VISCO HYDRAULIC (DYNAMIC SUSPENSION SPOOL VALVE) SHOCK ABSORBER

A Final Year Project Report

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of the Requirements for the Degree of
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ABSTRACT

In this world of modernity everything is evolving at a very greater pace so does the automobile. Fast moving cars follow the same trajectory of evolution to meet human demands, comfort, safety, and reliability etc. Racing community has evolved to a point where a small mistake can cost racer and his sponsors a lot in a jiffy. When we talk about Formula one, Desert rally and off-road racing, each component should be reliable in every changing environmental condition. As alluded to the above, a vehicle must have an adaptive suspension and effective damper which is essential for modern racing.

For this purpose, Dynamic Suspension Spool Valve (DSSV) dampers are particularly made for these applications. In these types of dampers, we control the damping by changing flow area in which the fluid is flowing. In spool valve technology we can easily change the orifice opening present on the spool valve which in result affects our overall damping. In MR dampers we can control the damping by changing the viscosity of the fluid.

The DSSV damper will provide a serene ride quality to the active damping system and is cheaper and simpler when compared to these latest technologies like MR and ER. The ride quality of conventional dampers is uncomfortable on varying road conditions, several active damping technologies like MR and ER damping are introduced which are rather expensive and much complicated.

ACKNOWLEDGMENTS

For the final outcome of this project, lot of guidance and assistance was required. We feel much honored to have all of them along with our journey. Supervision and assistance of our respected teachers made all this work possible.

We would like to express our special thanks to our Advisor (Dr. Samiur Rehman Shah) as well as our Head of Department (Dr. Emad uddin) who gave us the golden opportunity to do this wonderful project on the topic (Design of Vicso Hydraulic Dynamic Suspension Spool Valve Shock Absorber). They also helped us in doing a lot of Research as a result of which we came to know about so many new things for which we are thankful to them. Secondly, we would also like to thank our parents and friends who helped us a lot in finalizing this project within the limited time frame.

We are thankful to and fortunate enough to get constant encouragement, support, and guidance from all Teaching staffs of our department which helped us in successfully completing our project work.

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TABLE OF CONTENTS

LIST OF FIGURES

ABBREVIATIONS

MED	Mechanical Engineering Department
DSSV	Dynamic Suspension Spool Valve
CAD	Computer Aided Design
CNC	Computerized Numerically Controlled
F-V	Force-Velocity
MR	Magneto-Rheological Dampers
ER	Electro-Rheological Dampers
$\boldsymbol{\rho}$	density (kg/m3
$\mathbf{V}$	volume (m3)
$\mathbf{m}$	mass (m)
$\mathbf{K}$	Bulk modulus
$\boldsymbol{\mu}$	dynamic viscosity
$\boldsymbol{v}$	kinematic viscosity
$\mathbf{h}$	height (m)
$\mathbf{P1}$	Pressures (psi)
$\mathbf{Re}$	Reynold’s No
$\mathbf{D}$	Diameter of the pipe (m)
$\mathbf{Q}$	Discharge of fluid (m3sec)
$\mathbf{A}$	Area of flow of fluid (m2)
f	friction of pipe
$\mathbf{Cd}$	Discharge coefficient
$\mathbf{Ae}$	Effective area of flow (m2)
$\mathbf{x}$	extension in spring (m)

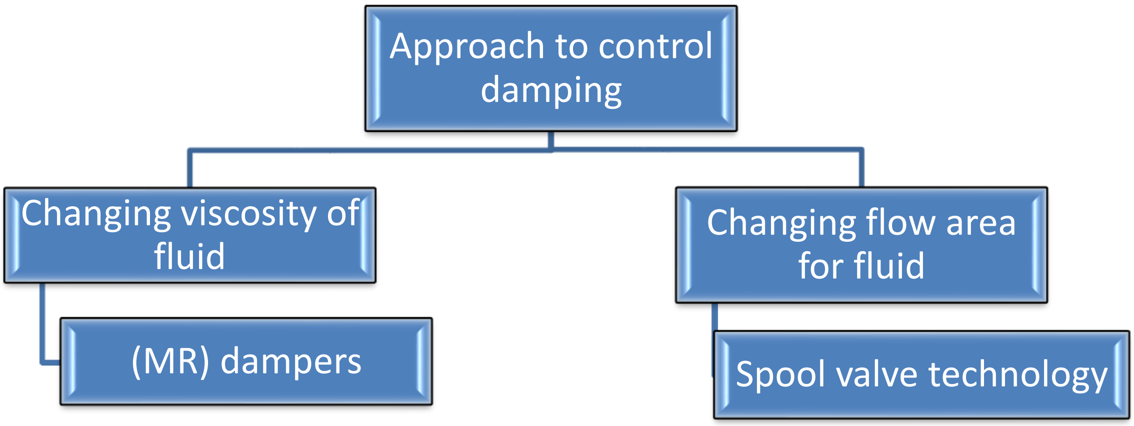
NOMENCLATURE

$\boldsymbol{F_R}$	Collector heat removal factor
$\boldsymbol{F_R U_L}$	Thermal losses of solar collector ((W/m^2)/°C)
$\boldsymbol{F_R(\tau\alpha)}$	Conversion factor (optical efficiency of solar collector)

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

The ride quality of conventional dampers is uncomfortable on varying road conditions, several active damping technologies like MR and ER damping are introduced which are rather expensive. The DSSV damper will provide similar ride quality to the active damping system and is cheaper and simpler when compared to these latest technologies.



1.2 Objectives

The objectives of thesis are listed in detail below.

1.2.1 Adaptive damper with passive technology

A DSSV damper can compete with the latest active damper technologies which include MR dampers, ER dampers and motorized hydraulic dampers. These technologies are much costly and only designed for luxury cars. DSSV dampers use a simple spring and sleeve assembly to provide adaptive damping which makes it much attractive when compared to the likes of other latest technologies that require complex designing and manufacturing. DSSV technology also has the upper hand in heat management when compared to other technologies.

1.2.2 Better damping than conventional systems

A conventional damper uses shims (flexible disks) to cover and uncover the piston orifices whereas DSSV damper uses its spring-sleeve assembly (spool valve) to cover and uncover the orifices. The major benefit of this modification is that it now has better life than conventional ones as the flexible disk is subject to fatigue which affects its strength and stiffness. With the introduction of spool valve, the life is enhanced and there is no change in the characteristics of orifice with respect to time and use.

1.2.3 Optimized design of spool valve aperture

- Any desired force velocity curve characteristics can be obtained by using specifically designed orifice shapes. Different shapes of orifices can be used to obtain damping characteristics for different applications.
- Conventional shim dampers require excessive trial and error test to achieve required damping characteristics whereas DSSV damping characteristics can be mathematically predicted.
- DSSV dampers can be easily tuned whereas conventional shim dampers cannot be tuned according to varying road conditions

1.3 Project Breakdown

The project is divided into two main stages. They are explained in great detail below.

1.3.1 Designing

A DSSV damper can compete with the latest active damper technologies which include MR dampers, ER dampers and motorized hydraulic dampers. These technologies are much costly and only designed for luxury cars. DSSV dampers use a simple spring and sleeve assembly to provide adaptive damping which makes it much attractive when compared to the likes of other latest technologies that require complex designing and manufacturing. DSSV technology also has the upper hand in heat management when compared to other technologies.

1.3.2 3-D Modelling

Developing the 3-D model of the damper components using SolidWorks and the assembly of these components. The main feature of our model is the spool valve assembly, two spool valve assemblies are designed independently for compression and rebound. By providing independent spool vale assemblies for compression and rebound the compression ad rebound curves can be tuned separately.

CHAPTER 2: LITERATURE REVIEW

2.1 Damper Fluid Mechanics

Various types of oils can be used in dampers, the primary concern is that it should have low coefficient of thermal expansion and so that during high temperature the oil does not undergo expansion. Sometimes mineral oil can be used, and synthetic oil is even more reliable, but it is expensive. In any damper viscosity of the fluid is not necessary but it plays its role in lubrication and to minimize leakage.

While applying Bernoulli's equation for the calculation of damping provided by the damper certain assumptions are made, of which first assumption is the density of the fluid which is assumed to be constant, and fluid is assumed to be incompressible in nature.

2.2 Fluid Properties

Fluid usually refers to any liquid or gas. Although most of the dampers are designed based on liquid fluids but dampers with gas as fluid are also still used now a day. Gas dampers are cheap, but they are not widely used because they cannot provide large damping, thus used in motor bikes and for light duty jobs. Gas dampers are also called air dampers [1].

The properties of damper fluids, mostly a mineral oil is basically classified in broad categories which are given below:

- Chemical structures and additives
- Thermal expansion
- Viscosity
- Density
- Compressibility
- Thermal capacity

- Thermal conductivity
- Vapor pressure

2.2.1 Density

"The density, represented by r (rho) is, of course, the mass per unit volume:

$$\boldsymbol{\rho = \frac{m}{v}} \qquad \textbf{(2.1)}$$

Density of the fluid is very important parameter for good performance of the damper. The density should be approximately equal to 860Kg/m3[2].

2.2.2 Compressibility

"The density of a liquid is affected by the pressure, in a fairly linear way for practical damper pressures.

$$\boldsymbol{\rho}=\boldsymbol{\rho_1}[\mathbf{1}+\boldsymbol{\beta}\ (\boldsymbol{P}-\boldsymbol{P_1})] \qquad \textbf{(2.2)}$$

Here, β is the compressibility of the fluid, which is the reciprocal of the bulk modulus K. A mineral damper oil has very large hydrocarbon chains due to which they do not pack in compact manner thus giving a high compressibility than ordinary liquids like water which comprises of small water molecules. For pure oil bulk modulus is about 1.5GPa, and reference pressure P 1 about 1 atm. Pressure (101325 Pa) giving compressibility β about 670 × 10^6/MPa = 0.07% /MPa. With required tolerance about 0.5% / MPa. In a practical damper the working pressure of 5 MPa will increase density by 0.35 % [2].

2.2.3 Viscosity

"Viscosity is defined as the resistance to shear motion. It is one of the most important parameters of the damper. Consider two plates with a liquid flowing in between, upper plate is moving with velocity 'V' the velocity gradient will be:

$$\frac{\mathbf{dV}}{\mathbf{dY}} = \frac{\mathbf{V1}}{\mathbf{h}} \qquad \mathbf{(2.3)}$$

The plate with area A will provide a shear force F opposing the motion with

$$F = \mu A \frac{dv}{dy} \qquad (2.4)$$

Where μ is the coefficient of dynamic viscosity, with the units Ns/m^2 or Pa [2]. In fluid dynamic problems the quotient m/r occurs frequently, and this has been given the name, kinematic viscosity which is given by:

$$\boldsymbol{v} = \frac{\boldsymbol{\mu}}{\boldsymbol{\rho}} \qquad \mathbf{(2.5)}$$

2.3 Governing Equations for Fluid Flow

The equations governing fluid flow through orifices are discussed in detail below.

2.3.1 Equation of continuity

The equation of continuity is based on the principal of conservation of mass for fluids. The mass flow rate in is equal to the mass flow rate out assuming non-compressible fluid. If fluid is assumed to have constant density, then equation of continuity is better explained in terms of volume flow rate.

2.3.2 Bernoulli's equation

"Bernoulli's equation is defined as the conservation of energy of flowing fluid assuming constant density."

Bernoulli’s equation is valid for fluid with zero viscosity and fixed density only.”[2] Bernoulli’s equation is expressed as:

$$p_1 + \frac{1}{2}\rho\mu_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho\mu_2^2 + \rho g h_2 \qquad \textbf{(2.6)}$$

For damper technology there is very small change in the potential energy of the system so ρgh term can be neglected and Bernoulli’s equation is simplified as

$$p_1 + \frac{1}{2}\rho\mu_1^2 = p_2 + \frac{1}{2}\rho\mu_2^2 \qquad \textbf{(2.7)}$$

2.3.3 Pipe flow

“Flow through any pipe was investigated by the Osborne Reynolds, and he provided a criterion for determining the type of flow through pipe of any shape. He came out with a formula that indicates the flow type, either it is streamline, turbulent or transition flow (both).

The criteria for this are the Reynold’s Number:

$$R_e = \frac{\rho\mu d}{\mu} \qquad \textbf{(2.8)}$$

For a circular cross section of the pipe

Re < 2000	**Laminar flow**
Re > 4000	**Turbulent flow**
2000 < Re < 4000	**Transition flow**

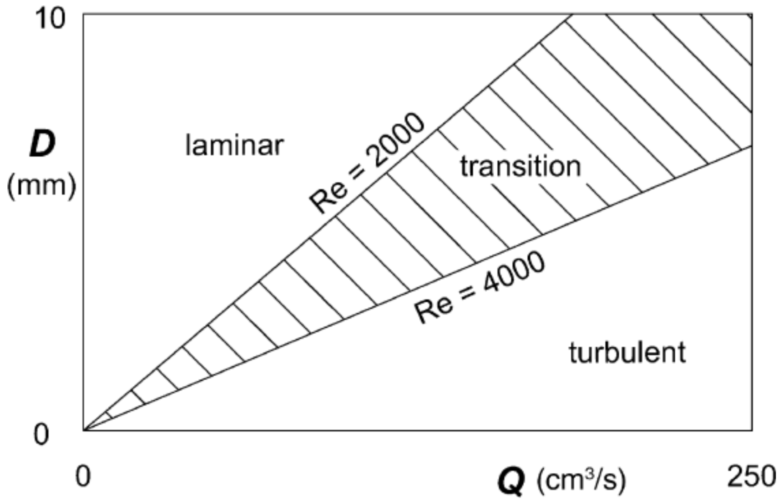


Figure 1 *Laminar / transition / turbulent flow regimes for various*

The flow rate through the circular cross section area is given by

$$\boldsymbol{Q = \frac{\pi}{4} d^2 \mu} \qquad \textbf{(2.9)}$$

So, Reynolds's number can also be expressed as:

$$\boldsymbol{R_e = \frac{4\rho Q}{\pi \mu d}} \qquad \textbf{(2.10)}$$

The figure 2.1 is showing turbulent, laminar and transition flow for various combinations of diameter and volumetric flow rate. In damper both types of flow occur but transition flow causes the uncertainty in the results and so it causes problems in normal operation of the damper. Thus, inconsistency occurs in the results.

For turbulent flow the pressure drop along a pipe is approximately proportional to the square of the mean velocity.

The mean speed is given by the formula:

$$\boldsymbol{\mu = \frac{Q}{A}} \tag{2.11}$$

The dynamic pressure will be

$$\boldsymbol{q = \frac{1}{2}\rho\mu^2 = \frac{\rho Q^2}{2A^2}} \tag{2.12}$$

So, the stagnation pressure loss will be

$$\Delta \boldsymbol{P_{st} = Kq} \tag{2.13}$$

Where K is the pressure loss coefficient. The pressure loss is the loss of stagnation pressure, but for a pipe of constant cross-sectional area the dynamic pressure is constant, so ΔP_{st} is seen as the change of static pressure.

The friction faced by the flow of liquid through the pipe is also related to the pressure loss coefficient by:

$$\boldsymbol{K = f\frac{L}{D}} \tag{2.14}$$

Then the pressure drop will be:

$$\Delta \boldsymbol{P_{st} = f(\frac{L}{D})\frac{1}{2}\rho\mu^2} \tag{2.15}$$

Which is also known as the Darcy–Weisbach equation. This equation gives the pressure drop as a function of pipe friction.” [2]

2.3.4 Relation between Flow Rate and Pressure Differential

"The volumetric flow rate 'Q' of damper oil through an orifice in practical condition is defined by the equation:

$$Q=C_d A \mu_T \tag{2.16}$$

Where

- Cd is the discharge coefficient having a value about 0.7 for dampers
- A is the passage minimum area
- μ is the exit speed
- μt is the theoretical speed found from the Bernoulli's equation by putting first reservoir at zero velocity, and to end at the exit vena contracta, where static pressure equals that of second reservoir, then

$$\frac{1}{2}\rho\mu_T^2 = P_1 - P_2 \tag{2.17}$$

$$\mu_T = \sqrt{\frac{2(p_1-p_2)}{\rho}} \tag{2.18}$$

Where,

P1 –P2 = the pressure difference across the orifice ρ= density (constant)

The real speed is less because of friction due to turbulence and viscosity, giving a velocity coefficient CV defined as the ratio of the mean speed at the vena contracta over the ideal speed, so:

$$\mu=C_V \mu_T \tag{2.19}$$

Also, effective exit area, A_E, at the vena contracta, is less than the orifice area A, the ratio of areas being the area coefficient C_A, so:

$$A_E = C_A A \tag{2.20}$$

And discharge coefficient is the product of velocity and area coefficients.

$$C_d = C_V C_A \tag{2.21}$$

Under practical conditions the discharge coefficient for damper is assumed to be 0.7. The pressure difference across the orifice of cross-sectional area 'A' and flowing incompressible zero Viscosity fluid having density ρ with volumetric flow rate Q using Bernoulli's equation is given by:

$$p = \frac{1}{2}\rho(\frac{Q}{C_d A})^2 \tag{2.22}$$

For pipe flow analysis with dynamic pressure loss coefficient K, the pressure will be:

$$p = K\frac{1}{2}\rho(\frac{Q}{A})^2 \tag{2.23}$$

The pressure loss coefficient 'K' is related to discharge coefficient Cd by the formula:

$$C_d = \frac{1}{\sqrt{K}} \tag{2.24}$$

The first approximation of discharge coefficient 0.7 is assumed and effective area 'A_E' of the orifice is determined.

For a pressure drop P across the orifice the following simple equations then summaries the flow in terms of the theoretical Bernoulli's speed U_T

$$U_T = \sqrt{\frac{2P}{\rho}} \tag{2.25}$$

$$A_E = C_d A \tag{2.26}$$

$$Q = A_E U_T \tag{2.27}$$

$$Q = A_E \sqrt{\frac{2P}{\rho}} \tag{2.28}$$

$$\frac{1}{2}\rho Q^2 = A_E^2 P \tag{2.29}$$

Last equation is especially useful for formulation of damper valve flows [2].

2.3.5 Basic valve models

“Consider an orifice with effective area, then its variable area may be expressed by an exponent with index ‘n’.

$$A = C_{AP} P^n \tag{2.30}$$

From above

$$p = \frac{1}{2}\rho\left(\frac{Q}{C_d A}\right)^2 \tag{2.31}$$

Putting equation 2 in equation 1 we get

$$P = \frac{1}{2}\rho\left(\frac{Q}{C_d C_{AP} p^n}\right)^2 \tag{2.32}$$

$$P^{1+2n} = \frac{1}{2}\rho\left(\frac{Q}{C_d C_{AP}}\right)^2 \tag{2.33}$$

$$P = C_1 Q^{2/(1+2n)} \tag{2.34}$$

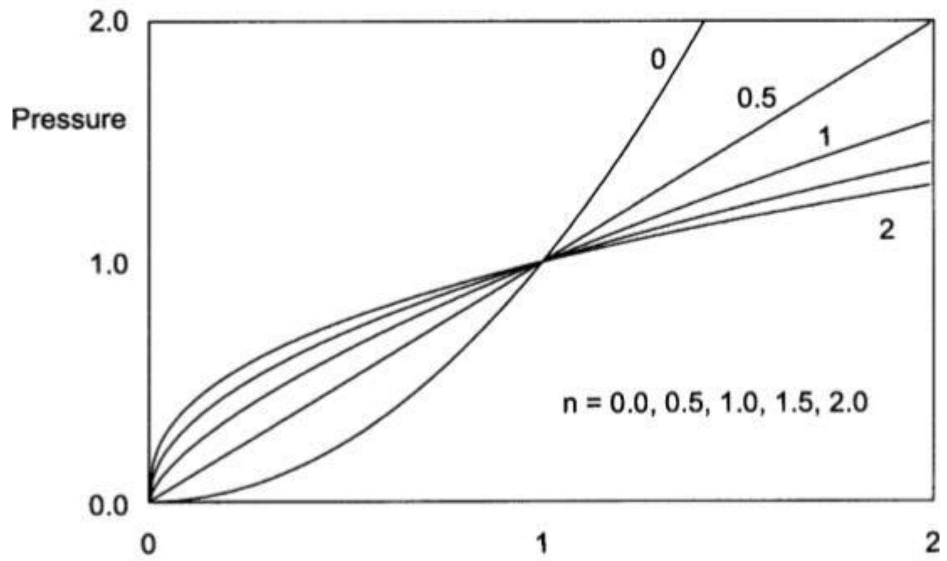


Figure 2 *Basic variable-area valve P(Q) characteristics*

In figure 2.3, area variation is shown with different values of ‘n’. For n=0 there is no area variation and so pressure drop occurs in a quadratic manner. For n=1/2 the pressure drop is proportional to discharge giving linear behavior. So higher values of n provide higher degree of decrement giving a knee shaped graph with high regressive characteristic in the graph.

We know that opening of aperture’s area is proportional to the square root of the extension produced in the spring which is given by the relation

$$\boldsymbol{A \propto \sqrt{\chi}} \qquad \textbf{(2.35)}$$

Or

$$\boldsymbol{\chi \propto \sqrt{F}} \qquad \textbf{(2.36)}$$

From basic assumption the lift or extension on the spring gives the opening of the aperture which is given by the formula A = BX, where B is the width of the aperture if supposed to be rectangle and the lift will be X = F/K. the force will be F =AFP

Where,

AF is the effective force pressure area The total valve area will be given by:

$$\mathbf{A_{VL}} = \frac{\mathbf{BA_F P}}{\mathbf{K}} + \mathbf{A_L} \quad \textbf{(2.37)}$$

And volumetric flow rate will be given by:

$$\boldsymbol{Q} = (\frac{\mathbf{BA_F P}}{\mathbf{K}} + \mathbf{A_L})\sqrt{\frac{\boldsymbol{2P}}{\boldsymbol{\rho}}} \quad \textbf{(2.38)}$$

At the input velocity at the piston the volumetric flow rate for incompressible liquid will be

$$\boldsymbol{Q} = \boldsymbol{V}(\boldsymbol{A_P} - \boldsymbol{A_R}) \quad \textbf{(2.39)}$$

The total area for 'n' orifice will be:

$$\boldsymbol{A_0} = \frac{\boldsymbol{\pi N d^2}}{\mathbf{4}} \quad \textbf{(2.40)}$$

Mean flow speed will be: **(2.42)**

$$\boldsymbol{\mu} = \frac{\boldsymbol{v(A_p - A_R)}}{\boldsymbol{A_0}} \quad \textbf{(2.41)}$$

Giving Reynold's no

$$\boldsymbol{R_e} = \frac{\boldsymbol{\rho\mu D}}{\boldsymbol{\mu}} = \frac{\boldsymbol{4\rho V(A_p - A_R)}}{\boldsymbol{\pi\mu N d}}$$

Ratio of fluid velocity to impact velocity [2].

$$R_V = \frac{\mu}{V} = \frac{(A_p - A_R)}{A_o} \tag{2.43}$$

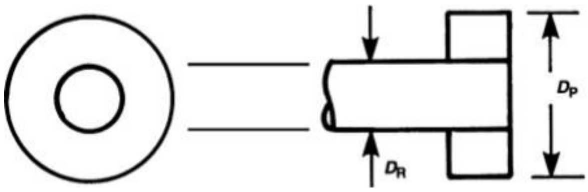


Figure 03 *Piston Geometry*

CHAPTER 3: METHODOLOGY

3.1 Project Methodology

The design of a project is basis or core of any project. It serves as a foundation which must be built first to move forward. Our project is both researches oriented as well as hardware based. The main aim of our project is to design and develop a damper for a car which can achieve an active damping using passive technology. It includes two major parts; Software part and Hardware part. The design part of our project includes all the research and brainstorming needed to develop a software part (Python model) and a computer aided design (CAD) needed to manufacture a physical model which serve as a hardware part.

3.2 Designing (Python)

The design of software for achieving an adaptive damping via precisely shaped ports (spool valve) includes a development of a software on Python which will give us Force-Velocity curve for any given spool valve. The F-V curve of any spool valve will determine how the damper will work in real world conditions. Thus, achieving damper predictability.

3.2.1 Calculation of Damping Force for impact velocities

When a vehicle passes over a bump, it experiences an impact on its tires which will transfer to shock absorber (damper). This impact on a damper is an input velocity which will determine the flow rate passing through orifice (spool valve). For any fixed impact velocity, we have a fixed flow rate. The concept here is to obtain exact amount of damping force required at a certain impact velocity.

So, in order to calculate the Damping Force for impact velocity, we used multiple approaches. Some of them did not converge, so we opted for other approaches.

3.2.1.1 First approach

Figure 3.2 shows the first successful approach that was used to calculate the damping force for impact velocity and hence ultimately getting the F-V curves for different orifices. In this method, first we assumed the value for spring constant (Ka). Then we assumed the diameters of internal and external pistons. These were used to calculate the cross-sectional areas for internal and external pistons respectively. Then we assumed the dimensions of our orifice and calculate the orifice area. Now, from a given value of impact velocity, we calculate the flow rate (Qp). Now we vary damping force, acting on piston surface area, to obtain different values of pressure difference across upper and lower chamber of cylinder in which piston is moving. For each fixed value of pressure difference and flow rate, we obtain an orifice opening (area) using Bernoulli's equation. From orifice area, we get the deflection of internal spring (which separates the sleeve valve and spool valve) which determines the opening of orifice. From this deflection, we get spring constant (stiffness). This value of spring stiffness is the calculated one, which is to be compared with given value of spring stiffness.

As long as calculated spring stiffness is smaller than given value of spring stiffness, we keep on increasing the damping force, which in turn, eventually increased the value of calculated spring stiffness. Once the calculated value exceeds the given value of spring stiffness, we have linearly interpolated between those two values to get the exact amount of damping force required relative to given spring stiffness. This process is repeated for different values of 'Fd' and 'Vp' and an 'F-V curve' is obtained for a particular orifice. Same method is repeated for different orifices.

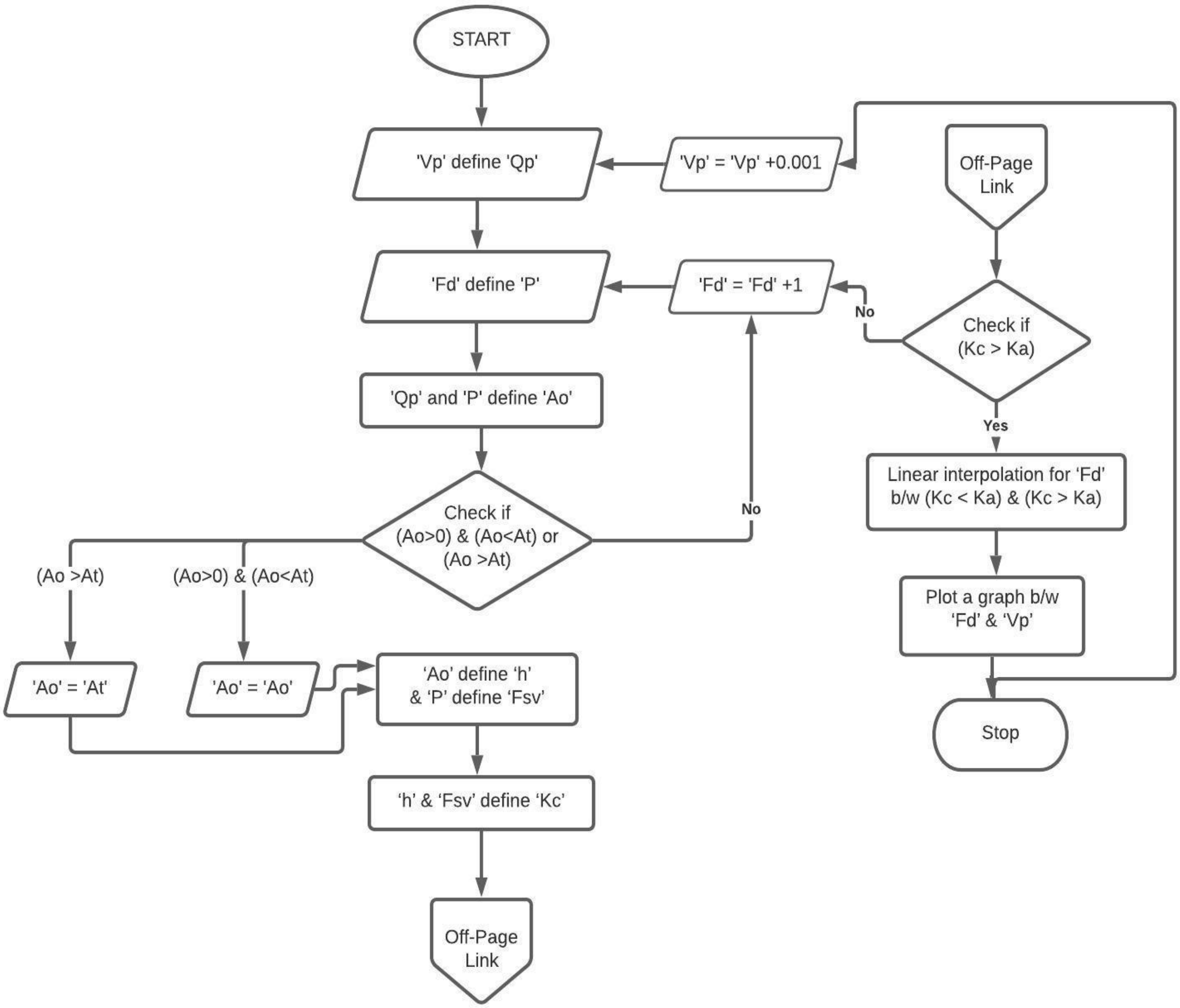


Figure 4 *Algorithm for calculation of damping force for impact velocity*

Although this was a successful approach to get F-V curves but it was quite length and the main reason we did not chose this approach was that we could not plot the F-V curve for circular orifice through this method because the area integration with respect to height was almost impossible using this approach.

3.2.1.2 Final Approach

Figure XX shows the final approach we used to plot V-F curves. Since this method is opposite to the earlier one, it gives us **'V-F' curves** instead of **'F-V' curves**. In this method, first we assumed the value for spring constant (Ka). Then we assumed the diameters of internal and external pistons. These were used to calculate the cross-sectional areas for internal and external pistons respectively. Then we assumed the dimensions of our orifice and calculate the orifice area. Now we vary damping force, acting on piston surface area, to obtain different values of pressure difference across upper and lower chamber of cylinder in which piston is moving. Now, from the pressure difference (P) and area of internal piston, we calculate the value of force acting on spool valve (Fsv). Them from Fsv and the assumed spring constant (K), we get the value of deflection (h). This deflection is used to calculate the area opening of orifice. For each fixed value of pressure difference and orifice opening (area) flow rate, we obtain a flow rate (Qp) using Bernoulli's equation. This value of Qp along with the area of external piston (Ap) is used to calculate the impact velocity (Vp).

This process is repeated for different values of 'Fd' and 'Vp' and a 'V-F curve' is obtained for a particular orifice. Same method is repeated for different orifices.

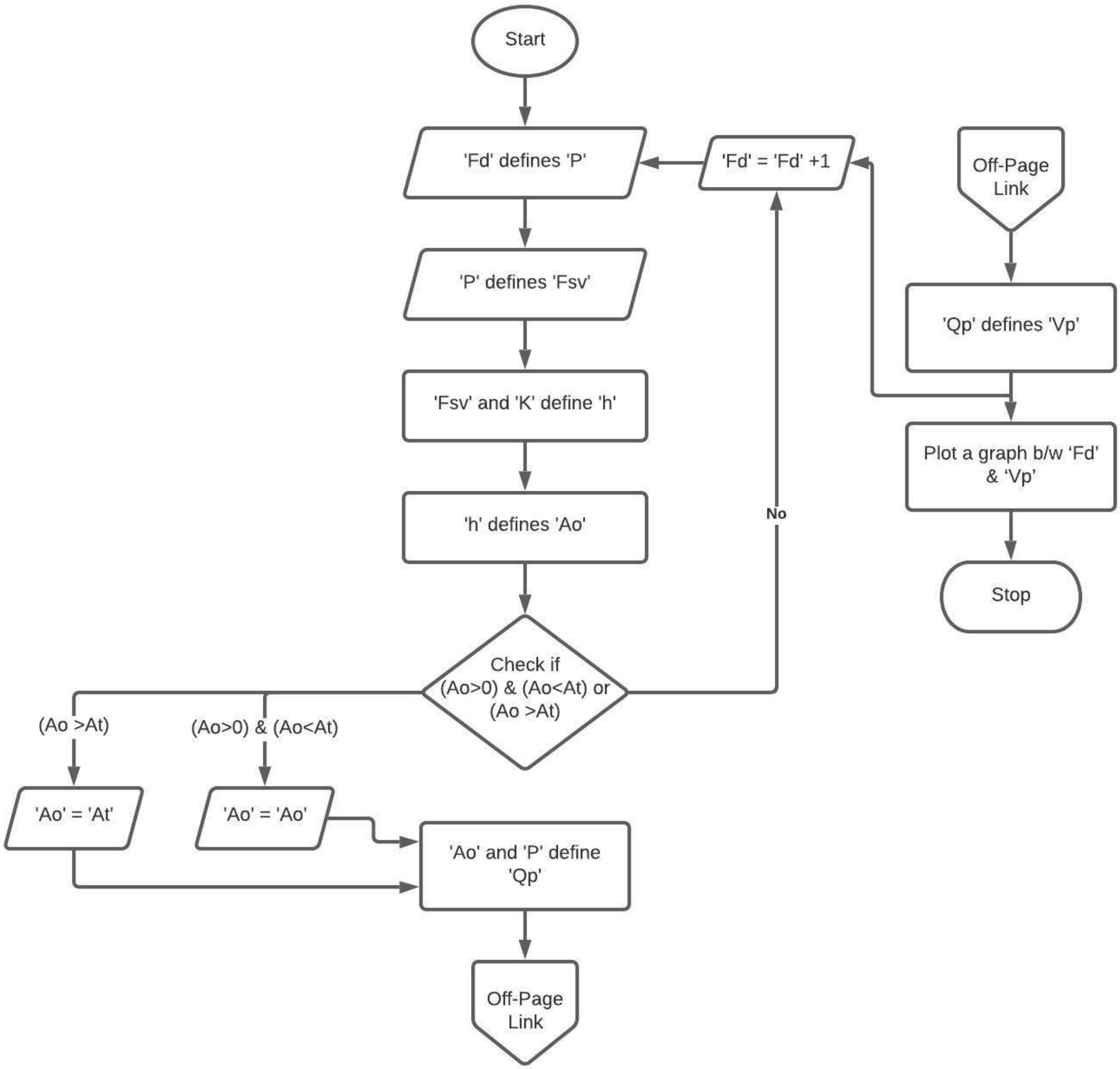


***Figure 5** Algorithm for calculation of impact velocity for damping force*

3.3 Hardware Design (CAD Model)

The Hardware design of any project is equally important as its software design. Just like software design serve as core or foundation of a project, its hardware design is necessary procurement for project to physically exist and work. Hardware design is a part of development process. In our project, Hardware design includes complete modelling of dynamic suspension spool valve damper on SolidWorks. Modelling includes all the basic parts necessary for damper production as well as sub-assemblies required to assemble the final product which includes spool-sleeve assembly, piston-rod assembly etc.

In this section, each sub-assembly is discussed in detail in order to provide an insight to dimensions behind spool-valve damper.

As we have discussed earlier that there is certain need to revolutionize the shock absorbers of our vehicle more dynamic and discuss the design. So, we have finalized the design of our shock absorber. It basically looks like all shock absorbers in the world, but the real magic is inside the DSSV Shock Absorber i.e. The spool valves. So, let’s sit down and discuss the parts of the shock absorber and get to know them in a better way.

3.3.1 Components

Basically, the shock absorber outer strut is the cylindrical holder with a piston holder. The rod designed inside the strut or lower mount would be connected to the spool valve Assembly. We will explain in detail that how these components are organized to make the prototype work.

First, we have the upper mount of the shock absorber. It has several operations and can be used to support the structure as well as contain the pressurized gas and oil chamber along with the Floating Piston.

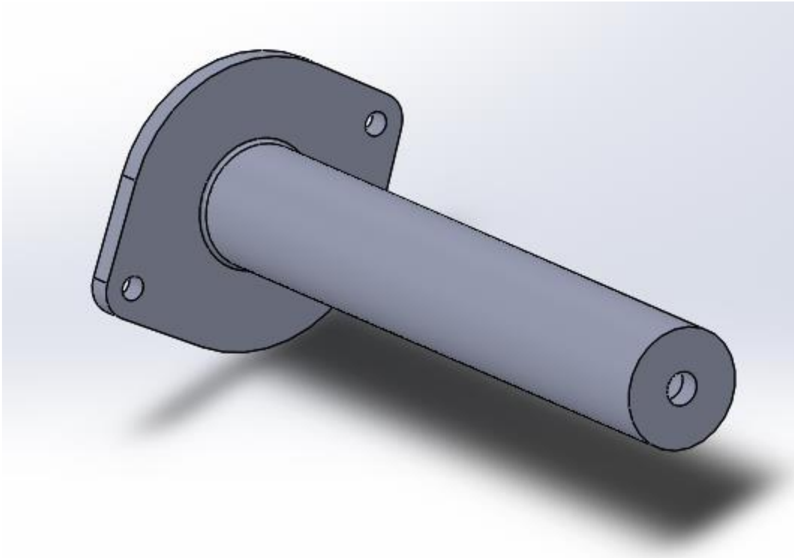


Figure 6 *Upper Mount*

Next up we must consider the lower mount, or the strut of the shock absorber and we will have to consider its utmost necessity and significance. The strut of the shock absorber contains an internal rod where the spool valves would be connected enclosed in a container this part will not have any oil in its cavity. Given below is the internal and external view of the strut or lower mount of the shock Absorber.

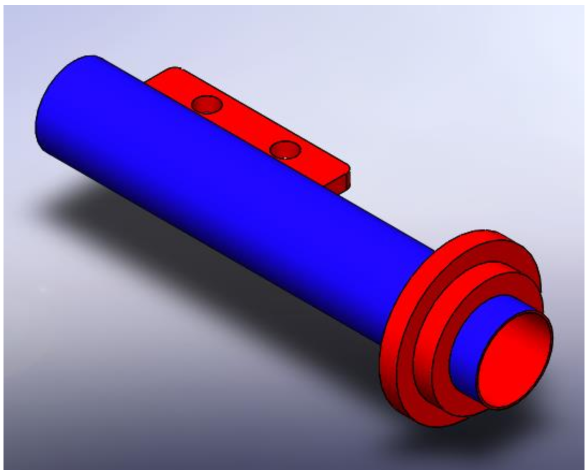


Figure 7 *Strut*

The restoring force would be given by the spring in between the upper and lower mount. It has an essential and vital role in our proposed design because the necessary restoring force that would help in minimizing the shock would be provided by the spring given.

Figure 8 *Spring*

The most essential and innovative part in the assembly of our shock absorber is the spool valve. It has replaced the former reed valve and as result will be very efficient in the off road/on road applications. The spool valve assembly mainly consists of four parts and in this way, it has the spring inside along with other components joined in such a way that when a shock would occur the momentum of the shock would displace the cylindrical disk enclosing the orifice in such a way that the oil would flow from one chamber to another. There would be two spool valves. Each would be operational at a time i.e., compression and restore stroke. In this way the parts will work in harmony.

Following are the parts of the spool valve assembly and the exploded view of the spool valve assembly.

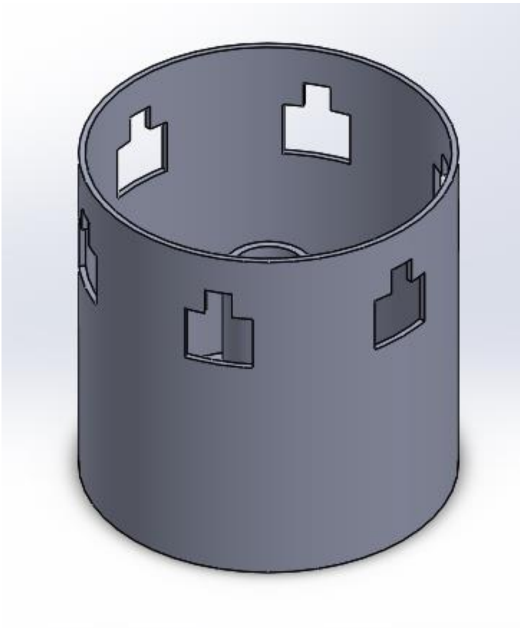


Figure 9 *Spool Container*

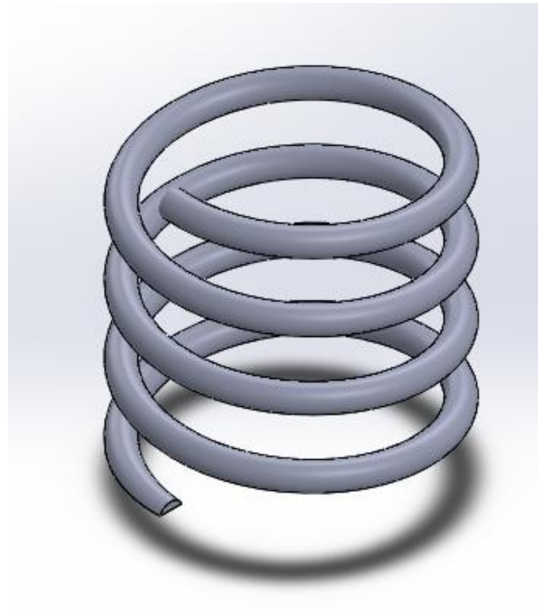


Figure 10 *Spring inside spool Valve*

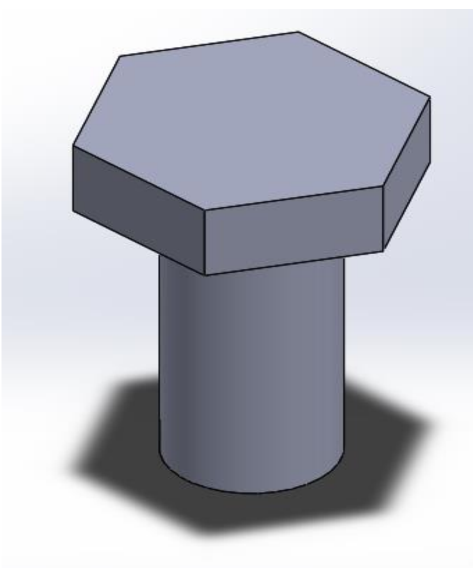


Figure 11 *Nut*

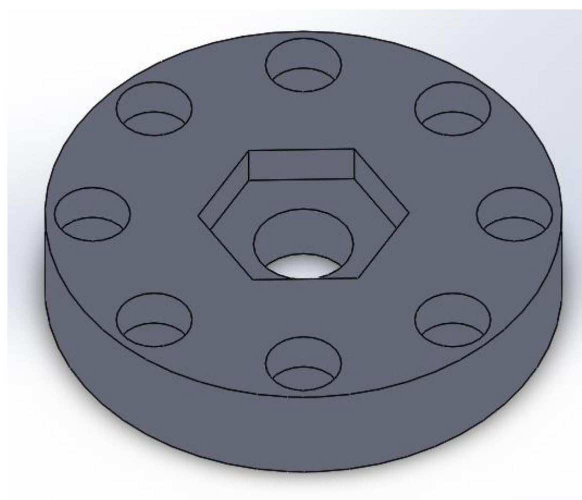


Figure 12 *Disk Valve Controller*

As explained earlier, we have two spool valve assemblies, and one will work for compression and the other for rebound stroke. The assembly given above will work for the restore stroke. While for the compression Stroke, the spool container would have rectangular orifices.

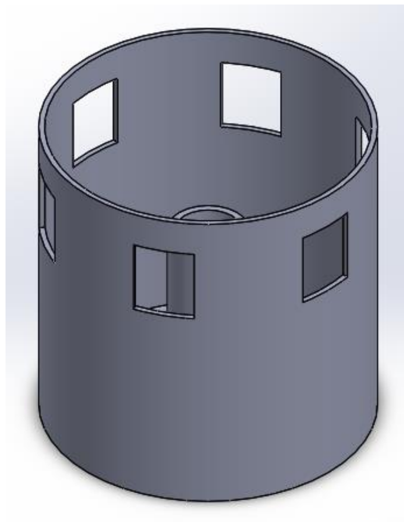


Figure 13 *Spool Container Compression Stroke*

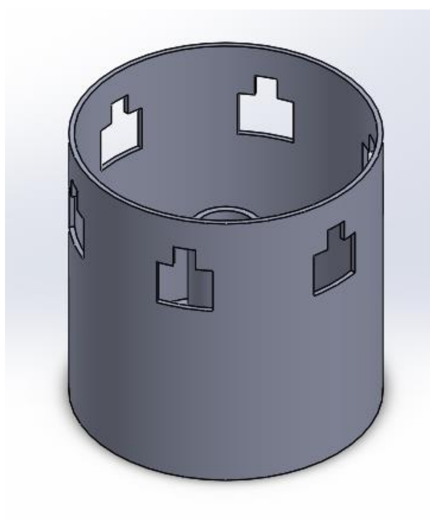


Figure 14 *Spool Container*
Rebound Stroke

Now the overall two spool valve assemblies are as follows,

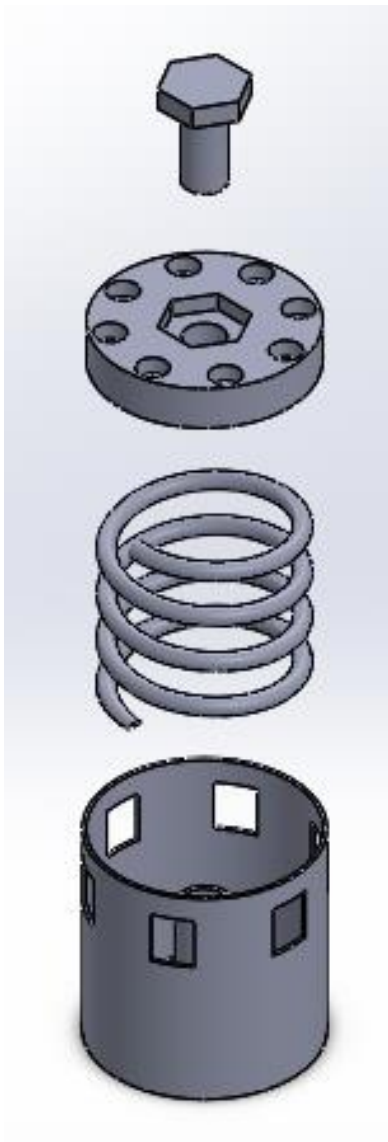


Figure 16 *Spool Valve Assembly (Compression Stroke)*

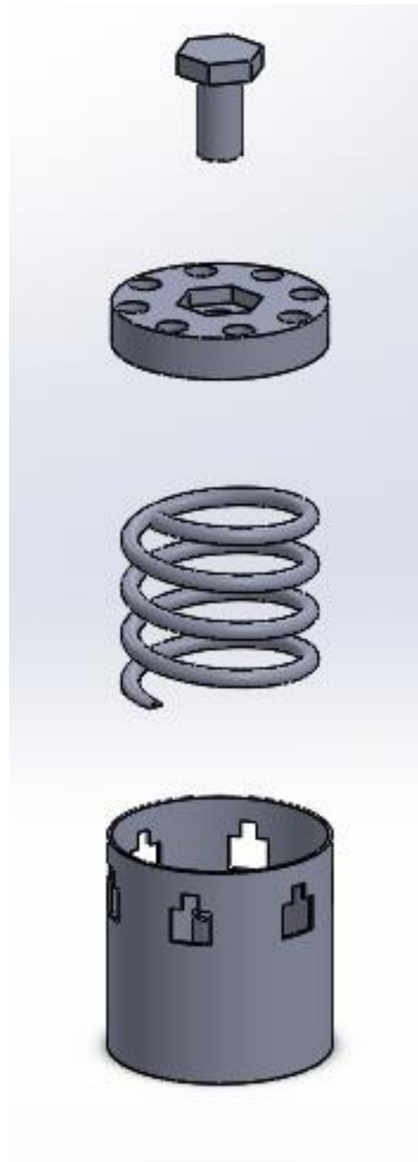


Figure 15 *Spool Valve Assembly (Rebound Stroke)*

In compact form the spool Valves are as shown below:

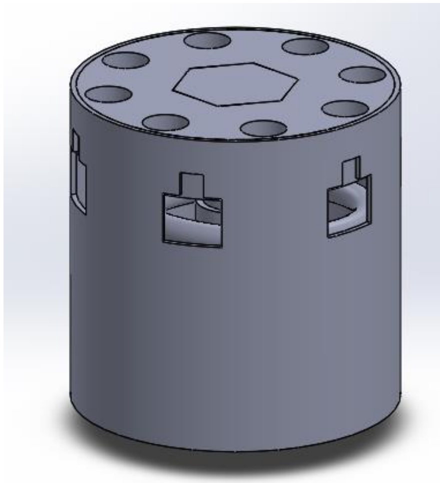


Figure 18 *Spool Valve Assembly (Rebound Stroke)*

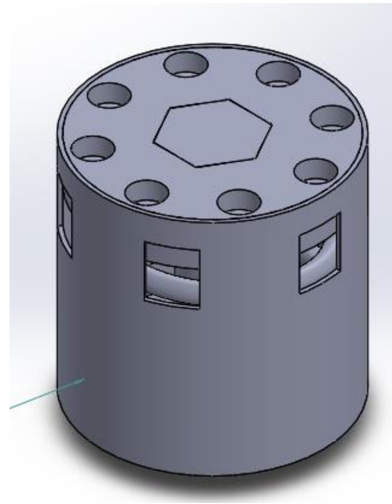


Figure 17 *Spool Valve Assembly (Compression Stroke)*

Now the two oil chambers are connected inside a container that has a byzantine path and now the paths for the oil to follow has a curve and causes the hinderance in sudden shock and this way the shocks can be reduced. This is the way the spool valve Assembly works. These two spool valves are enclosed inside a Container. The container is as follows:

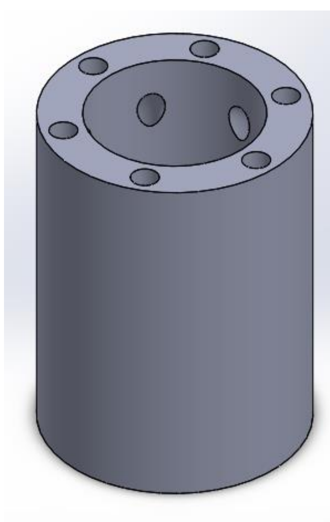


Figure 19 *Container of Spool Valves*

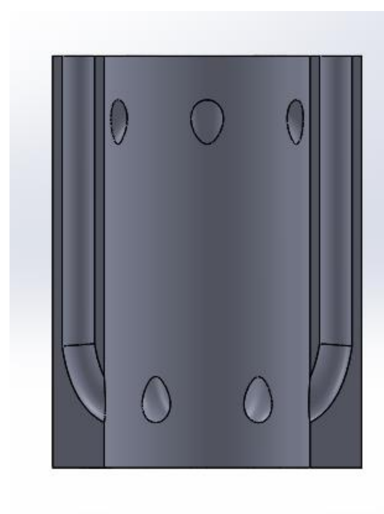


Figure 20 *Container of Spool Valves (Sectioned view)*

Now the spool valve assembly is overall is as follows,

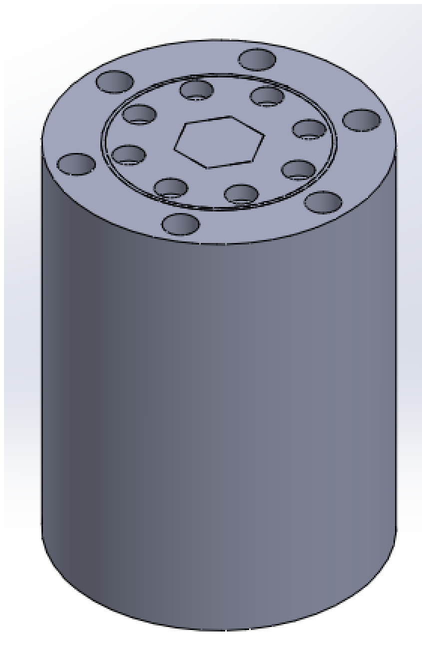


Figure 21 *Spool Valve Assembly*

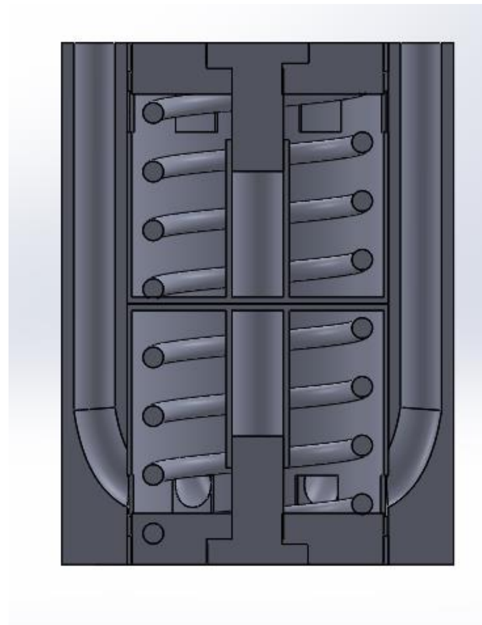


Figure 22 *Spool Valve Assembly (Sectioned View)*

Now that we have described all the parts, let's get to see how our part final design would look like after the complete production or fabrication. Here is the proper design:

3.4 Oil Testing

Choosing the right oil for this complicated setup was very essential and an effective experiment was designed to get the desired parameters required to make the hefty decision of choosing the perfect shock oil.

3.4.1 Oil Viscosity Experiment

3.4.1.1 Apparatus

- 6mm thick MS plate (4ft by 4ft) (one side completely cleaned off)
- IR thermometer
- Boiling water
- Flame torch
- Beakers
- Supporting clamps
- Stop watch
- Buckets/tubs

3.4.1.2 Procedure

The metal plate was wiped clean to remove any debris, then clamped on tilted at 45^o using the supporting clamps. Centimeter Scale was marked on the side of the plate. Hot boiling water was poured on the metal plate evenly on all areas and its temperature measured till it touched 40^oC. Both oils were dropped side 2ft apart and their area coverage time measured. Time over the distance of 10cm was taken and then divided by 10 to minimize error. 3 readings of each were taken making sure the temperature was maintained before every reading. Mean of the readings was calculated and noted down.

2nd piece of data was required on 100^oC. For this, first the boiling water then the flame torch was used to achieve 100^oC, 102^oC was achieved to minimize error as the temperature of the plate dropped quick. Then the experiment was repeated and readings recorded.

3.4.1.3 Oils Used

- Honda CD-70 Motor Oil 10W-40

- ABRO Shock Oil 5W

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Simulation in Python

A Python code to developed for calculating the results for different orifice shapes and sizes. This code is flexible enough so that values of spring stiffness, impact velocities and other boundary conditions can be altered to check results at desired conditions. The Damping Force vs Impact Velocity curves that were generated for different orifice shapes are as follows.

4.1.1 F-V Curve of Rectangular shaped orifice

The force velocity curve of a rectangular shaped orifice is obtained from the procedure explained in previous sections. The dimensions of an orifice were pre-defined in Python code as well as CAD model. We see that curve adopt a digressive behavior in beginning to a certain point where orifice starts acting as a fixed orifice on high impact velocity. This point is indicated in F-V curve. This transition point from where curve changes its behavior can be moved either towards origin or away from origin (towards positive x-axis) by either increasing the spring stiffness or by changing the dimensions of orifices or Number of such orifices. Since changing dimensions or number of orifices is not possible in real time, so we can change the spring stiffness by changing a spring. Stiffer the spring, higher impact velocity is required for orifice to act as fixed or in other words, higher impact velocity will be required to open-up orifice.

Note: We are using six such orifices to regulate oil flow.

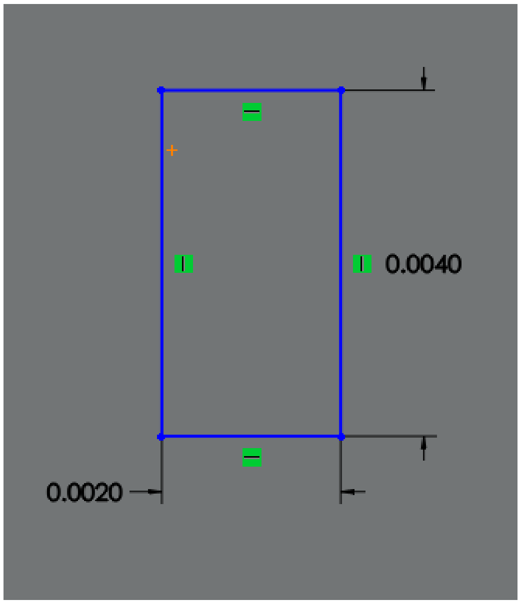


Figure 23 *Rectangular orifice dimensions*

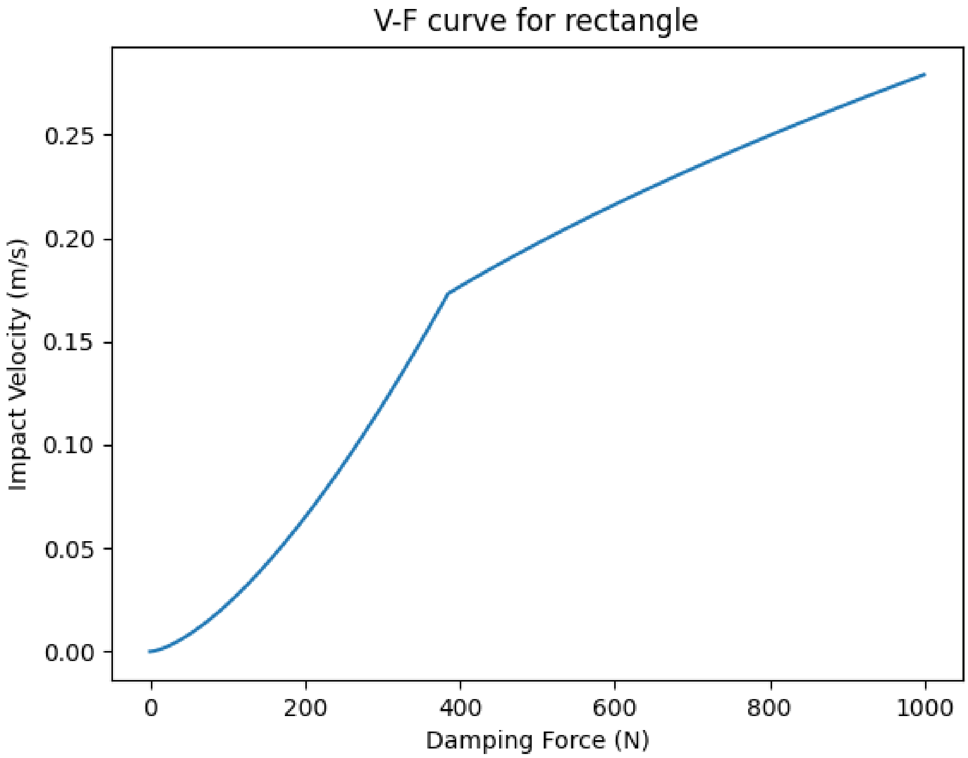


Figure 24 *V-F curve for rectangular orifice*

4.1.2 F-V Curve of Triangular shaped orifice

We have used the same procedure to obtain F-V curve of Triangular shaped orifice as explained in previous section. Again, dimensions of orifice are pre-defined in Python code as well as CAD design. The curve obtained in this case is also of digressive nature but rather smooth as compared to rectangular orifice. That means, at higher velocities it tends to straighten-up and thus less damping force is produced. It must be kept in mind that for each value of impact velocity, we have different orifice opening and thus different Damping force. Hence, Orifice has variable area. Notice that, when orifice is triangle, its area is increasing at a greater rate when compared to rectangle.

Note: We are using six such orifices to regulate oil flow.

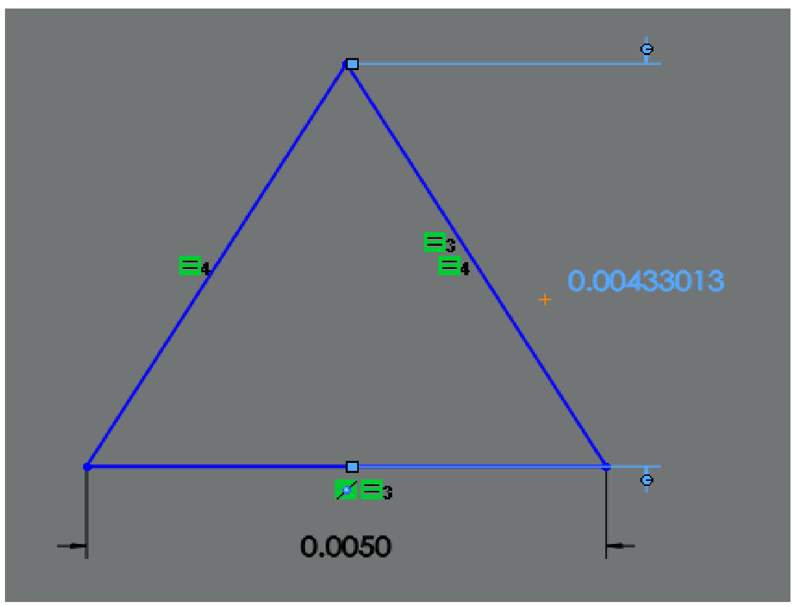


Figure 25 *Triangular orifice dimensions*

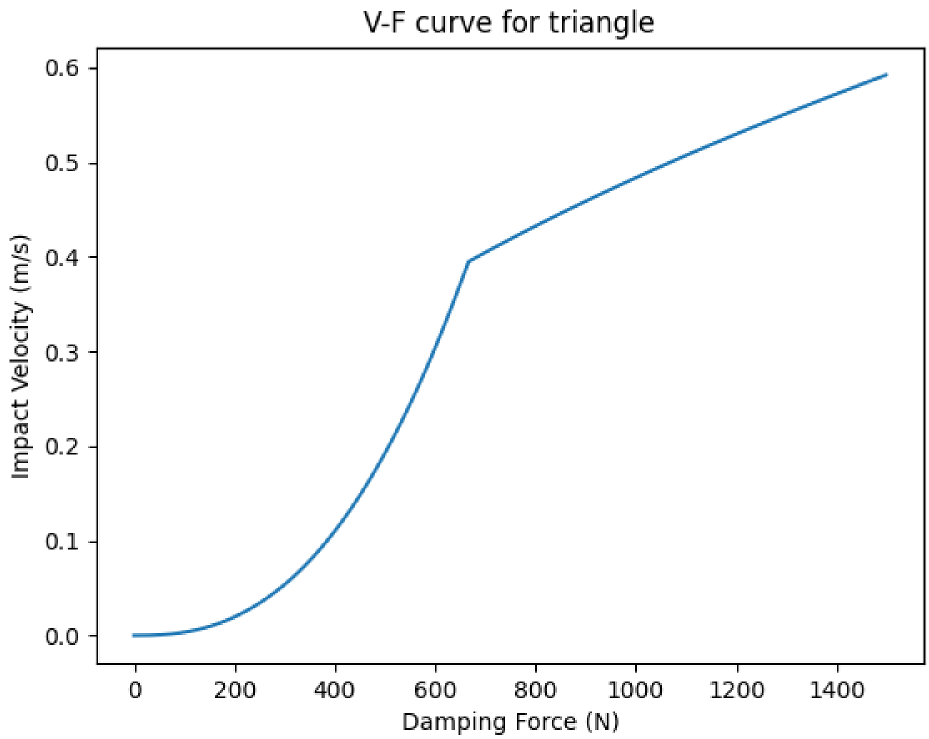


Figure 26 *V-F curve for triangular orifice*

4.1.3 F-V Curve of Complex shape-1 orifice

The curve obtained in Complex shape-1 is again of digressive nature with a slight fluctuation in damping force in the beginning of curve which is due to sudden change in orifice area. When orifice area increases exponentially, pressure difference and hence damping force decreases. This sudden decrease in damping force can be useful in off-road conditions where at high bump/hump you need to soften the damper. Since changing dimensions or number of orifices is not possible in real time, so we can change the spring stiffness by changing a spring. Stiffer the spring, higher impact velocity is required for orifice to act as fixed or in other words, higher impact velocity will be required to open-up orifice.

Note: We are using six such orifices to regulate oil flow.

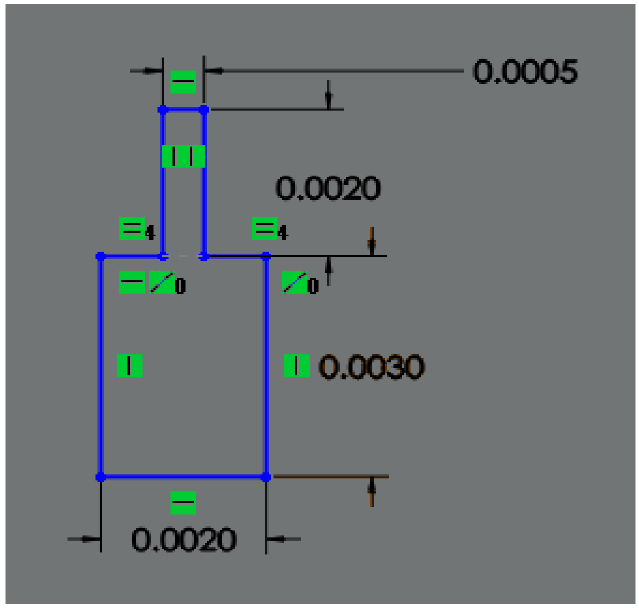


Figure 27 *Complex shape-1 orifice dimensions*

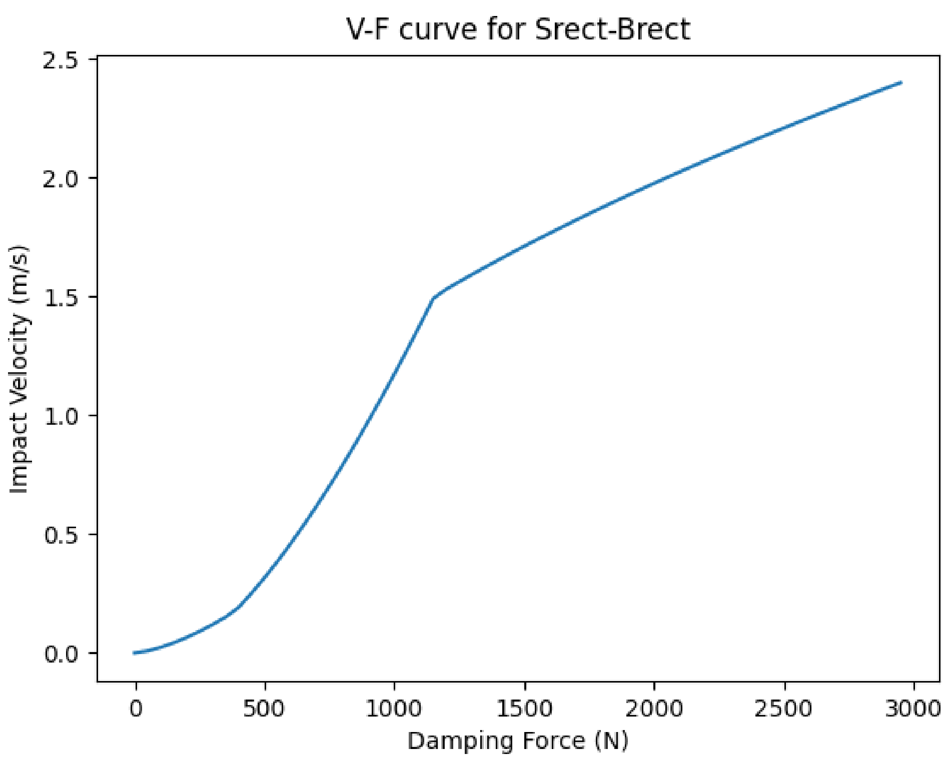


Figure 28 *V-F for Complex shape-1*

4.1.4 F-V Curve of Complex shape-2 orifice

The curve obtained in Complex shape-2 is again of digressive nature with a slight fluctuation in damping force in the ending of curve which is due to sudden change in orifice area. When orifice area increases exponentially, pressure difference and hence damping force decreases. This sudden decrease in damping force can be useful in off-road conditions where at high bump/hump you need to soften the damper. Since changing dimensions or number of orifices is not possible in real time, so we can change the spring stiffness by changing a spring. Stiffer the spring, higher impact velocity is required for orifice to act as fixed or in other words, higher impact velocity will be required to open-up orifice. This shape is similar to the complex shape-1 but inverted.

Note: We are using six such orifices to regulate oil flow.

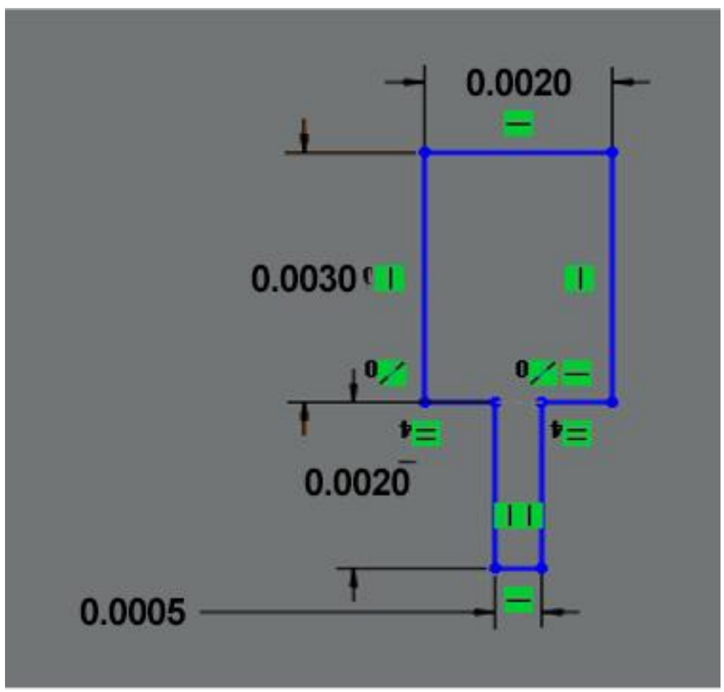


Figure 29 *Complex shape-2 orifice dimensions*

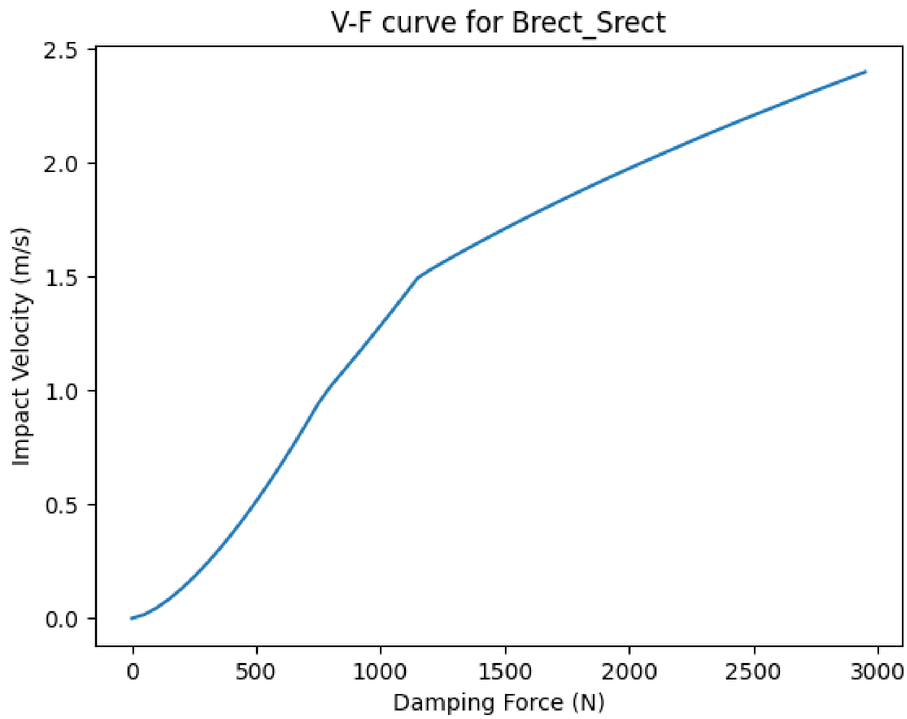


Figure 30 *V-F for Complex shape-2*

4.1.5 F-V Curve of Complex shape-3 orifice

The curve obtained in complex shape-3 is generally of digressive nature with two shifts in the curve at beginning which shows area shift or change in orifice areas. When area moves from rectangular region to trapezoidal region, curve shifts and again when area moves from trapezoidal region to rather bigger sized rectangle region, curve shifts. From onwards, it follows digressive pattern until at certain high impact velocity where it will start acting as a fixed orifice and follows exponentially upward curve. Since changing dimensions or number of orifices is not possible in real time, so we can change the spring stiffness by changing a spring. Stiffer the spring, higher impact velocity is required for orifice to act as fixed or in other words, higher impact velocity will be required to open-up orifice.

Note: We are using six such orifices to regulate oil flow.

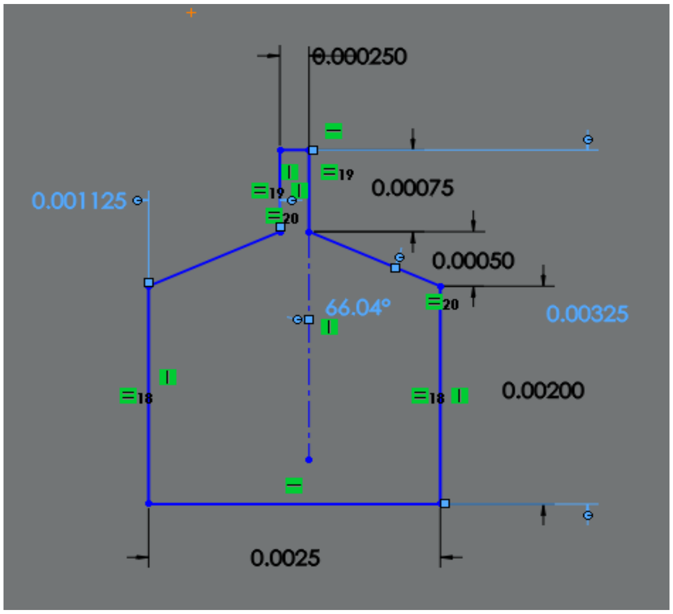


Figure 31 *Complex shape-3 orifice dimensions*

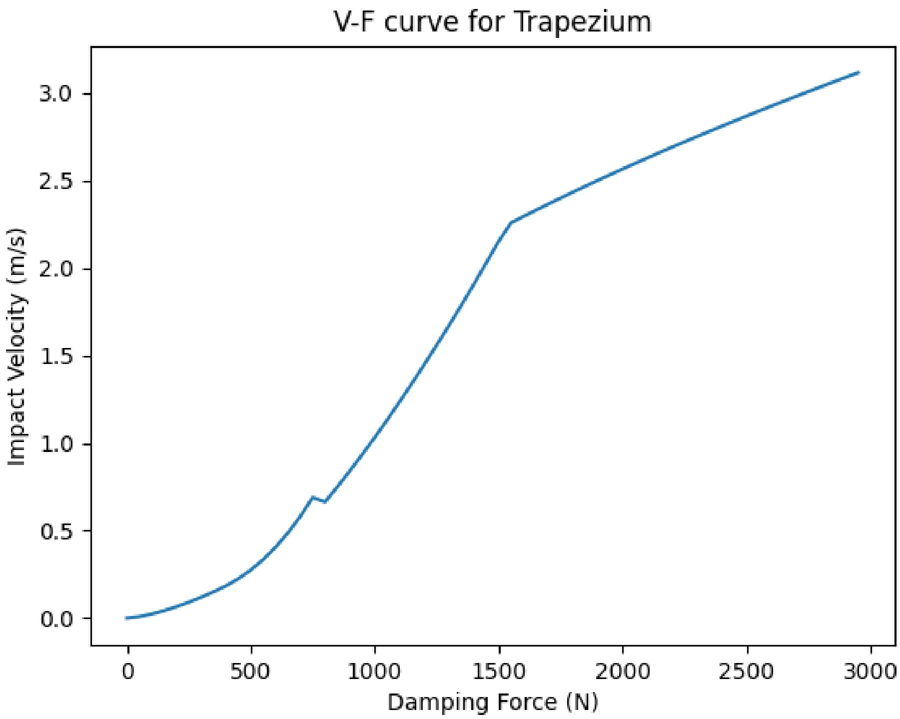


Figure 32 *V-F for Complex shape-3*

4.1.6 F-V Curve of Circular shaped orifice

The force velocity curve of a circular shaped orifice is obtained from the procedure explained in previous sections. The dimensions of an orifice were pre-defined in Python code as well as CAD model. We see that curve adopt a digressive behavior in beginning to a certain point where orifice starts acting as a fixed orifice on high impact velocity. This point is indicated in F-V curve. This transition point from where curve changes its behavior can be moved either towards origin or away from origin (towards positive x-axis) by either increasing the spring stiffness or by changing the dimensions of orifices or Number of such orifices. Since changing dimensions or number of orifices is not possible in real time, so we can change the spring stiffness by changing a spring. Stiffer the spring, higher impact velocity is required for orifice to act as fixed or in other words, higher impact velocity will be required to open-up orifice.

Note: We are using five such orifices to regulate oil flow.

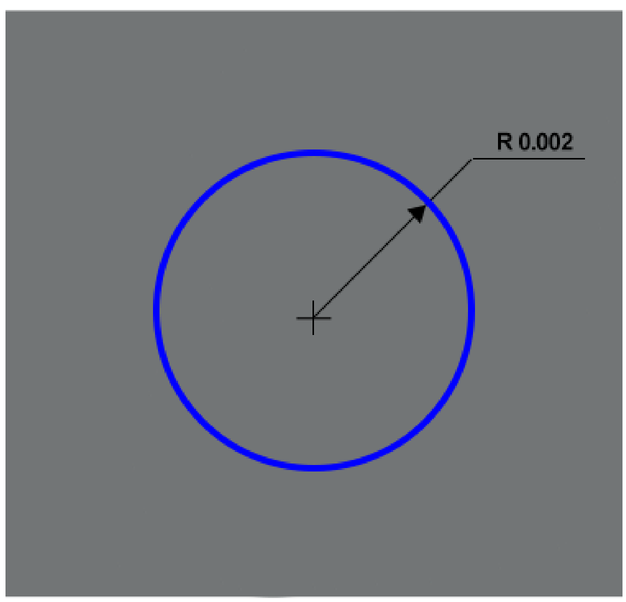


Figure 33 *Circular orifice dimensions*

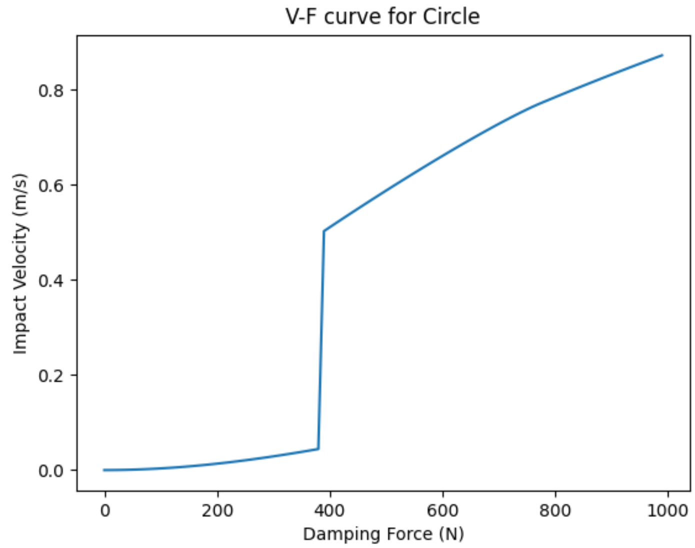


Figure 34 *V-F for Circular orifice*

4.2 Oil Testing

We performed an effective experiment to get the desired parameters required to make the hefty decision of choosing the perfect shock oil. The experiment was designed to choose between two potential candidate oils, i.e. Honda CD-70 Motor Oil 10W-40 and Abro Shock oil 5W.

4.2.1 Results

Oil	CentiStokes @40°C cSt	Centistokes @100°C cSt	Density @20°C Kg/m³
Honda MotorOil 10W-40	20.2	4.1	870
Abro ShockOil 5W	15.1	3.8	860

Note: 1 CentiStoke (cSt) = 1mm²/sec

4.2.2 Oil Selection

The oil testing experiment clearly identifies the **ABRO shock oil 5W** as the winner with lower density and a much higher resistance to temperature variations. Not only it provides the required performance, it keeps margin for safety factor in tough conditions. This gives us the confidence that our first production unit will tackle the harshest conditions of Cholistan, Sarfaranga, Jhal magsi and Katpana before giving up.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

6.1 Conclusion:

The main aim of this type of damper is to provide active damping using passive technology. Since these dampers use spool valves, the purpose of which is to vary the aperture area to achieve variable damping. Normally, variable damping is achieved either by using shim valves or by using electronic control system such as Electrorheological or Magnetorheological dampers. Shims wear out with time and MR/ER are expensive.

Considering all these technologies, Spool valve dampers are better option because of their better level of damper predictability, accuracy and repeatability in regulating oil flow and thus, damper curves.

We have designed a computer code on PYTHON for different geometric configurations of aperture and how these shapes behave differently than others. Each shape provides a unique force-velocity curve which determines the damper characteristics. Generally, we opt for a geometric configuration which provides close to straight line in force-velocity curve.

Damper is modelled on a SolidWorks. The modeling includes all the parts such as main piston, spool valve assembly, reservoir assembly including minor parts such as springs, seals and bump stops. Important point to note here, we have modelled the damper considering the extended/compressed length and stroke of Toyota Prado 2002-2009 model. The sleeve with a circular orifice was also designed and modelled for same car considering its weight and required damping force. Important parameter to note here, weight of vehicle determines the required force in compression and rebound strokes. In our case, we needed around 700 N force in compression stroke and around 2550 N force in rebound stroke for an impact velocity of approximately 0.52 m/s. So, from the F-V curves we obtained, we selected the **‘Complex shape-1’** orifice for **‘Compression’** spool valve and **‘Rectangular’** orifice for **‘Rebound’** spool valve since these provide required damping force. All other sleeves with different shapes were also modelled when designing a computer code.

6.2 Commercial Worth

This damper is designed, fabricated and assembled after in depth research of related field and market. As explained earlier, this damper finds its application in modern racing particularly in off-road racing and desert rallies. Off-road Racing industry is new in Pakistan and is gaining more attention with every passing year. We feel opportunities are wide open to be settle in this field. Local market is not producing premium off-road shocks and majority of people participating in rallies are importing it from outside Pakistan. Therefore, we have designed and manufactured this adaptive damper using passive technology which will provide a cost-effective solution to racing industry.

6.3 The Value We Add

Spool valve dampers are proven to provide damping equivalent to MR and ER dampers but at a fraction of the cost. But what we did was to make them better and useable in the Pakistani market.

- The damper we designed is specifically tuned for a 2009 Toyota Land Cruiser Prado KDJ 120 but at the same time is highly configurable for a wide range of applications. The KDJ 120 being a dominant rally entrant in Pakistan was an easy market but we still kept the design configurable with just a few variations, the damper can perform to its full in almost all rally trucks.
- As the oil testing done contributed to the perfect oil for the job being chosen, our damper design provides highly repeatable and consistent damping characteristics with enhanced damper tunability.
- Our design caters valve-in-body problems and is highly resistant to cavitation which are the prime cause of damping inconsistency.
- As these shocks are built for the wild, they are meant to be abused in harsh conditions and these ones specially a specifically built to take the beating. For

that these are very insensitive to high temperatures so they don't change damping curves with high temperatures.

6.4 Future Extension

There is room for improvement in every aspect of life. Therefore, we feel our damper can also be improved and further extended in number of ways. Possible extensions are mentioned below,

1. Design can be improved by making it more compact so that manufacturing cost can be reduced.

2. Various sleeves with different apertures can be tried and tested.

3. Compression adjusters and rebound adjusters can be added to give more control to driver in adjusting damping.

4. Bypass can be added to current dampers to make it position sensitive, currently it is velocity sensitive.

5. An independent software to be made particularly for this damper which will serve as a foundation for comparing different spool valve configurations and their respective force-velocity curves.

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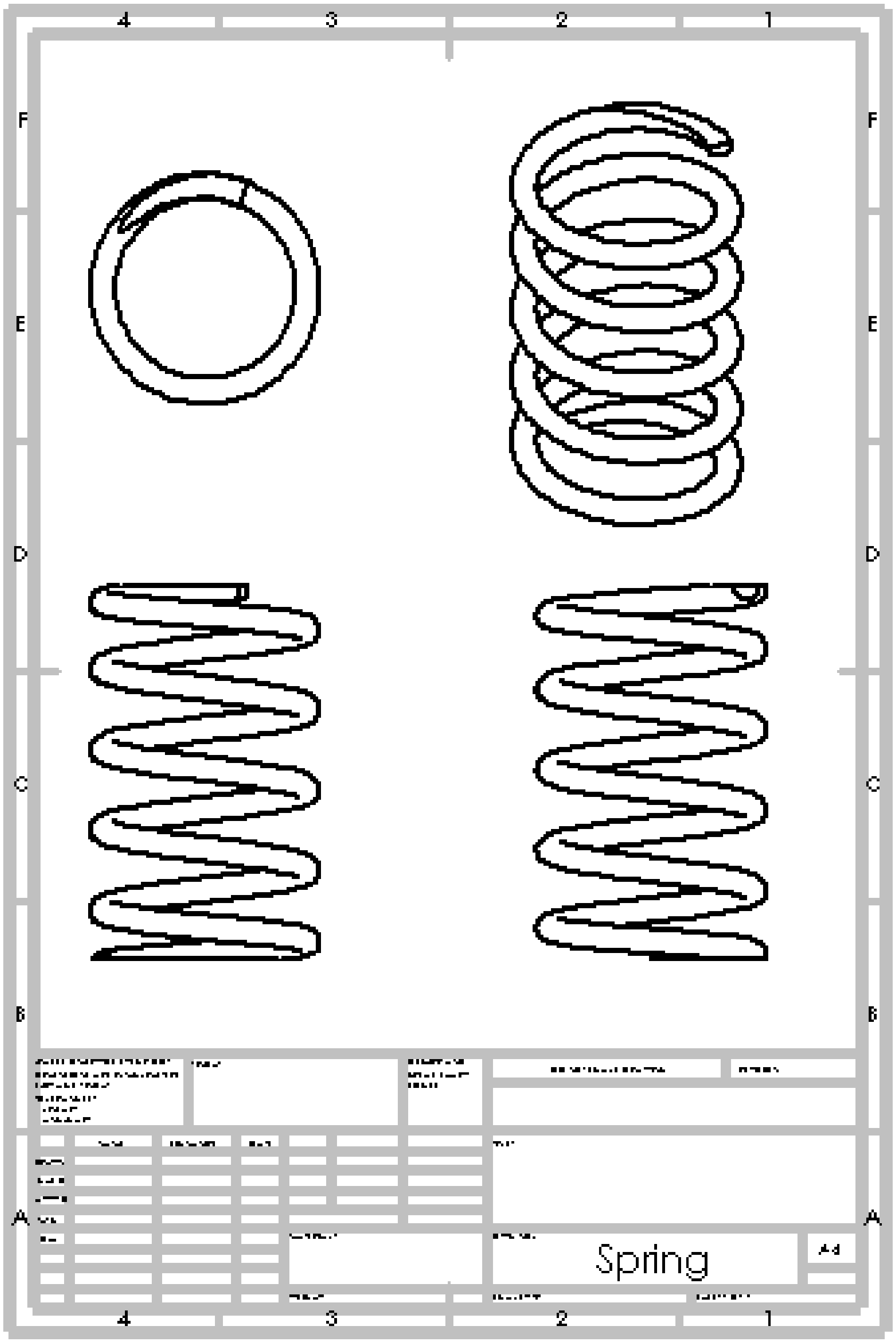
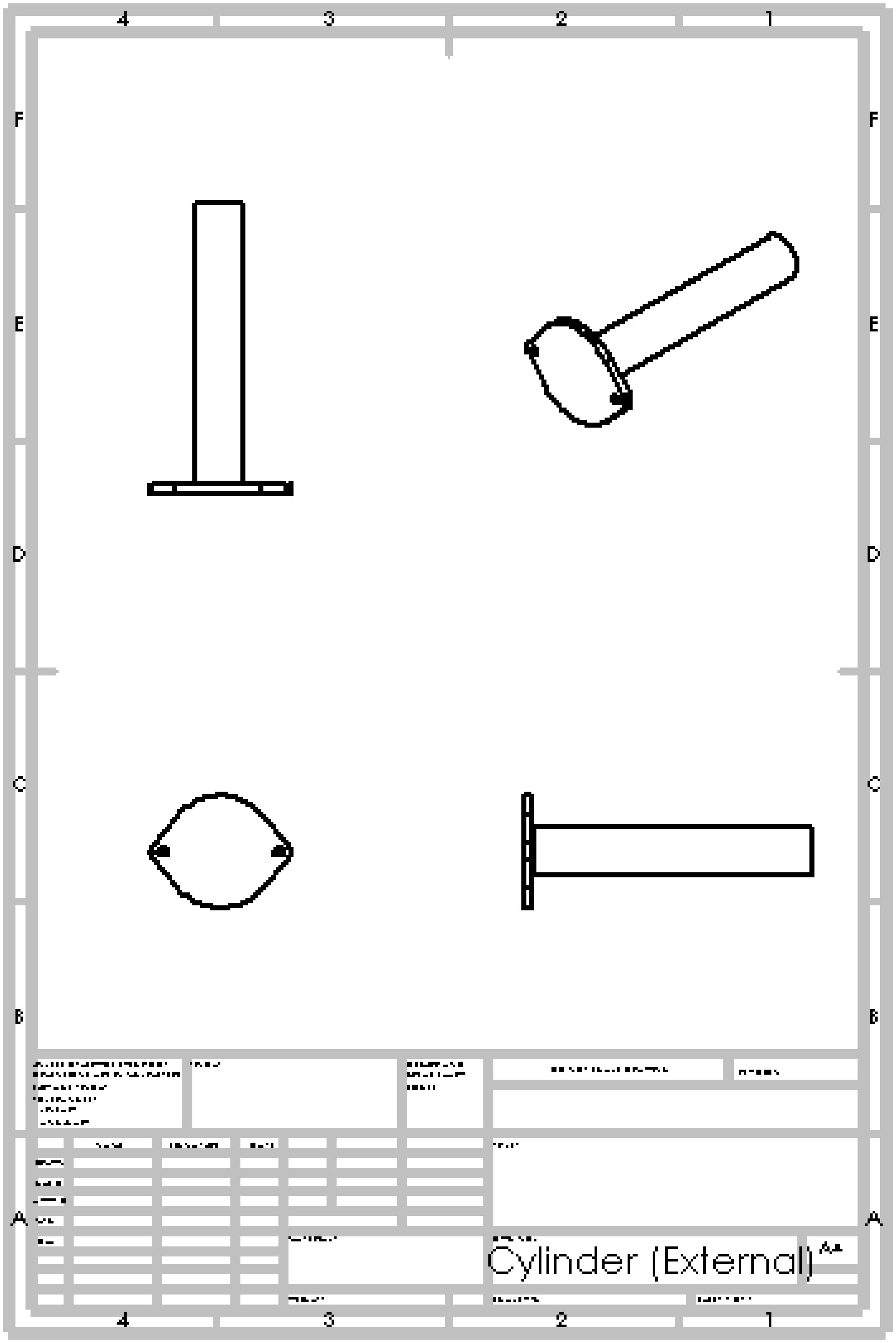
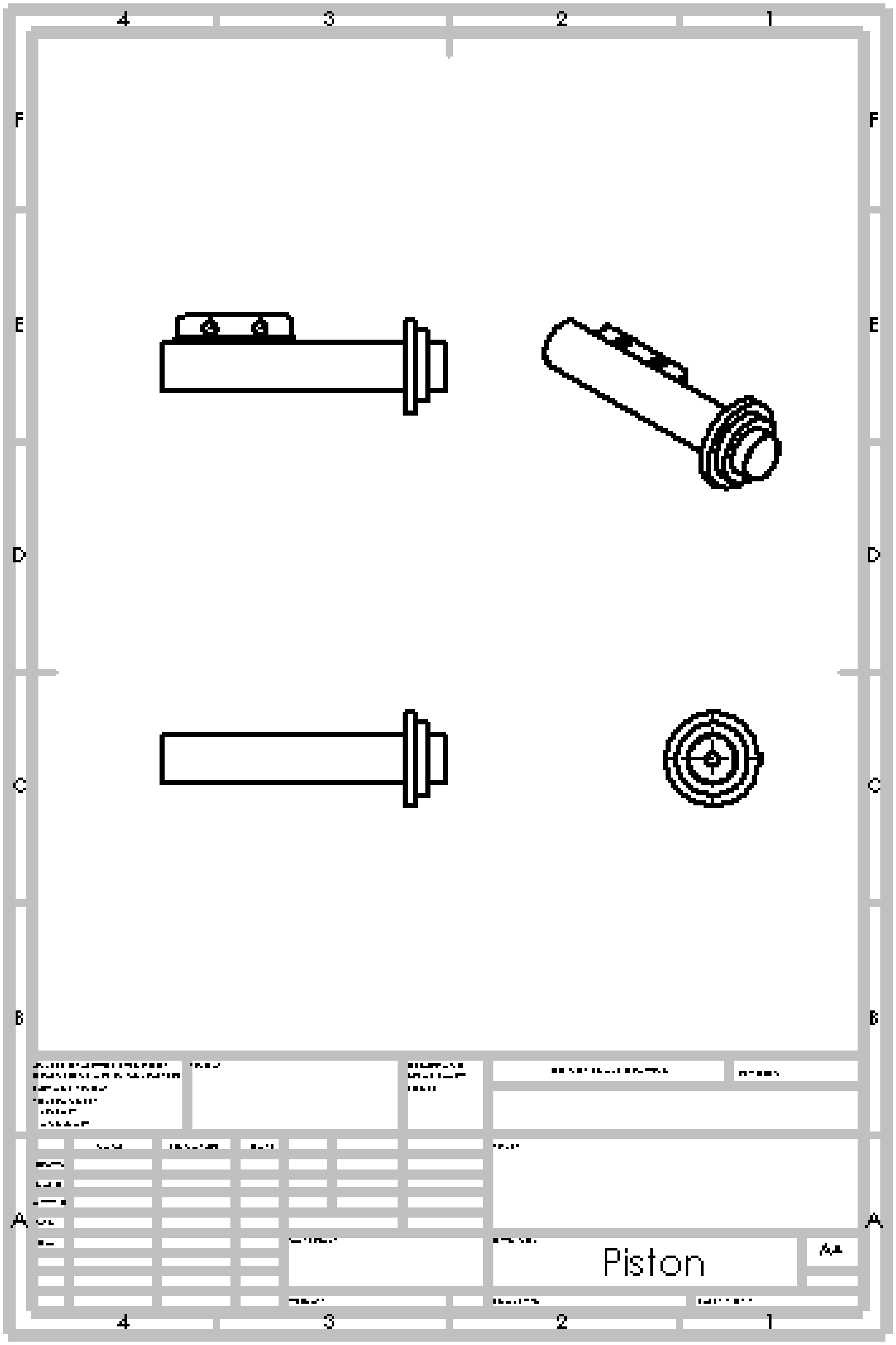
APPENDIX I: MATERIALS

Part Name	Material
Main Cylinder	1045 Steel
Bearing Housing	Brass
Internal Floating Piston	Aluminum 6061 T6
Piston Rod	1045 Steel
Teflon Rings	Teflon
O-rings	Rubber
Compression Spring Jacket	Aluminum 6061 T6
Stopper for rod	Rubber
Hexagonal Nut M12	Steel
Compression Sleeve	Brass
Rebound Sleeve	Brass
Spool valve casing Centre	Aluminum 6061 T6

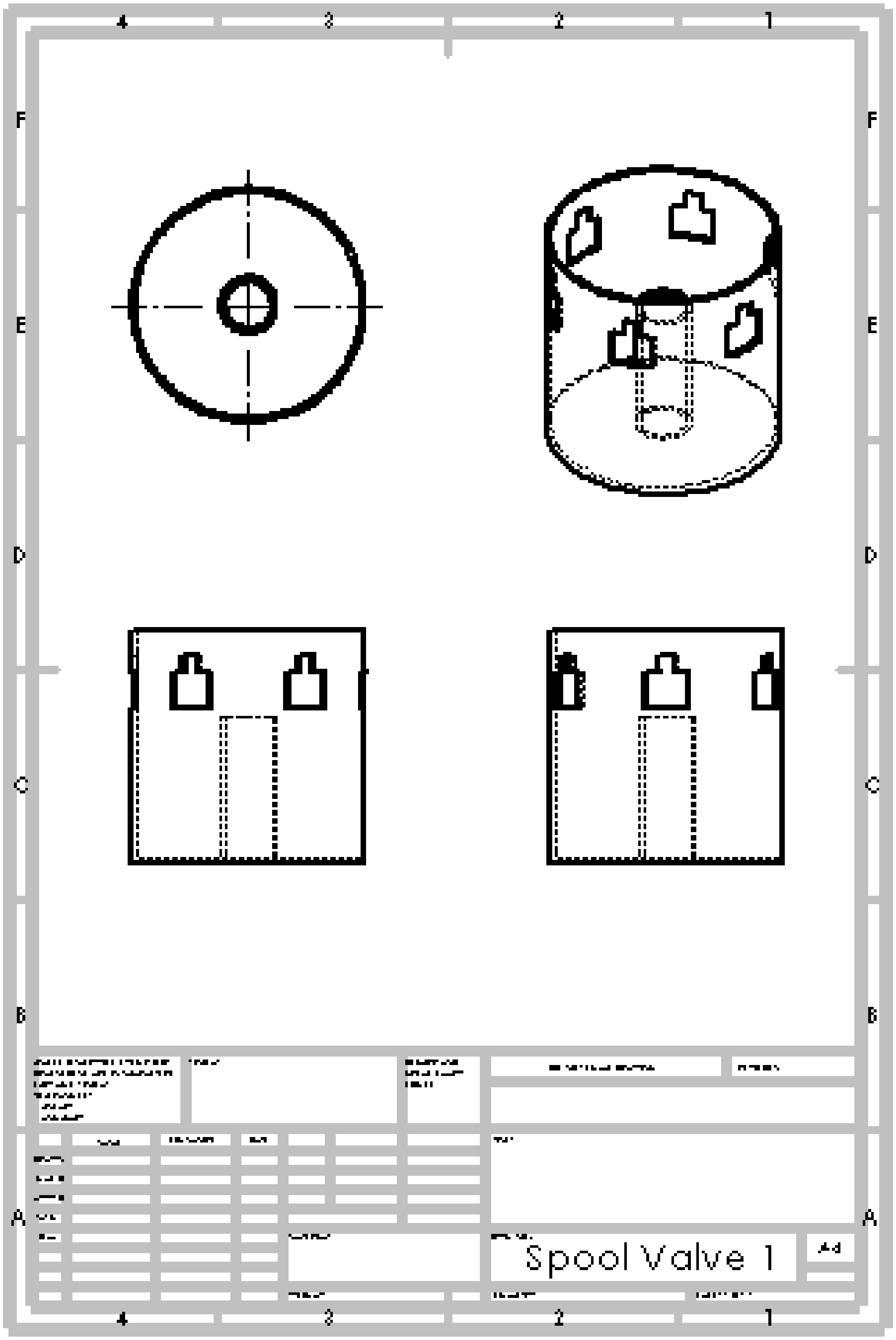
APPENDIX II: DRAWING OF IMPORTANT PARTS




Cylinder (External)



Piston
A4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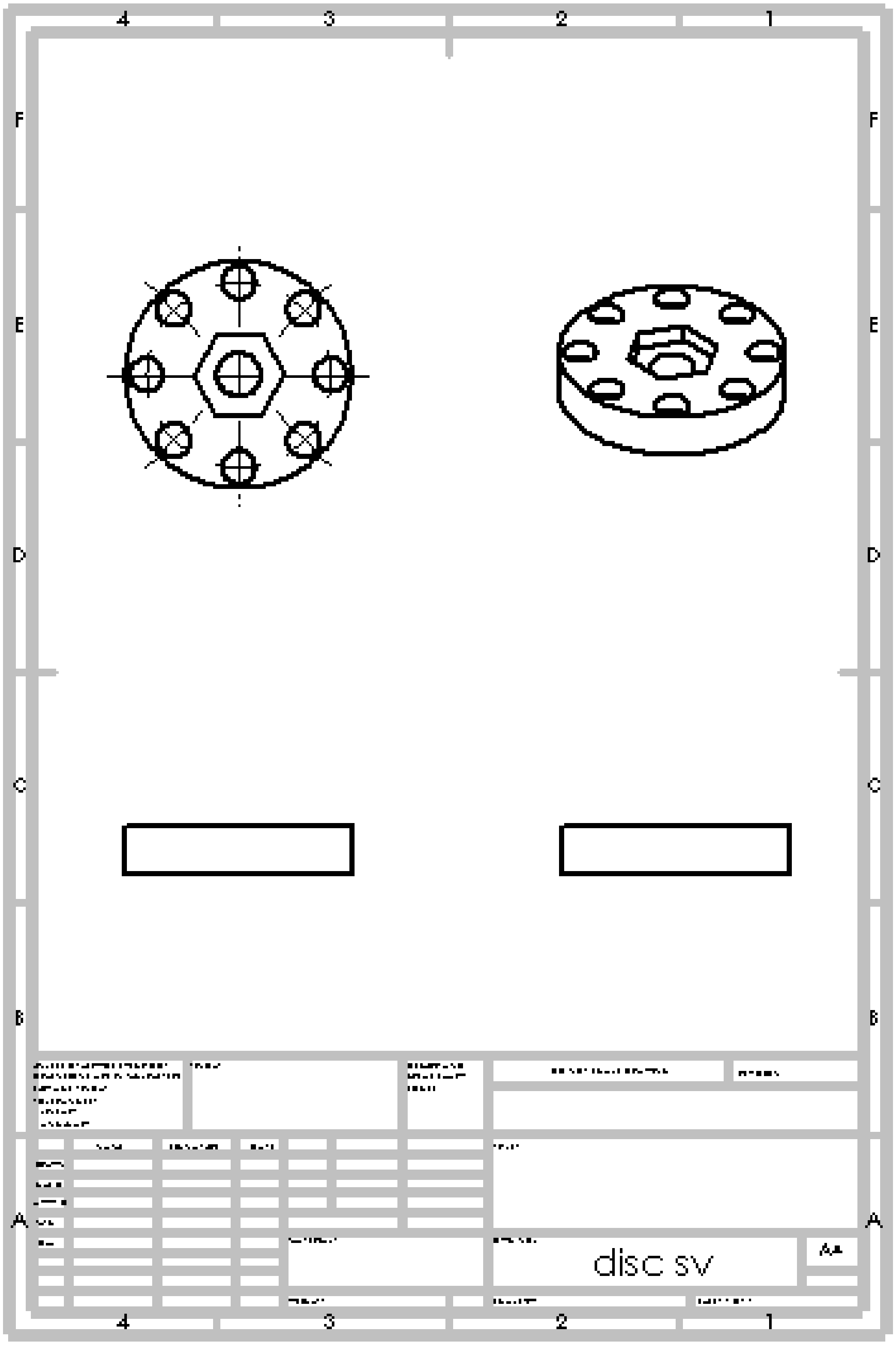

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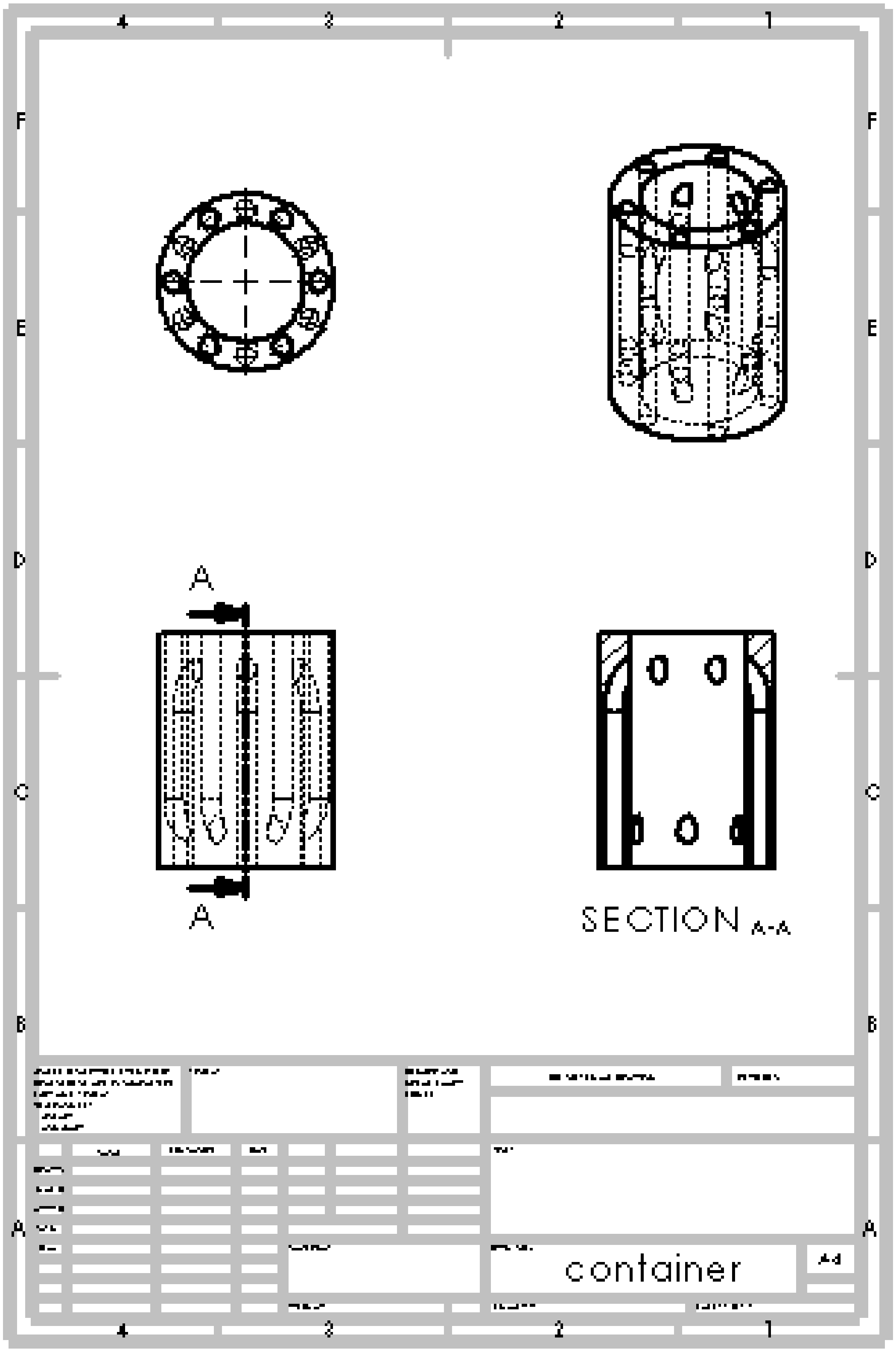
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SECTION A-A
container
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