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Research Paper

"Design and Analysis of Braking System of All Terrain Vehicle"

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Abstract
All-Terrain Vehicle(ATV) is a vehicle that can be driven on almost all types of terrain with maximum ease. The Society of Automotive Engineers(SAE), India organizes an ATV event for engineering students known as BAJA. SAE BAJA event involves basic preliminary designing, fabrication, and validation of a single-seater ATV which takes part in a series of different events which test its acceleration, gradeability, maneuverability, durability, and braking efficiency. As we know, driver safety is the most important factor in such events, so the ATV needs to possess an efficient braking system to assure the driver's safety. This paper aims to design and analyze a hydraulic braking system for a Baja SAE vehicle that is safe & reliable considering the scenarios of the events yet able to produce adequate braking force to meet competition regulations while being as lightweight as possible. The system should also limit the unsprung weight to help improve maneuverability.
Keywords— *All terrain Vehicle(ATV), hydraulic braking system, SAE BAJA*

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I. Introduction

SAE BAJA India organized by the Society of Automotive Engineers(SAE) involves the design, manufacturing, and validation of an ATV by following specific regulations formulated in the Baja rulebook.

The braking system of a vehicle plays a prominent role in the event as well as in the safety of the driver. Brakes are mechanical devices whose basic function is to decelerate the motion of a moving vehicle or to stop a moving vehicle. The main objective of the braking system is to lock all four wheels of the ATV. The braking system works on the principle of energy conversion in which kinetic energy is converted into thermal energy. When the brake is applied, the brake pads squeeze against the disc brake rotor, and the conversion of kinetic energy into thermal energy via friction takes place which leads to effective braking.

The main objective is to design a fully effective braking system in the limited space allocated to it. As Baja ATV needs to be light in weight so it requires a light and compact braking system which can be reliable and can work under extremely stressful conditions. A proper selection and placement of the components of the braking system in the minimum possible space are necessary.

II. Rules of braking subsystem

1) The braking system must be segregated into at least two (2) independent hydraulic circuits such that in case of a leak or failure at any point in one system, effective braking power shall be maintained on at least two wheels. Each circuit brake system shall be designed to achieve a minimum 50% prescribed dynamic performance requirement.
2) Each hydraulic circuit must have its separate fluid reservoir either through physically separate reservoirs or by the use of a full-height dam in an OEM-style reservoir.
3) The brake(s) on the driven axle must operate through the final drive. Inboard braking through universal joints is permitted. Braking on a jackshaft through an intermediate reduction stage is prohibited.
4) Hand or feet-operated "cutting brakes" are permitted provided section B.7.1 is also satisfied. A primary brake system must be able to lock all four wheels with a single foot. If using two separate pedals to lock two (2) wheels apiece; the pedals must be close enough to use one foot to lock all four wheels.
5) All brake lines shall be securely mounted to the vehicle and not projected below the vehicle frame or suspension components.
6) All brake lines shall be routed and oriented such that they are not pinched by steering or suspension parts, nor engaged with sharp edges.

7) All brake lines shall have a full range of motion within the steering and suspension system. IS 7079 compliance flexible Hydraulic Brake hose assembly, must be used to cater to relative movements of the steering and suspension system and any other.
8) All brake lines shall be designed for the pressures expected in the braking system and be chemically compatible with the brake fluid as per IS 8654.
9) Teams are recommended and advised to operate the brake pedal on the right foot, which requires the pedal to be placed on the right side of the steering column. This is a recommendation made considering the requirement of adequate foot pressure to be applied on the brake pedal for effective braking.

III. Overview of the braking system

The main objective of the braking system is to increase the safety and maneuverability of the vehicle by statically and dynamically locking all four tires on both paved and unpaved surfaces.

The brake system was designed to the rules, restrictions, and requirements provided by the SAE to ensure the vehicle can decelerate and stop within a reasonable distance. According to the rules provided by SAE, we used a hydraulic braking system. The braking system we selected for our ATV is the disc braking system. The reason for choosing disc brakes for ATVs was of the following advantages of disc brakes over drum brakes.

3.1 Disc Brake Vs Drum Brake :

For our application disc brakes are going to work much better than drum brakes ever could. We are going to endure a long, rough, and wet endurance course that will put our braking system through a lot of challenges. From the study, it is easy to see that disc brakes will work much better for this application for many reasons.

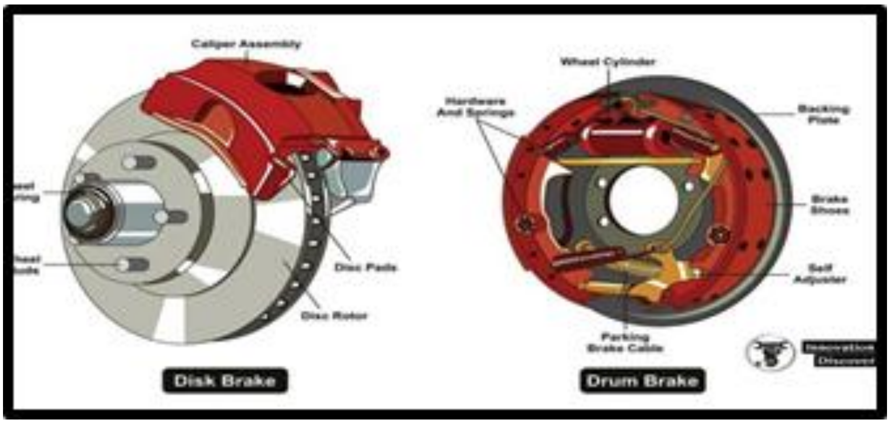

Fig. 3.1.1. Disc brake and Drum brake

Disc Brake	Drum Brake
1. Better ventilation	1. Low ventilation
2. Design is easy	2. Design is complex
3. Uniform wear of the pad	3. Non-uniform wear of the pad
4. Replacing the pad is easy	4. Replacing the pad is difficult
5. The total frictional area on the disc is less	5. The total frictional area in the drum is more
6. Lightweight	6. Heavyweight
7. highly efficient	7. less efficient
8. It has better anti-fade characteristics.	8. It has poor anti-fade characteristics.

Table 3.1.1. Disc brake and Drum brake

Disc brakes are fairly simple to work with, once we know the parts and their functions. The main components of a disc brake are :

1. Master Cylinder
2. Rotors
3. Brake Calipers
4. Brake Pedal

5. Brake Fluid
6. Hydraulic Lines

3.1.1. Master Cylinder :

In Automotive Engineering, the master cylinder is a control device that converts non-hydraulic pressure (commonly from a driver's foot) into hydraulic pressure. Basically has two types:

a. Single Circuit Master Cylinder
b. Tandem Master Cylinder

We are using 2 single-circuit master cylinders for developing more pressure with less effort because of less bore diameter. This will also reduce the overall weight of the system, cost, efficient and easy to assembly due to these key factors we decided to use Pulsar 220's rear master cylinder and its specifications are given below:

Fig 3.1.1.1 Master Cylinder

3.1.2. Rotors :

The brake disc or rotor is the main rotating component of the disc brake unit. It's usually made of stainless steel. The brake rotors are a part of the system that can be optimized to gain performance. Rotors can be solid, vented, cross-drilled, grooved, or some combination thereof.

The selection of rotor material is the key factor because the rotor must withstand high temperatures which are generated due to the braking phenomenon of conversion of kinetic energy to heat energy. Therefore the material used must have high thermal conductivity, strength, and anticorrosion properties as it has to face all terrains. The disc must have a design that will help it to cool faster and increase the surface area in contact with the air.

The material selection of the disc was done with the most common materials cast iron, steel, and stainless steel. The chromium content in the selection of material is an important factor as the disc travels through mud and water, the chances of being corroded decrease due to higher chromium content in the disc and increases rotor's durability and anticorrosive property.

Table 3.1.2.1. Chemical composition of SS420

Material Name	Cast iron	SS 420	Steel
Tensile strength (MPa)	350	1690	400
Young's modulus (GPa)	110	190	200
Thermal conductivity (BTUs)	35	24.9	26.1
Chromium content (%)	0.05	14	0.5 - 2

The rotor chosen for our ATV was a vented rotor of material SS420 as this has many advantages as:

- Good heat dissipation capacity due to the presence of vents.
- Light in comparison to fully solid rotors which are heavy. Hence, it will reduce the unsprung mass of the vehicle.
- Better durability due to its anti-corrosion property.

Fig. 3.1.2.1. Rotor made out of SS420

3.1.3. Brake Calipers :

Brake Calipers possess pressure energy which is applied on the rotating disc via brake pads and braking action is completed. The disc brake caliper assembly is bolted to the vehicle axle housing or suspension.

There are two main types:

- Fixed Calipers
- Sliding/Floating Calipers

Fixed calipers can have 2, 3, or 4 pistons. 2 piston calipers have one piston on each side of the disc. Each piston has its own disc pad. When the brakes are applied, hydraulic pressure forces both pistons inwards, causing the pads to come in contact with the rotating disc.

The sliding or floating calipers have 2 pads but only 1 piston. The caliper is mounted on pins or bushes that let it move from side to side. When the brakes are applied, hydraulic pressure forces the piston inwards. This pushes the pad against the disc. The caliper is free to move on slides, so there is a clamping effect between the inner and outer pads. Equal force is then applied to both pads which clamp against the disc.

To achieve perfect biasing we have decided to use two different brake calipers of different bore sizes for the rear and front brake systems.

Table 3.1.3.1. Chemical composition of SS420

Caliper	**Front**	**Rear**
Model	Vespa 150 R	RTR Apache 160
Type of caliper	Fixed	Floating
Boar size	32 mm	25.4mm
No of pistons	2	2
Quantity required	2	1

3.1.4. Brake Pedal :

The brake pedal uses leverage to transfer the effort from the driver’s foot to the master cylinder. Different lever designs can alter the effort the driver needs to make, by using different levels of mechanical advantage. Brake pedals should be mounted securely, free from any excessive sideways movement. We use the first kind of lever with a pedal ratio of 1.3:1.

Table 3.1.4.1. Brake Pedal(Mild Steel)

3.1.5. Brake Fluid :

Brake fluids are fluids used in hydraulic brakes. Fluid for the system was selected according to the thermal nature of the disc. The following comparison was made for the selection:

Table 3.1.5.1. Brake Fluid

Fluid	Dry (°C) BP	Wet BP (°C)
DOT 3	205	140
DOT 4	230	155
DOT 5	260	180
DOT 5.1	270	190

3.1.6. Brake Lines :

Brake lines carry brake fluid from the master cylinder to the brakes. They are basically the same on all brake systems. For most of their length, they are steel, coated to reduce the possibility of corrosion, and attached to the body with clips or brackets to prevent damage from vibration. In some vehicles, the brake lines are inside the vehicle to protect them better from corrosion.

The brake lines must be able to transmit considerable hydraulic pressure, so they are mostly made of steel, rather than of a softer but less corrosive and easier-to-fit material such as copper. However, a flexible section must be included between the body and suspension to allow for steering and suspension movement. These flexible hoses are made of tough reinforced tubing, to contain the pressures as well as to protect them from objects that could be thrown by the tires. If a brake line is damaged, it is usually replaced rather than repaired.

IV. Brake Calculations

Calculations for the system design are as follows:

4.1. Master cylinder calculations:

As we have to stop the vehicle with a minimum speed of 45 kmph within 15 feet (as per the brake test guidelines in the rulebook).

According to Newton's law of motion:

$$v^2 = u^2 + 2as$$

$$a = \frac{v^2 - u^2}{2s}$$

$$= \frac{0 \quad -11.11^2}{2 \times 4.1954}$$

$$= 14.7134 \ \frac{m}{s^2}$$

Here u=final speed
v=initial speed
a= deceleration
s= stopping distance

4.1.1. Inertial force calculations:

Inertial force acting on vehicle $= \frac{mass\ of\ vehicle \times deceleration}{graviational\ acceleration}$

$$= \frac{270 \times 14.7134}{9.81} \qquad = 404.9546 \text{ N}$$

4.1.2. Dynamic weight transfer calculations:

Dynamic weight transfer $= \frac{Inertial\ force \times C.G}{Wheel\ base}$

$$= \frac{404.9546 \times 22}{58} = 153.6034 \text{ kg}$$

From the dynamic weight transfer, we will get 56.89 % weight transfer of the vehicle in front and 43.10 % in the rear. And from F=ma we get total force then will find required force on front and rear wheels.

Then for Torque on front wheel,

Brake Torque = $Force\ at\ front \quad \times Radius\ of\ tire$

$= 2260.02 \quad \times 0.2794 \quad = 315.725$ Nm

Clamping force = $\frac{Brake\ Torque}{Radius\ of\ disc}$

$= \frac{315.725}{0.0755}$ = 4181.7891 N

Braking force = $\frac{Clamping\ force}{2\mu}$

$= \frac{4181.78906}{2\times0.8}$ = 5227.24 N

Pressure required to develop in caliper = $\frac{Brake\ force}{Area\ of\ caliper\ piston}$

$= \frac{5227.24}{1815.84}$ = 2.8786 Nmm²

The force required to generate pressure in caliper

Force (F1) = $Pressure\ generated\ in\ calipers \times Area\ of\ master\ cylinder$

$= 2.8786 \times 78.5714 = 226.1825$ N

Then for Torque on rear wheel,

Brake Torque = $Force\ at\ rear \times Radius\ of\ tire$

$= 856.29 \times 0.2794$

= 239.248 Nm

Clamping force = $\frac{Brake\ Torque}{Radius\ of\ disc}$

$= \frac{239.248}{0.0905}$ = 2643.62 N

Braking force = $\frac{Clamping\ force}{2\mu}$

$= \frac{2643.62}{2\times0.8}$ = 3304.53 N

Pressure required to develop in caliper = $\frac{Brake\ force}{Area\ of\ caliper\ piston}$

$= \frac{3304.53}{1013.82}$ = 3.2594 Nmm²

The force required to generate pressure in caliper,

Force (F2) = $Pressure\ generated\ in\ calipers \times Area\ of\ master\ cylinder$

$= 3.2594 \times 78.5714$

= 256.102 N

Pedal ratio = $\frac{Load\ of\ lift(F2)}{Force\ applied\ by\ driver} = \frac{256.102}{196.2}$ = 1.305

4.2. Thermal calculations

As the brake disc is a perfect example of a forced convection system in Heat and mass Transfer by using the same we can predict the temperature rise of the disc. Some physical quantities of the brake disc and dynamic conditions raise the temperature of the disc

As the total kinetic energy of the vehicle is going to be transformed into the waste heat energy, it can be easily verified by the rise in temperature of the disc.

Total Kinetic Energy = $Q = \frac{1}{2} m\ v^2$

$= \frac{1}{2} \times 357.31 \times 11.11^2$ = 11028.1 J

The rise in temperature can be analytically calculated as follows;

$$Q = m\ c_p \Delta T$$

………………..(1)

Here,

Q= kinetic energy of mass acting on one tire

m= mass of disc

Cp= specific heat of disc material (SS 420)

ΔT=change in temperature of disc

Equation (1) becomes;

$$\Delta T = \frac{Q}{mc_p}$$

$$= \frac{11028.1}{0.401 \times 475}$$
$$T_{disc} - T_{air} = 57.8979$$
$$T_{disc} = 84.8979$$

4.2.1. Heat flux calculation:

To validate the answer obtained from the analytical method and as brake disc is an example of forced convection we require some basic entities for steady state simulation on software. Those are heat flux, convective heat transfer coefficient and can be calculated by Fourier's law, Nusselt's number, Prandtl's number and Reynold's number.

$$Nusselt'snumber = 0.029 \quad Re^{0.8} Pr^{0.33}$$
$$\frac{2hD}{k} = 0.029 \quad \frac{pv2D}{\mu}^{0.8} \frac{\mu c_p}{k}^{0.33}$$
$$h = 77.2249 \text{ W/m}^2 \text{ K}$$

Here,
h=convective heat transfer coefficient W/m²K
D=characteristic dimension (diameter of disc)= 0.18 m
k=thermal conductivity of air = 0.02778 W/mK
ρ=density of air =1.107 kg/m³
v=velocity of air (m/s) =11.11 m/s²
μ=dynamic viscosity of air = 0.00001934 (Pas)
Cp=specific heat of air =1007 J/kgK
Now according to Fourier's law,
$Q = -k.A.$ dT/dx

$$\text{Heat flux} = \frac{Q}{A} = k\frac{dT}{dx}$$
$$= \frac{24.9 \times 57.8979}{0.18} = 8009.21 \text{ W/m}^2$$

Where,
Q=heat lost by the body (W)
k=thermal conductivity of material =24.9 W/m
dT/dx=temperature gradient
dx= diameter of disc
Heat flux = Q/A

V. Finite Element Analysis

The deformation and bending of the disc must be calculated so as to prevent any measured accident while driving. The forces acting on brake discs are clamping force offered by the brake caliper and the bending moment due to the same force due to clamping action on disc.

5.1. Results:

The observed results after simulation are as follows:

5.1.1. Temperature of disc:

As the temperature of disc is 74.05 °C analytically and Tmax denoted in result is 56 °C hence the analytical calculations are validated.

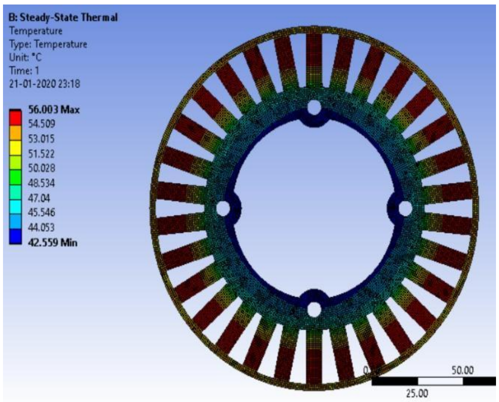

Fig. 5.1.1.1. Temperatures of Front Disc

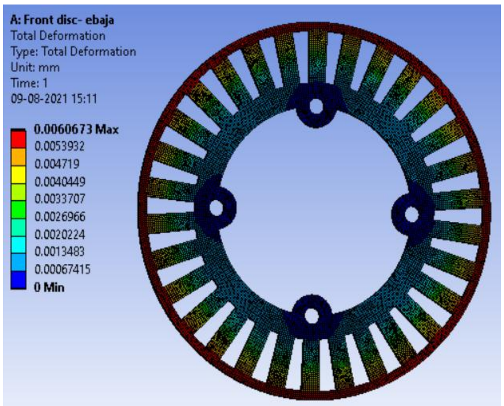

Fig. 5.1.1.2. Deformation of Front Disc

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