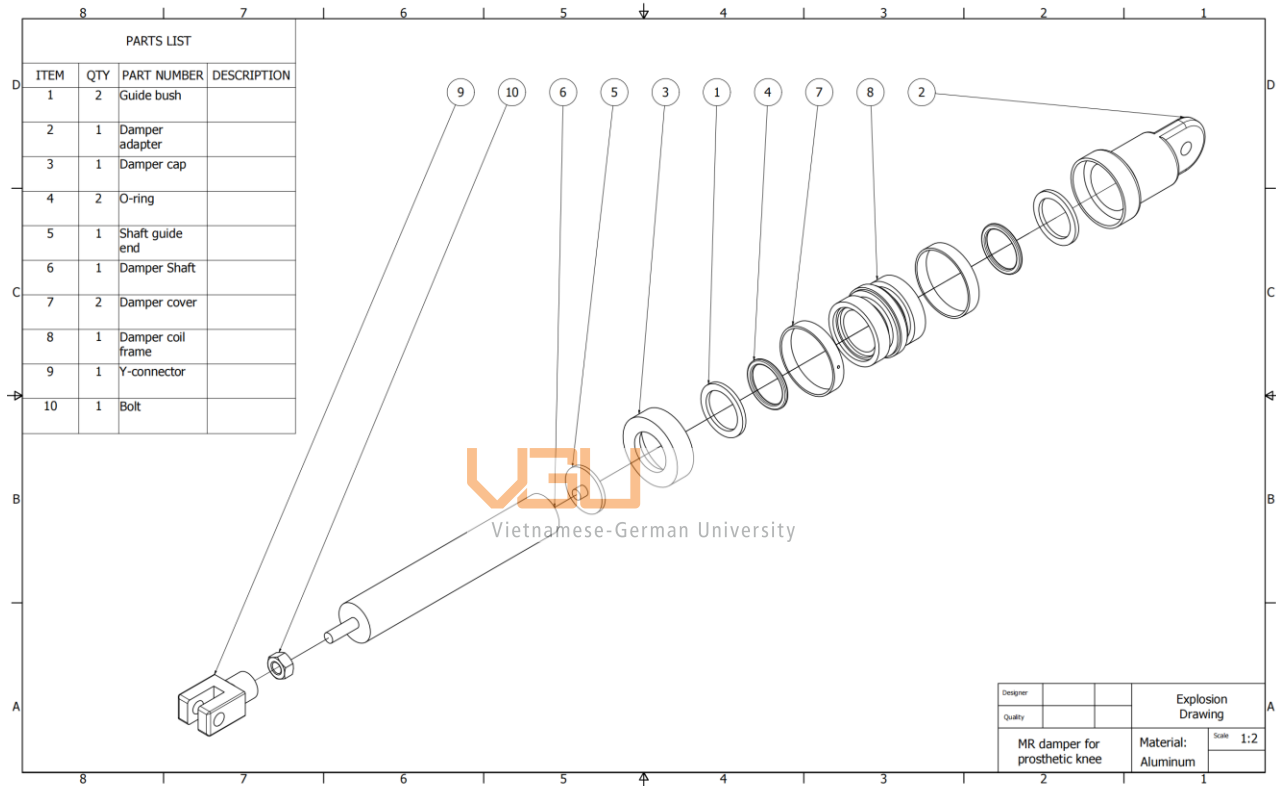


Figure 4.1: Explosion drawing of MR Damper

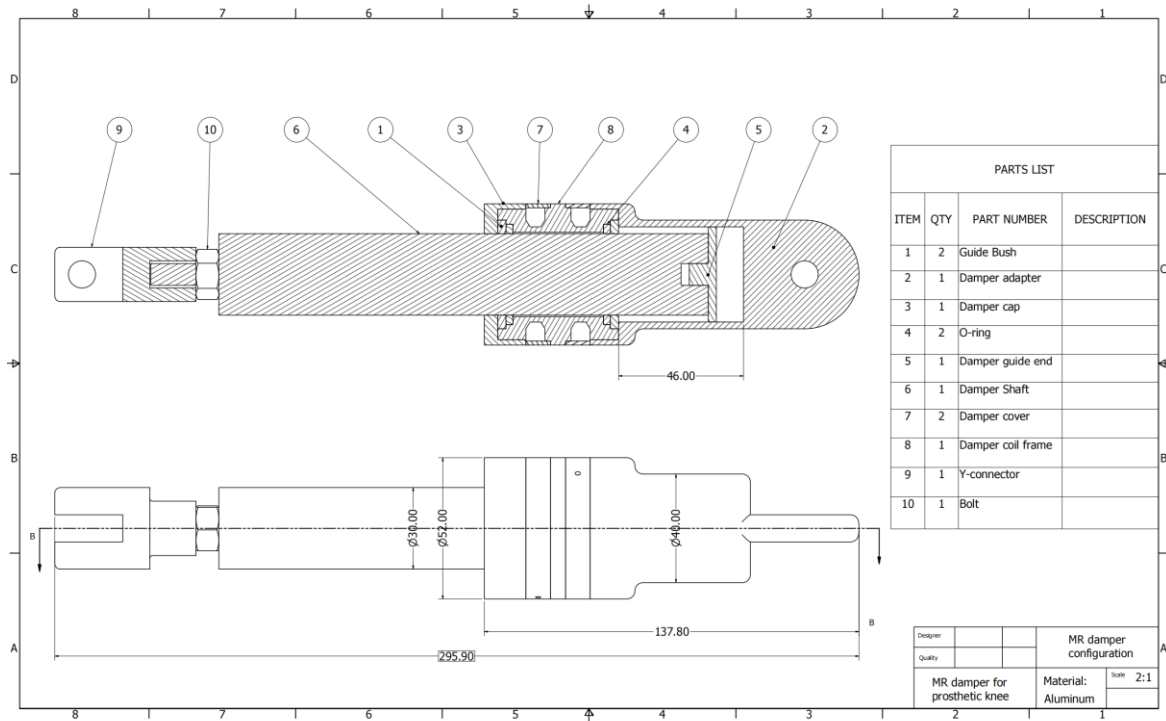


Figure 4.2: Assembly drawing of MR Damper



Figure 4.3: MR damper assembly with prototype prosthetic knee

4.2 Detail Drawing of MR Damper

4.2.1 Coil frame:

The main compartment of the chamber body since it contained the groove for winding the copper wire, the inner circumference of this cylinder will make direct contact with the MRF. To completely seal the MRF, the part is designed with grooves for positioning the O-ring and guide bush. The groove for the O-ring need to fit so that when the damper is assembled, which is when the O-ring is compressed by 15% (illustrated in **figure 4.8**). With the O-ring is 3mm thick, to compress 15% , the thickness gap for the O-ring should be :

$$t_{OR} = 3.085 = 2.55 \text{ (mm)}$$

Commercial guide bushes usually have an inner diameter and outside diameters from 28mm to 30mm. The need for minimum weight mean it should be chosen with an inner diameter of 28mm. Next, the guide bush is designed with the inside diameter to fit loose with the piston and the damper body, TI tolerance is chosen since using larger upper tolerance for a loose fit can help the piston move more freely and give the guide bush space to vibrate when orienting. The two heads of the damper body are designed with thread to make it easier to install the damper cap and damper adapter.

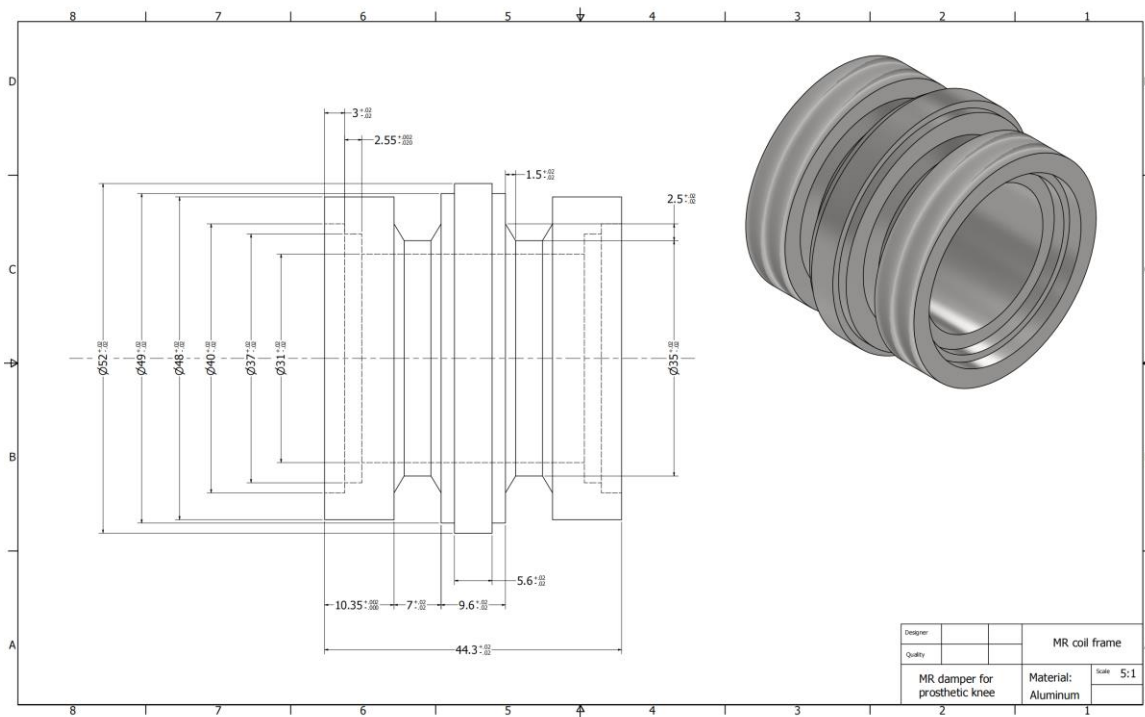


Figure 4.4: Detail drawing for MR coil frame

4.2.2 Damper cover

Damper cover are essentially the cover for the damper to protect the MR coil from outside environment. The damper is designed as a loose attachment since its purpose is only to cover the coil and have a hole for winding, the cover ring will be clamped between the middle raised edge of the inner frame and the damper cap

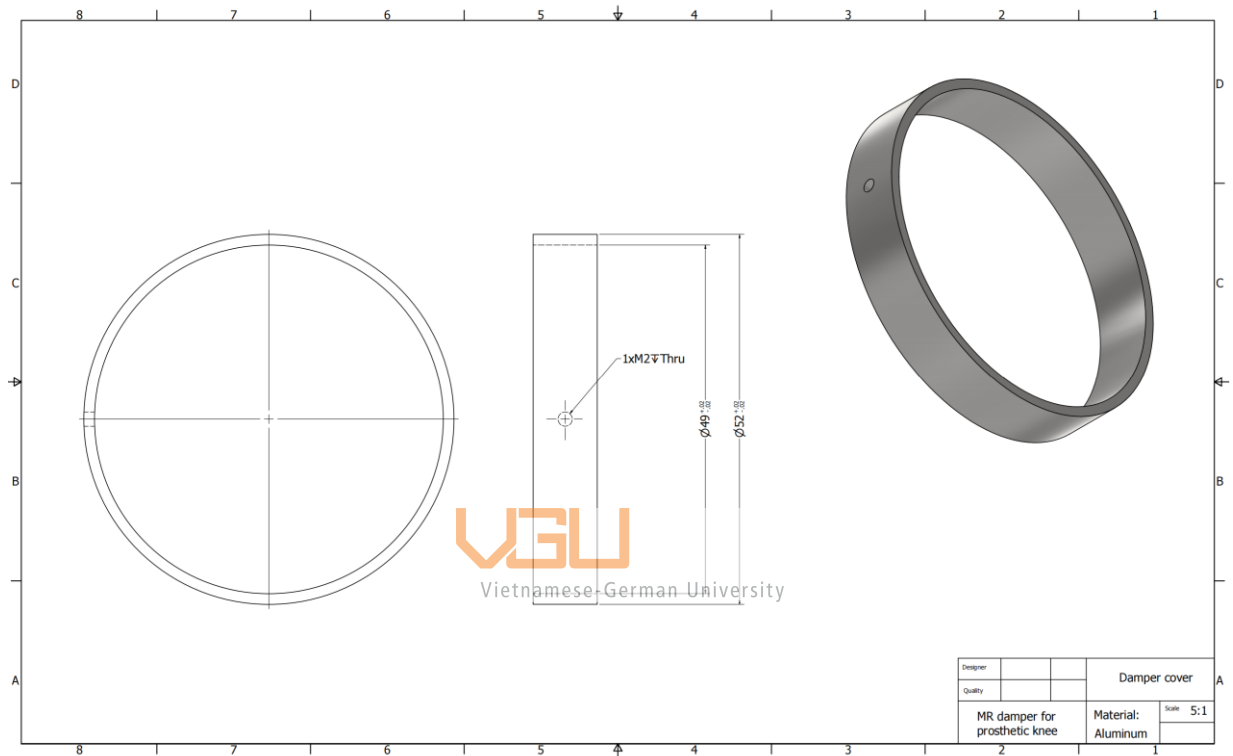


Figure 4.5: Detail Drawing for damper cover

4.2.3 Damper Body Adapter:

main use is to connect to the damper body and also serve as a damper cap, keeping the head fixed and linked to the frame of the damper body. The height of piston cap can be varied when designing to adjust to the suitable dimension. The tolerance for the Hole is set as TI12 for freely moving.

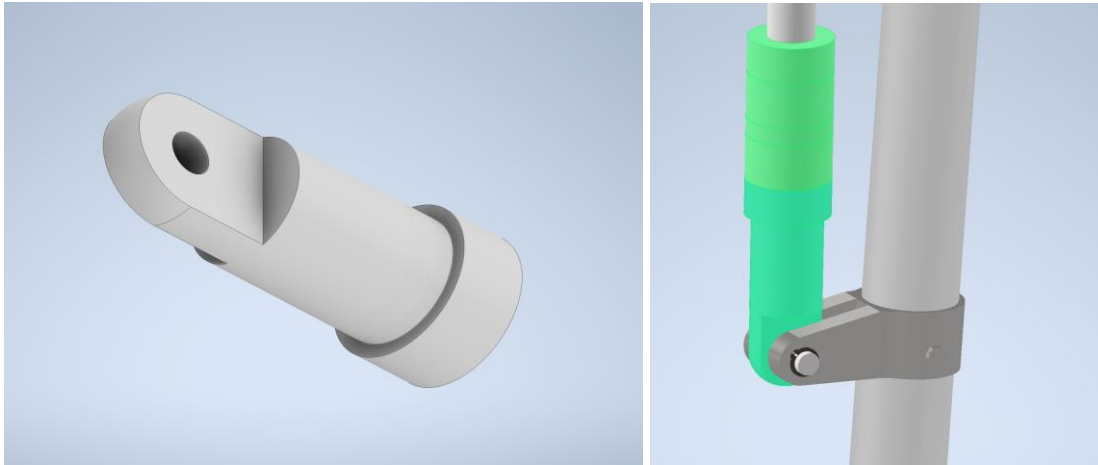


Figure 4.6: Detail Drawing for Damper Adapter

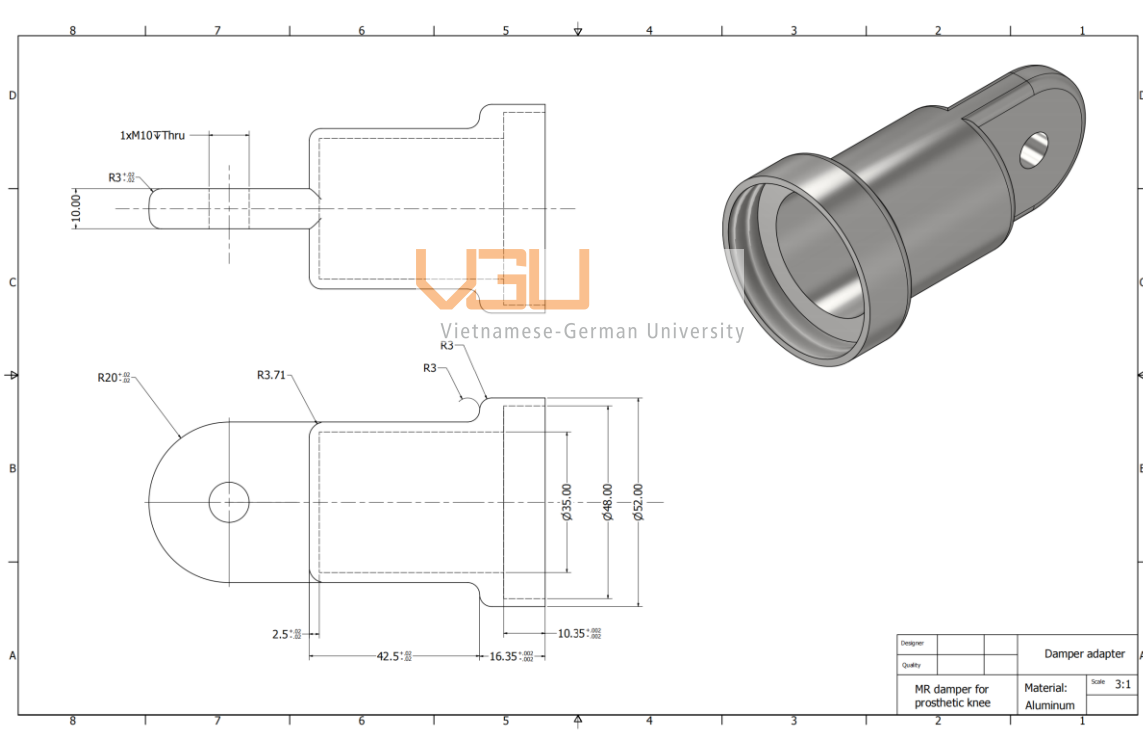


Figure 4.7: Detail Drawing for Damper Adapter

4.2.4 O ring

main function is to keep the seal between the shaft and damper body, make sure no MRF can escape the damper. The O-ring is used most effectively when compressed at the compression rate required by the manufacturer, when the ring is compressed, it will create elastic disformation to help fill in the gap, support the MRF sealing and have time to use. Long service life thanks to the elastic resilience of the inner material.

O-ring is easily damaged when used at high speed and the temperature is too high leading to hardening of the material, fortunately our o-ring design runs at very slow speed so the temperature is not an issue. In this case, we use O-ring NBR 70 Neurometer with the recommended compression rate is 15%.



Figure 4.8: O-ring

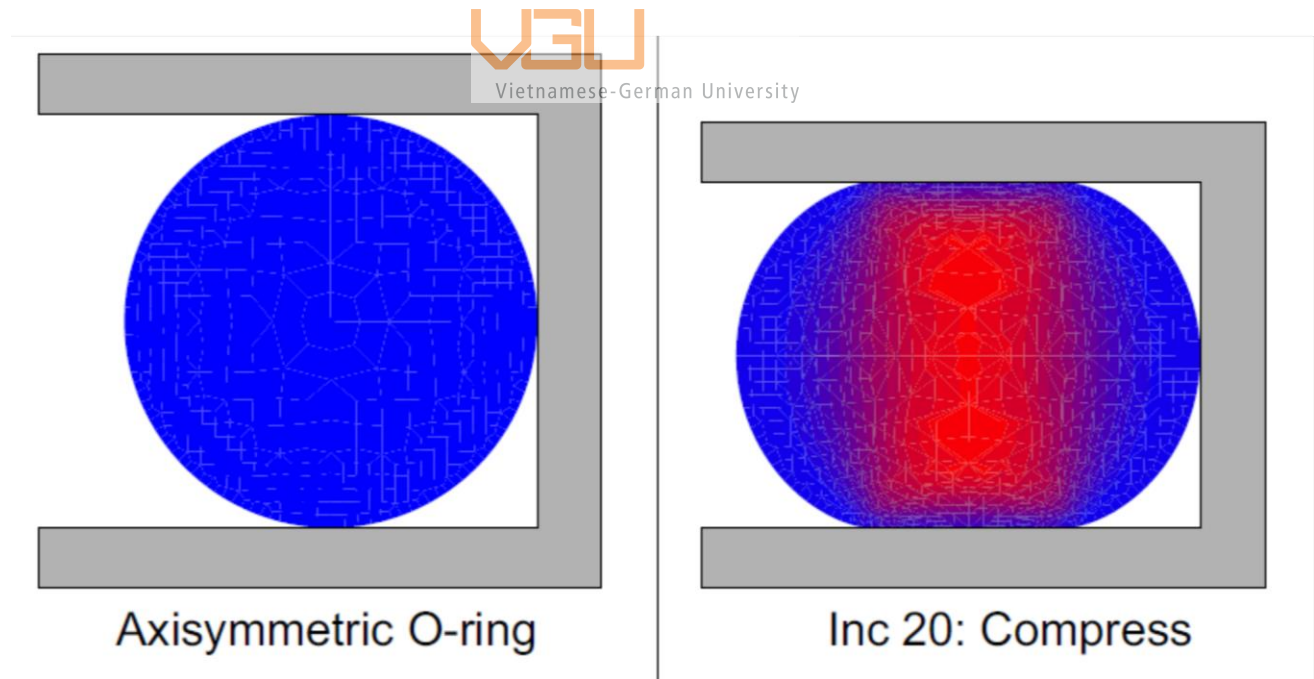


Figure 4.9 : O-ring behavior under compression

4.2.5 Guide Bush

The guide bush help the piston to align the piston shaft with the damper body which reduce material wear and heat generation due to material vibration and friction. In this case the guide bush also helps locate the O-ring in the correct position for securing the MRF.



Figure 4.10: Guide Bush

4.2.6 Piston Cap

Main function of piston cap is to secure the upper head of the damper, securing the MR fluid in the damper by securing the guide bush and the O-ring. The design uses a threaded mechanism to connect these 2 parts together

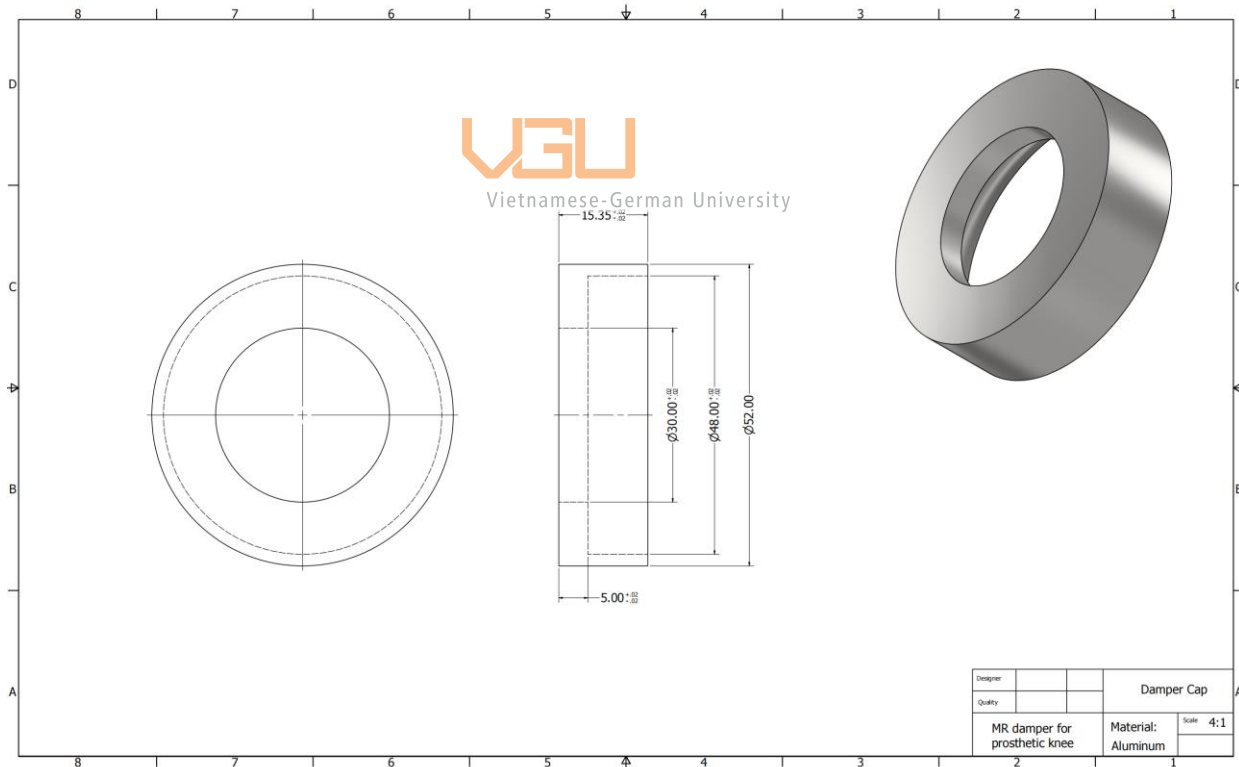


Figure 4.11: Detail drawing of damper cap

4.2.7 Damper shaft

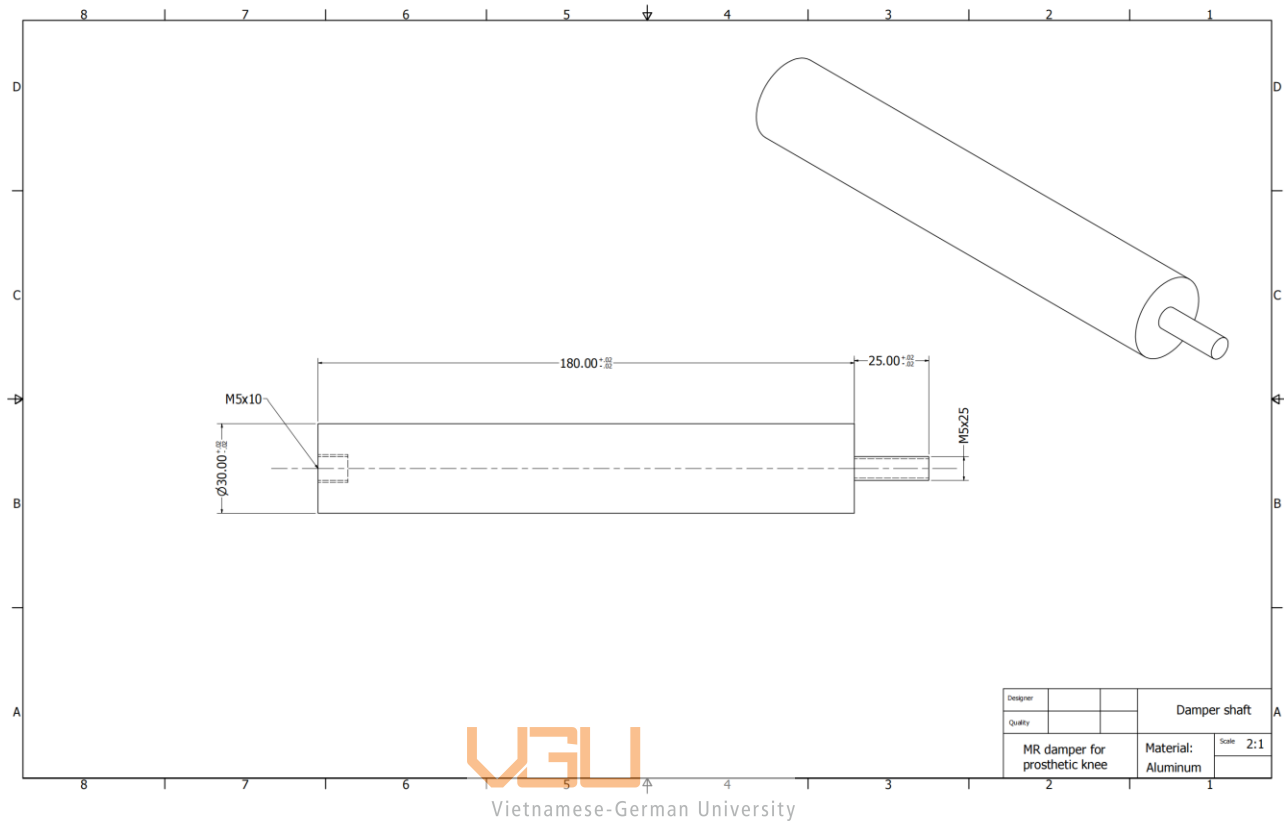


Figure 4.12 : Detail Drawing of damper shaft

The damper shaft functions to convert the rotating motion of the prosthetic knee into reciprocating motion within the damper. The shaft is configured as a straight shaft, the right side has a convex thread to connect to the y-connector, which receives motion directly from the movement of the L2 part. On the other end of the shaft is a threaded hole for connecting to the shaft guider.

4.2.8 Shaft guider

The main function of shaft guider when connect to the shaft is to help guiding and aligning the movement direction of the shaft, it acts in similar manner to a guide bush in this scenario. Furthermore, the range of movement of the damper is also limited by this part when connected to the damper adapter.

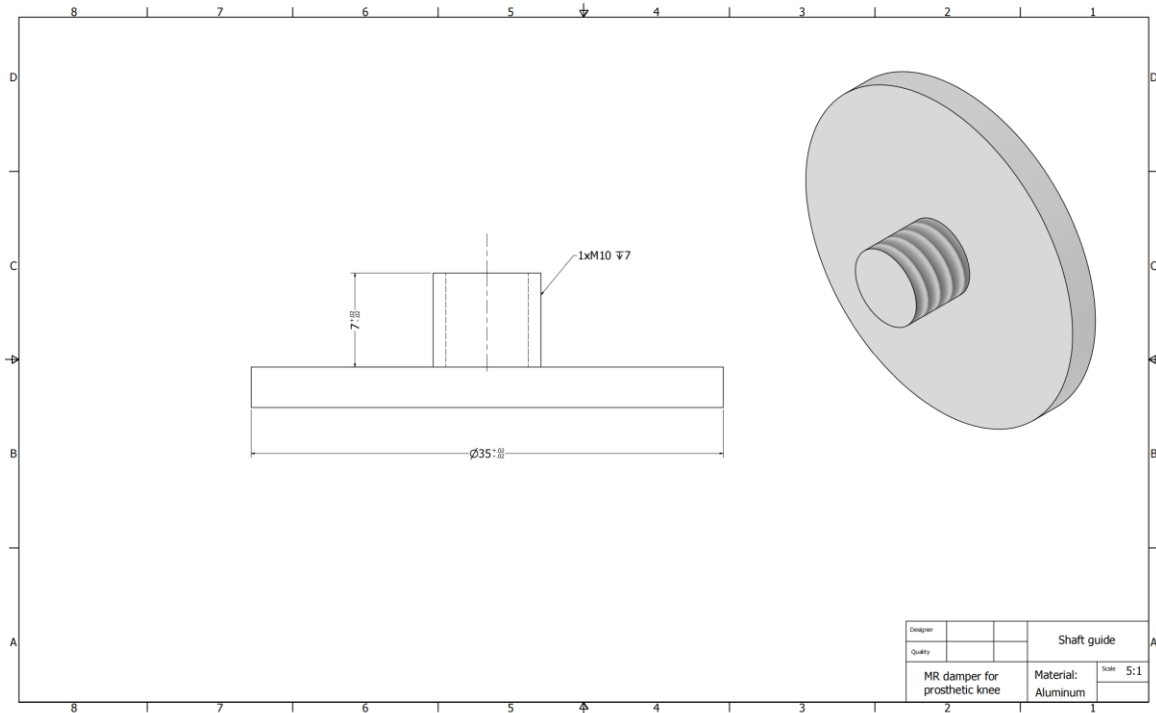


Figure 4.13 : Detail drawing of shaft guider



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4.3 Additional parts

4.3.1 Extended L2:

In this design we decide to extend the end of part L2 to a L shape to create space for designing the damper. The length of the extended part should be long enough for the damper while not too long to not create too much weight and may cause to push the knee centroid back posterior. The 50mm long side is added to satisfy these criteria, the motion amplitude and material resistance are described in the simulation.

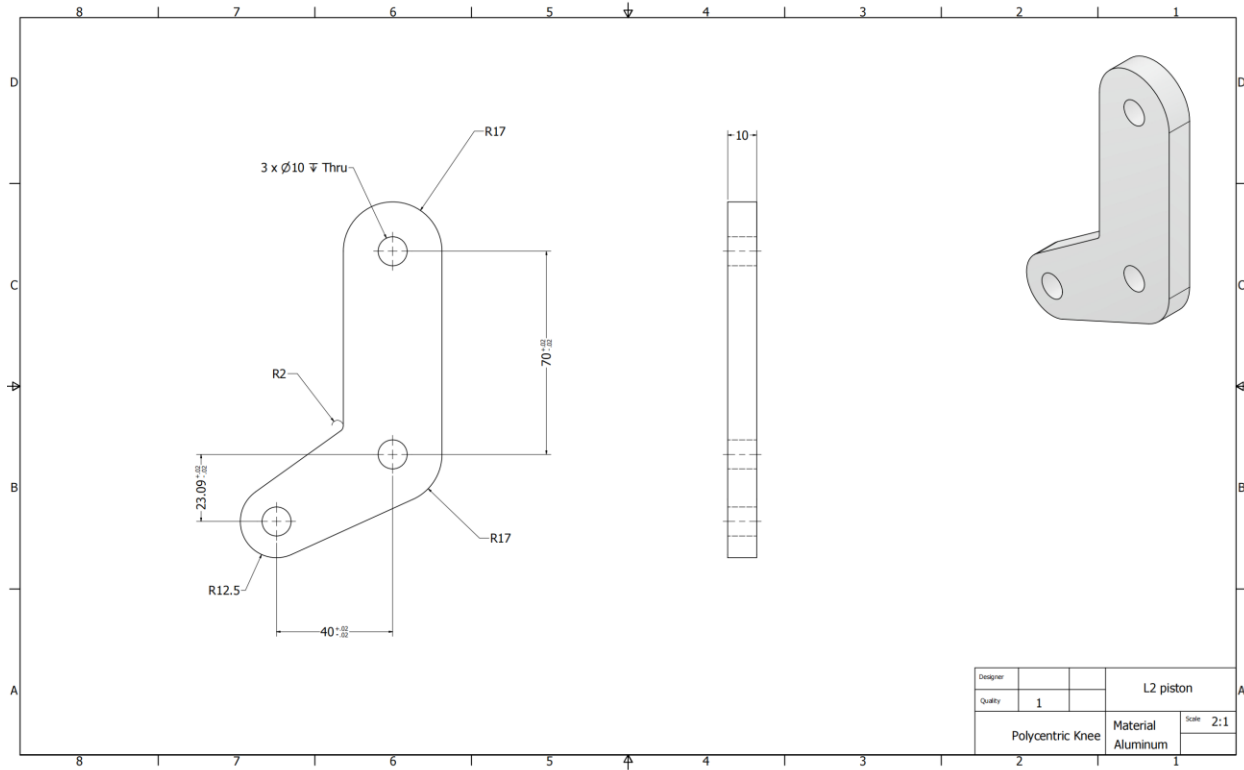


Figure 4.6: Detail Drawing for extended L2

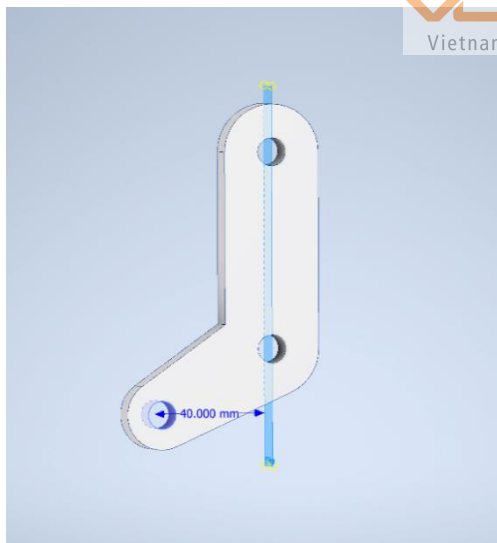


Figure 4.7: Horizontal distance of the extended hole



Figure 4.8: L2 assembly

4.3.2 Bottom mount

is used commercially in damper design, a piston needs a part to hold the damper body firmly in place, keep the damper right on the rotational plane, so that when the piston moves, accurate data will be obtained.

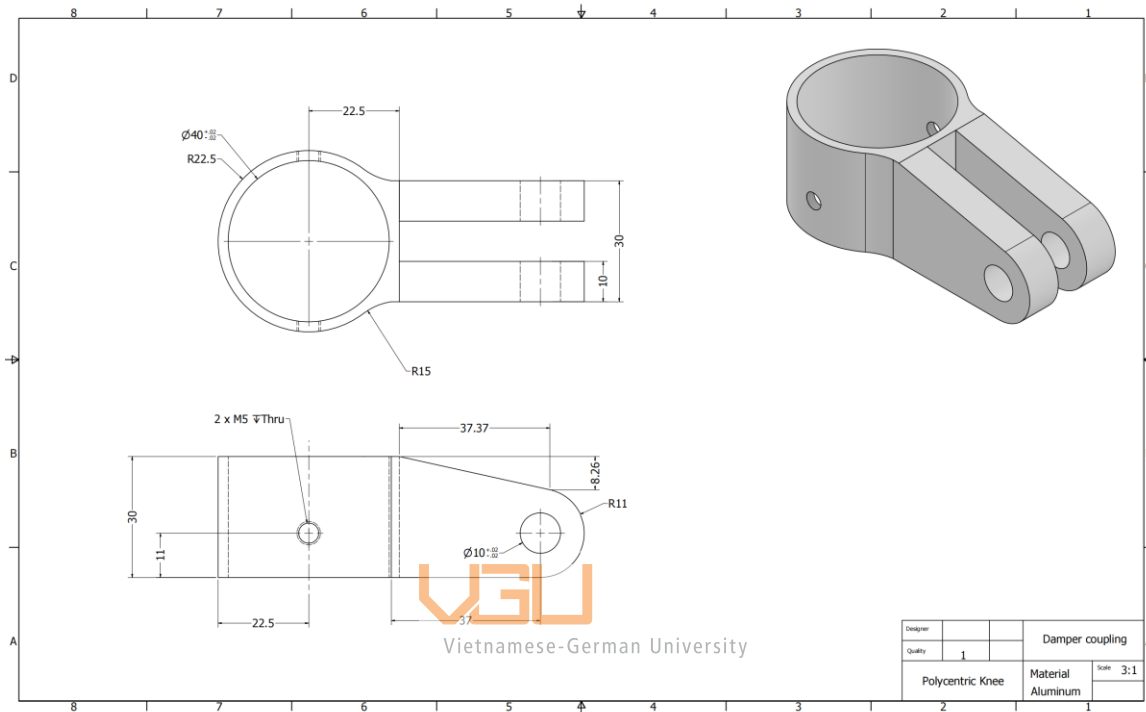


Figure 4.9: Guide Bush drawing

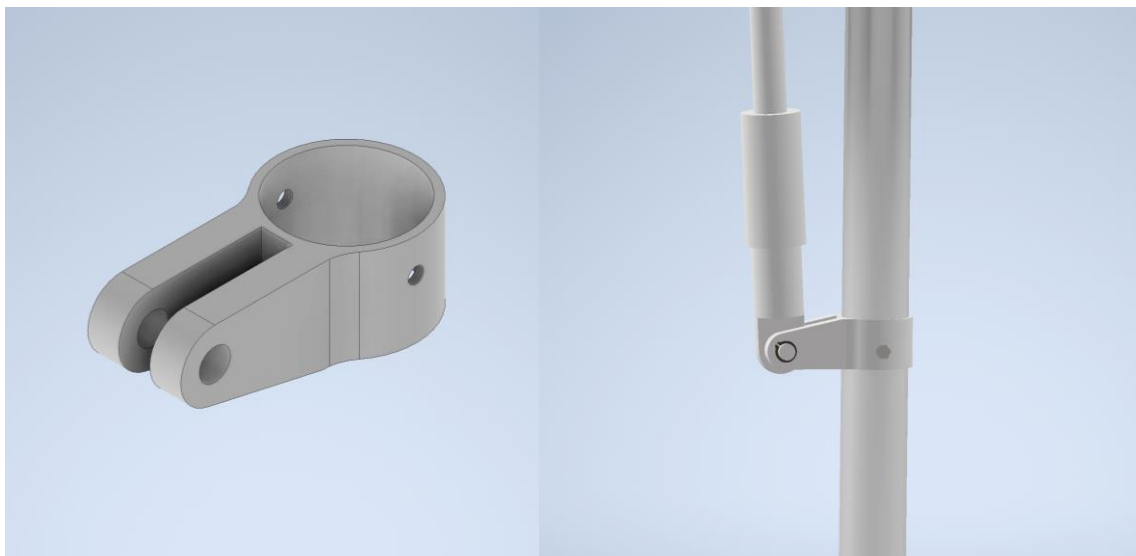


Figure 4.10: Guide Bush design

Figure 4.11: Guide Bush assembly

4.3.3 Y connector

Y connector has the function to make the piston shaft can rotate and bear the direction of L2 to rotate comfortably in the damper body. Design connection with Y connector in L2 bar should use loose connection to do not restrict user movement, therefore TI12 tolerance is chosen for the L2 extended hole.



Figure 4.12: Guide Bush

CHAPTER 6: CONCLUSION AND FUTURE WORK

Conclusion

To summarize the conceptualizing, calculation, designing and assembling stages of the thesis project have been conducted. The prototype is made and the result is meet the given requirement, however, there is still room for further improvement. After the research and implementation of the thesis:

" DESIGN, FABRICATION AND TESTING OF MR DAMPER FOR PROSTHETIC LEG".

The following criteria were achieved through this study:

Understand the state of the smart suspension and anti-vibration industry with future opportunities and challenges, as well as inadequacies and limitations, especially in terms of size and weight for useful applications. Due to the flexibility in control output force, the damper size and the amount of MRF used must be compensated, which, creates disadvantages when designing. Although many studies have evaluated the superiority in damping force of the design mechanism of flow mode compared with slide mode. Through concept selection and calculation, we have been able to demonstrate that the MR damper can achieve damping force equivalent to a damper made with slide mode configuration by using a double coil slide mode configuration.

The damper is then performed optimization on ANSYS to get the most optimal value to depend on the conditions for maximum damping force and minimum for the net weight of the MR damper, which, the damper also proves to be capable of adjusting the knee swing speed for commercial use for different age groups.

Future Work

In order to increase the performance and safety of the damper, a study is proposed on combining the functions of the MR by creating a control system with PIC and PID control methods integrated with other components. different types of sensors. Creating an integrated damper with a prosthetic leg that can adjust the walking speed to suit the user while acting as a shock absorber damper. Noted that when designed as a shock absorber, a breaking mechanism should be integrated with the control loop for the damper to prevent overextension of the knee, which may cause the knee to overlocking.

In addition, with a damping force of up to 180N and a compact design, the damper represents suitable for any purposes other than integration for prostheses such as shock absorbers for systems subject to a lot of vibration.



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