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Design and Analysis of Hydraulic Brake Caliper

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Abstract: ***An important factor in handling of any vehicle is making it to come quick and easy stop. Retarding a vehicle in manner such that driver has complete control over it is essential. The safety while braking is paramount and is quantified by evaluating mathematical model of braking. The evaluation of model is done by calculation of braking torque and comparing it with required value. The paper discusses ideas for using various components in the system, design variables and logic behind selecting correct values of those variables. The design of braking system consists of evaluating multitude of scenarios and using them to achieve optimum, yet effective braking. The data related to them is used to extract average values of design parameters, making the theoretical calculations as realistic as possible. Baja SAE is an intercollegiate design competition run by the Society of Automotive Engineers (SAE). Teams of students from universities all over the world design and build small off-road cars. The goal in Baja SAE racing is to design, build and race off-road vehicles that can withstand the harshest elements of rough terrain. The vehicles used in Baja SAE racing are often similar in appearance to dune buggies. The Main objective of the event is to design and build a vehicle which is safe, easily transported, easily maintained and fun to drive. Each Teams goal is to a build an ATV with least weight without compromising to the build quality of the vehicle. Using OEM components in vehicle leads to increase the overall weight of the vehicle, so the Design and Development of each component owing to required specifications becomes a necessary part while designing the vehicle. OEM Brake Caliper increases the weight of the vehicle with its technical specifications not conforming to the required necessity of the BAJA vehicle. The OEM caliper are designed according to the requirement of the vehicle and the Motorsport Company producing it. The Endurance limit and factor of safety of the OEM caliper are considered according to the use of caliper and the fatigue life of the vehicle. Design of Customized Brake caliper for BAJA vehicle is therefore necessity of the team to reduce the weight of the vehicle. This will enable us to decrease the unsprung mass of the vehicle along with decrease in Scrub radius of the vehicle. The Design specifications of the customized Brake 1alliper are specified according to the use of the vehicle, fatigue life and conforming to the mathematical calculations required to stop the vehicle. Mathematical Calculations were done for the braking force, clamping force, stopping distance of the vehicle owing to the requirement of the BAJA vehicle keeping in mind the dynamic events held at the competition. According to the calculations and the required specifications, Design of Customized Brake caliper were done for BAJA vehicle 2019. The Design specifications of the caliper are specified in the report below along with the design of the caliper and Design Analysis of the caliper.***

Keywords: BAJA, SAE, OEM Brake Caliper, Unsprung mass, Braking Systems, Scrub Radius, Analysis, Frictional Braking, Biasing effect, Weight Transfer, Hydraulic Pressure, Pascal's Law

1. Introduction

1.1 Introduction

The basic function of braking system is to retard a vehicle in motion A quality braking system enables driver with range of braking effort. This will allow him to feather the pedal for obtaining required amount of braking, getting desired motion while navigating corners and curves. In this way, braking system contributes majorly in terms of safety and handling. Importance of reliable braking mechanism in any vehicle is paramount. Brakes use principle of energy conversion, transforming kinetic energy in heat, thereby retarding velocity of vehicle. This is achieved by fiction between brake rotor and pads along with clamping force applied by caliper pads. This generates large amount of heat which is dissipated to air. The components in vicinity of such high temperature exhibit excellent thermal stability. The common goal of designing braking system is to implement a fully effective braking system in allocated space. The features of system should not have interference with other assemblies, either in static or dynamic condition. Therefore, the mounting and packaging of various sub-assemblies is as unique as the design of vehicle it is implemented in. BAJA buggies require compact and light weight systems which are reliable and provide satisfactory braking under tough conditions. This calls for proper selection of components and their placing in minimum space possible. Components such as rigid pipes are routed such that they do not hinder any other assembly on vehicle. The pedal box requires arrangement such that driver is able to actuate system on moment's notice and can comfortably ride for four hours of endurance race. An array of calculations dictates the design procedure and validates the condition of wheel-lock. These are performed in iterations to achieve required results. Braking system is an energy converting system that converts vehicle movement into heat while on application of clamping force using friction pads on brake rotor. This is done by applying pressure on back side of piston pushing the brake pads against the rotor disc causing frictional force at contact and inhibiting the motion of the vehicle.

The components of a brake caliper are as follows:

1. Caliper body
2. Piston
3. Retraction seal
4. Scrapper seal
5. Friction pads
6. Bleed port
7. Fluid inlet port

Figure 1:-Exploded View of Brake Caliper

The main function of the caliper is to support the brake pads and the clamping force is applied by the piston. Important aspects of a caliper is low weight but at the same time high stiffness. High stiffness and an evenly distributed pressure on the pads are necessary to achieve optimal braking force. An evenly distributed pressure results in evenly heat distribution which is crucial for wear and to avoid noise which occurs by variations in disc temperature. These characteristics are a result from the choice of material, manufacturing precision and the design of caliper.

1.2 Necessity

The braking system is an important system in the vehicles used to slow down or stop the vehicle in motion. It is also used to prevent the vehicle from moving when it is stationary. During field operations it helps in taking sharp turns by applying differential brakes on the two rear wheels. The brakes use the financial force to reduce the motion of the wheels. Friction is used to convert the kinetic energy into heat. The brake arrangement serves to intentionally offer resistance to the movement of the vehicle. Most common are the friction brakes. These are essentially heat devices that change the kinetic energy of the moving vehicle into heat, by virtue of friction between a rotating component and a stationary component which are mechanically moved so that they come in contact with the rotating component. The stationary are lined with a hard wearing friction material. When this material is moved into contact with the rotating component, braking takes place. Brake is used to stop or slow down the motion of a vehicle. It is mounted on the driving axle and operated by two independent pedals. Each pedal can be operated independently to assist the turning of vehicle during the fieldwork or locked together by means of a lock.

1.3 Objectives

1. To make a perfectly working hydraulic brake Caliper.
2. To ensure the vehicle stops when brakes are applied.
3. To manufacture a cost efficient Caliper as compared to OEM Calipers.
4. To manufacture a light weighted Caliper to enhance vehicle's overall performance.
5. Study of various types of Brake Caliper.
6. Applying the known knowledge and the outcome of the education for design of caliper.

2. Theory

2.1 Brake

A **Brake** is a mechanical device that inhibits motion by absorbing energy from a moving system. It is used for slowing or stopping a moving vehicle, wheel, axle, or to prevent its motion, most often accomplished by means of friction. Vehicle can be regard as energy conversion device, which transfers the momentum into heat, in other words, which transfers the kinetic energy into thermal energy. The brakes are used to reduce the speed of the vehicle, and the speed of conversion determines the rate of the vehicle slows down.

2.2 Background

Most brakes commonly use friction between two surfaces pressed together to convert the kinetic energy of the moving object into heat, though other methods of energy conversion may be employed. For example, regenerative braking converts much of the energy to electrical energy, which may be stored for later use. Other methods convert kinetic energy into potential energy in such stored forms as pressurized air or pressurized oil. Eddy current brakes use magnetic fields to convert kinetic energy into electric current in the brake disc, fin, or rail, which is converted into heat. Still other braking methods even transform kinetic energy into different forms, for example by transferring the energy to a rotating flywheel.

Brakes are generally applied to rotating axles or wheels, but may also take other forms such as the surface of a moving fluid (flaps deployed into water or air). Some vehicles use a combination of braking mechanisms, such as drag racing cars with both wheel brakes and a parachute, or airplanes with both wheel brakes and drag flaps raised into the air during landing.

Since kinetic energy increases quadratic ally with velocity ($K=mv^2/2$), an object moving at 10 m/s has 100 times as much energy as one of the same mass moving at 1 m/s, and consequently the theoretical braking distance, when braking at the traction limit, is 100 times as long. In practice, fast vehicles usually have significant air drag, and energy lost to air drag rises quickly with speed.

Almost all wheeled vehicles have a brake of some sort. Even the baggage carts and shopping carts may have them for use on a moving ramp. Most fixed-wing aircraft are fitted with wheel brakes on the undercarriage. Some

aircraft also feature air brakes designed to reduce their speed in flight.

2.3 The Basic Physics Principle Used in Braking System

The main function of the brake system is to decelerate or decrease the speed of a vehicle. By stepping on the brake pedal, the brake pads compress against the rotor attached to the wheel, which then forces the vehicle to slow down due to friction. As we know when we step the brake pedals or handbrakes, the cars transmit the force from our feet or hands to the brakes. Actually the car commands a stopping force ten times as powerful the force that puts the cat in motion. Because the brakes need a much greater force than drivers could apply with legs, the car must multiply the force of the foot. To stop a car, the brakes have to get rid of that kinetic energy. They do so by using the force of friction to convert that kinetic energy into heat. When you press your foot down on the brake pedal, a connected lever pushes a piston into the master cylinder, which is filled with hydraulic fluid.

An object remains in its state of rest or in motion until and unless acted upon by an external force" Newton's first law of motion, this law by Sir Isaac Newton gave rise to the development of braking system in an automobile, developing an automobile vehicle not only requires the power source but also the efficient braking system as higher the horse power higher will be the brake force required to stop or de accelerate that vehicle. This thought gave rise to many researches in the field of braking and results in its evolution due to which today we have flexibility in choosing a suitable braking system according to our need. So let's just start our article with the curiosity about the various types of braking system.
In an automobile vehicle, a braking system is an arrangement of various linkages and components (brake lines or mechanical linkages, brake drum or brake disc, master cylinder or fulcrums etc.) that are arranged in such a fashion that it converts the vehicle's kinetic energy into the heat energy which in turn stops or de accelerate the vehicle.

The conversion of kinetic energy into heat energy is a function of frictional force generated by the frictional contact between brake shoes and moving drum or disc of a braking system.

2.4 Need of Braking System

In an automobile vehicle braking system is needed;

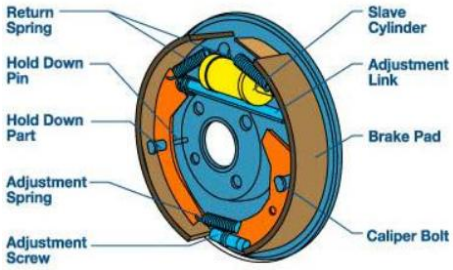
- To stop the moving vehicle.
- To de accelerate the moving vehicle.
- For stable parking of a vehicle either on a flat surface or on a slope
- As a precaution for accidents.
- To prevent the vehicle from any damage due to road conditions.

2.5 Classification of Braking System

A) On Power Source Basis:

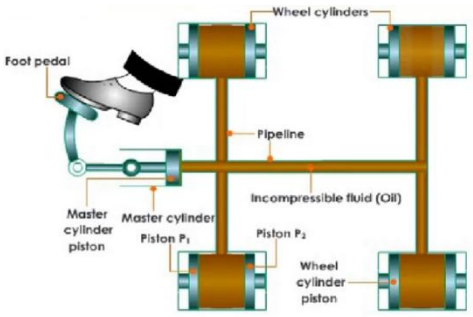
1. Mechanical Brakes

It is the type of braking system in which the brake force applied by the driver on the brake pedal is transferred to the final brake drum or disc rotor through the various mechanical linkages like cylindrical rods, fulcrums, springs etc. In order to de accelerate or stop the vehicle. Mechanical brakes were used in various old automobile vehicles but they are obsolete now days due to their less effectiveness.



2. Hydraulic Brakes

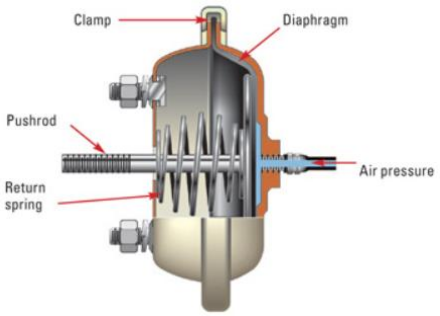
It is the type of braking system in which the brake force applied by the driver on brake pedal is first converted into hydraulic pressure by master cylinder (for reference read article on master cylinder) than this hydraulic pressure from master cylinder is transferred to the final brake drum or disc rotor through brake lines. Instead of mechanical linkages, brake fluid is used in hydraulic brakes for the transmission of brake pedal force in order to stop or de accelerates the vehicle. Almost all the bikes and cars on the road today are equipped with the hydraulic braking system due to it high effectiveness and high brake force generating capability. All the modern cars and Automobiles use this type of Braking System.



3. Air or Pneumatic Brakes

It is the types of braking system in which atmospheric air through compressors and valves is used to transmit brake pedal force from brake pedal to the final drum or disc rotor. Air brakes are mainly used in heavy vehicles like busses and trucks because hydraulic brakes fails to transmit high brake force through greater distance and also pneumatic brakes generates higher brake force than hydraulic brake which is the need of the heavy vehicle. The chances of brake failure is less in case of pneumatic

brakes as they are usually equipped with a reserve air tank which comes in action when there is a brake failure due to leakage in brake lines. High end cars these days are using air brakes system due to its effectiveness and fail proof ability.

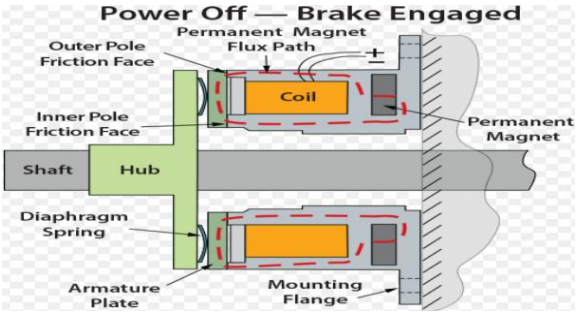


4. Vacuum Brakes

It is the conventional type of braking system in which vacuum inside the brake lines cause's brake pads to move which in turn finally stops or de accelerate the vehicle. Exhauster, main cylinder, brake lines, valves along with disc rotor or drum are the main components that combines together to make a vacuum braking system Vacuum brakes were used in old or conventional trains and are replaced with air brakes now days because of its less effectiveness and slow braking. Vacuum brakes are cheaper than air brakes but are less safe than air brakes. Vacuum Brakes are less efficient compared to other types of brakes.

5. Magnetic Brakes

In this types of braking system, the magnetic field generated by permanent magnets is used to cause the braking of the vehicle. It works on the principle that when we pass a magnet through a cooper tube, eddy current is generated and the magnetic field generated by this eddy current provide magnetic braking. This is the friction less braking system thus there is less or no wear and tear. This is the advanced technology in which no pressure is needed to cause braking. The response to the braking in this is quite quick as compared to other braking systems.



6. Electrical Brakes

It is type of braking used in electric vehicle in which braking is produced using the electrical motors which is the main source of power in electric vehicles, it is further divided into 3 types-

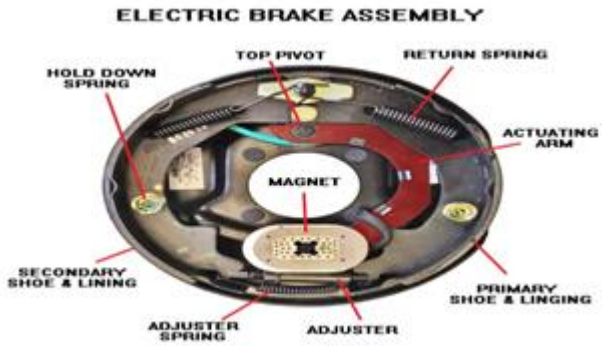
(i) Plugging Brakes-When the brake pedal is pressed in the electric vehicle equipped with plugging braking, the polarity of the motors changes which in turn reverses the direction of the motor and causes the braking.

(ii) Regenerative Braking-It is the type of electrical braking in which at the time of braking the motor which is the main power source of the vehicle becomes the generator i. e. when brakes are applied, the power supply to the motor cuts off due to which the mechanical energy from the wheels becomes the rotating force for the motor which in turn converts this mechanical energy into the electric energy which is further stored in the battery.

Regenerative braking saves the energy and are widely used in today's electric vehicles.

Tesla Model-S provides the most effective regenerative braking.

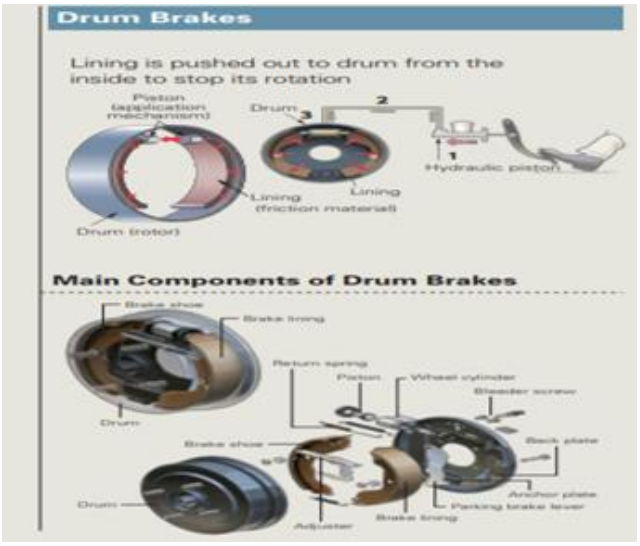
(iii) Dynamic or Rheostat Braking-It is the type of electrical braking in which resistance provided by the rheostat causes the actual braking, in this type a rheostat is attached to the circuit that provides the resistance to the motor which is responsible for de acceleration or stopping of the vehicle.

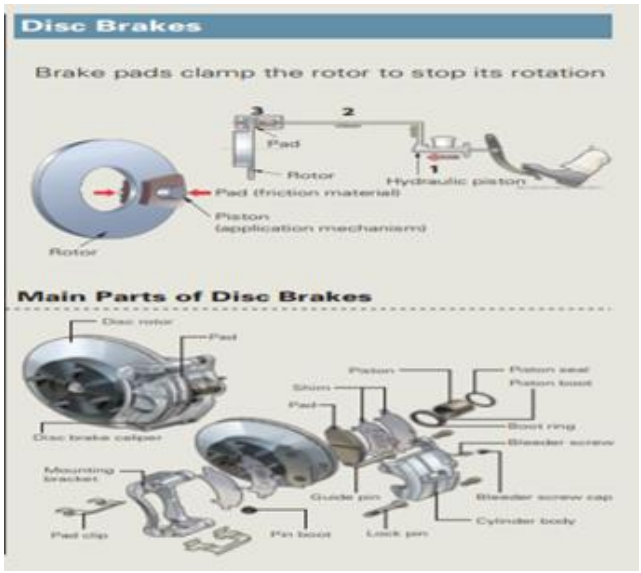


B) On Frictional Contact Basis:

1. Drum Brakes or Internal Expanding Brakes:

It is the type of brake system in which a drum which is the housing of the brake shoes along with actuation mechanism is attached with the wheel hub in such a fashion that the outer part of the drum rotates with the wheel and inner part remains constant. When brakes are applied the actuating mechanism (wheel cylinder or mechanical linkage.) causes the brake shoes to expand due to which the outer frictional surface of the brake shoes makes frictional contact with the rotating drum part which in turn stops or de accelerate the vehicle.





Drum Brake

Disc Brake

2. Disc Brake or External Contracting Brakes

It is the types of braking system in which instead of a drum assembly a disc rotor attached to the hub of the wheel in such a fashion that it rotates with the wheel, this disc rotor is clamped in between the caliper which is rigidly fixed with the knuckle or upright of the vehicle.

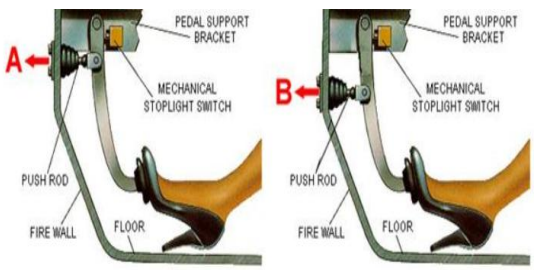
This caliper used is the housing of the brake shoes along with the actuation mechanism (mechanical linkages or caliper cylinder).

When the brakes are applied the actuation mechanism contracts the attached brake shoes which in turn makes the frictional contact with the rotating disc rotor and causes the braking of the vehicle.

C) On Application Basis:

1. Service Brake or Foot Brakes-

It is the type of brakes in which the brakes are applied when the driver presses the brake pedal mounted inside the cockpit or at the foot space of the vehicle with his foot, this pedal force applied by the driver is further multiplied and sent to the braking drum or disc either by mechanical linkages or by hydraulic pressure which in turn causes braking. In cars foot operated brakes are used and in bikes the combination of foot and hand operated brakes are used.



2. Hand Brake or Parking Brake–

This type of brakes are also known as emergency brake as they are independent of the main service brake, hand brakes consists of a hand operated brake lever which is connected to the brake drum or disc rotor through the metallic cable. When hand brake lever is pulled, tension is created in the metallic rod which in turn actuates the brake drum or disc rotor mechanism and final braking occurs. Hand brakes are usually used for stable parking of the vehicle either on flat road or slope that is why it is also called parking brakes.

D) On Brake Force Distribution Basis:

1. Single Acting Brakes-

It is the type of braking in which brake force is transferred to either a pair of wheels (in cars) or to the single wheel (in bikes) through single actuation mechanism (mechanical linkages or master cylinder). These types of braking system are commonly used in bikes or in light purpose vehicles.

2. Dual Acting Brakes-

It is the type of braking in which the brake force is transferred to all the wheels of the vehicle through dual actuation mechanism (tandem master cylinder or mechanical linkages).

This type of braking is used in cars as well as in heavy purpose vehicle.

3. Literature Review

3.1 Brake System Review

A brake is a device by means of which artificial frictional resistance is applied to moving machine member, in order to stop the motion of a machine (SAE International, 2003). A brake 6alliper usually made of cast iron or ceramic, is connected to the wheel or the axle. To stop the wheel, friction material in the form of brake pads (mounted in a device called a brake 6alliper) is forced mechanically, hydraulically or pneumatically against both sides of the disc. Friction causes the disc and attached wheel to slow or stop.

Belhocine Ali and **Bouchetara Mostefa** (2013), analysed the thermomechanical behavior of the dry contact between the brake disc and pads during the braking phase. The thermal-structural analyse is then used to determine the deformation and the **Von Mises stress** established in the disc, the contact pressure distribution in pads.

Anders Forsman and **Mikael** (2009), investigated the possibility to improve the performance of the brake caliper for a GM project. The aim is to design a caliper with less amount of material but with the same stiffness. The delimitations are that the manufacturing costs should be unchanged and the design should work without modifications of the surrounding parts. Design and Analysis an Efficient Lightweight Brake Caliper for KUIM Electric Vehicle **Muhammad Hazwan Bin Md Jamal, Mohd Kadri Bin MdSaleh**.

The detailed and refined finite element model of a real disc brake considers the surface roughness of brake pads and allows the investigation into the contact pressure distribution affected by the surface roughness and wear. It also includes transient analysis of heat transfer and its influence on the contact pressure distribution. The focus is on the numerical analysis using the finite element method. The simulation results are supported with measured data in order to verify predictions. An improved numerical methodology is presented by considering three-validation stages, namely, modal analysis at component and assembly levels and verification of contact analysis. Prior to that, a realistic surface roughness of the brake pad at macroscopic level is considered in the finite element model instead of assuming a smooth and perfect surface that has been largely adopted by most previous researchers. These two aspects have brought about significant improvement to the validation as well as analysis. Wear and thermal effects are other distinct aspects of disc brakes that influence contact pressure distributions and squeal generation in a disc brake assembly and they are also included in the current investigation. Transient analysis of disc brake vibration using a large FE model that includes thermal effects is carried out.

4. Methodology

4.1 Design Parameters

The calculation and verification of braking force is a crucial step in the design process of an automobile as the braking system directly factors as a good control and safety feature in the product. While designing, the main objective is to generate more braking force than ideally required to account for inefficiencies in mechanical linkages and hydraulic systems. Figure 2 shows the flow chart of Methodology for design of Brake Caliper.

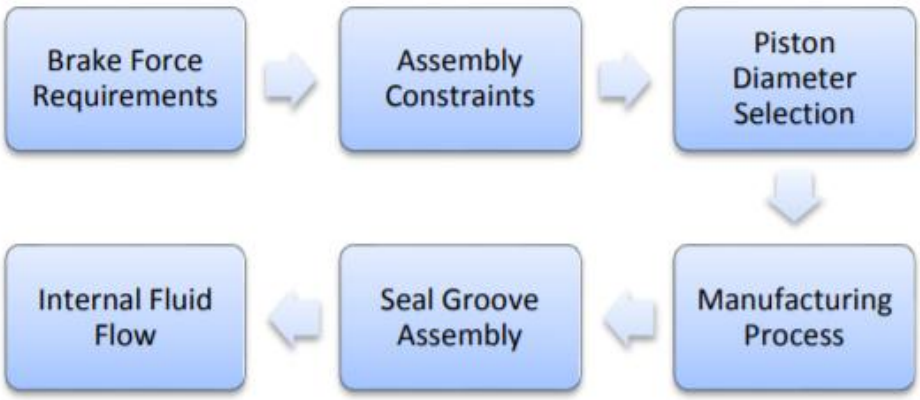


Figure 2: Methodology for design of Caliper

4.2 Calculations

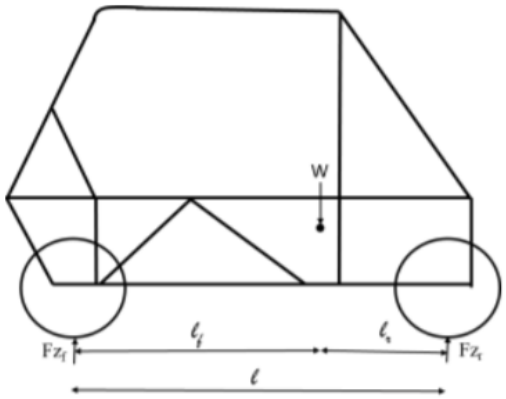


Figure 3:-Schematic representation of weight distribution

Following calculations are founding stones for designing the braking system. They validate that design satisfies necessary requirements:

	Standard		*Metric*	
Weight of car under both front wheels	lb	94.5	kg
Weight of car under both rear wheels	lb	115.5	kg
Aerodynamic downforce at top speed	lbf	0	kgf
Wheelbase of car	in	1422.4	mm
Distance from center of gravity to ground	in	435	mm
Distance from front axle to center of downforce	in	1500	mm
Total area of front brake caliper pistons	in²	11304	mm²
Total area of rear brake caliper pistons	in²	5024	mm²
Effective radius of front brake rotors	in	127	mm
Effective radius of rear brake rotors	in	140	mm
Rolling radius of front tires	in	241.3	mm
Rolling radius of rear tires	in	266.7	mm
Coefficient of friction of front tires		0.9	
Coefficient of friction of rear tires		0.9	
Coefficient of friction of front brake pads		0.35	
Coefficient of friction of rear brake pads		0.35	
Tandem Master or Dual Master Cylinders		1	
Brake booster assist ratio	: 1	0	: 1
Brake pedal ratio	: 1	5.33	: 1
Force on brake pedal for maximum deceleration	lbf	19	kgf

1) Force applied on pedal (F) = 350N
2) Bore diameter of master cylinder (db) = 0.01905 m
3) Piston diameter of caliper (d) =0.032 m
4) Number of pistons (n) = 1

a) Bore area of master cylinder (Acb) =

$$(A_{cb}) = \frac{\pi}{4} \times d^2$$
$$= \frac{\pi}{4} \times (0.01905)^2$$
$$= 0.0002848 m^2$$

b) Pressure at caliper end

$$(P) = \frac{F}{A_{cb}}$$
$$= \frac{350}{0.0002848}$$
$$= 1228932.58 \text{ N}$$

c) Area of caliper piston

$$(A_p) = \frac{\pi}{4} \times d^2$$
$$= \frac{\pi}{4} \times (0.032)^2$$
$$= 0.00080424 m^2$$

d) Total force on brake pad by single piston $(F_t) = P \times A_p$
$$= 1228932.58 \times 0.00080424$$
$$= 988.356 \text{ N}$$

e) Clamping force on disc

$$(F_{clamp}) = F_t \times n$$
$$= 988.356 \times 1$$
$$= 988.356 \text{ N}$$

5. Modeling of Caliper

Modeling of caliper was done as per requirement of the piston diameter and assembly constraints in the wheel rim.

Modeling was done on CATIA V5. Parametric modeling was used in modeling of caliper.

Figure 4: CAD Model of Caliper

6. Finite Element Analysis

After the numerical calculations, all the parameters such as bore diameter, seal groove, mounting, etc. are decided and then the CAD modelling of the caliper was done using CATIA V5. This model was analyzed by applying the forces and pressure. Static structural analysis of the CAD model was carried out in ANSYS 15.0. Following material parameters were considered.

Table 1: Properties of AI 7075

NO	Parameter	Value
1	Density	2700 kg/m^3
2	Young's Modulus	72 GPa
3	Yield Ten sile Strength	503 MPa
4	Ultimate T ensile Strength	590 MPa

6.1 MESING

The different mesh parameters like aspect ratio, skewness were considered too improve the mesh quality. Out of the different element types like hex dominant, sweep etc. tetra elements were considered as they capture the curvatures more accurately than in any other method. Proximity and curvature was used in order to ensure finer mesh along the curved regions and varying cross sections.

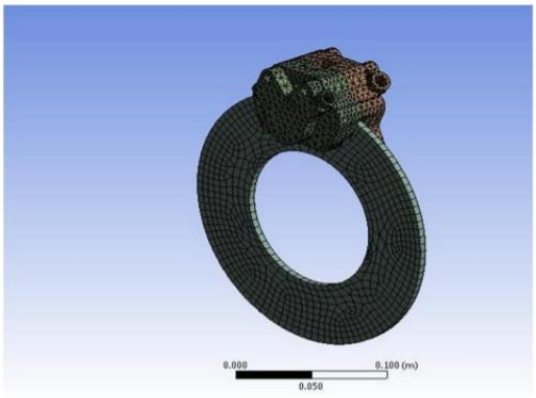


Figure 5:-Meshed Model of Brake Caliper

Caliper body is subjected to mainly following three loads:

1. Reaction on caliper due to the hydraulic pressure applied on piston
2. Reaction on the caliper body due to clamping force
3. Frictional force on pad, transmitted to the friction pad mounts.

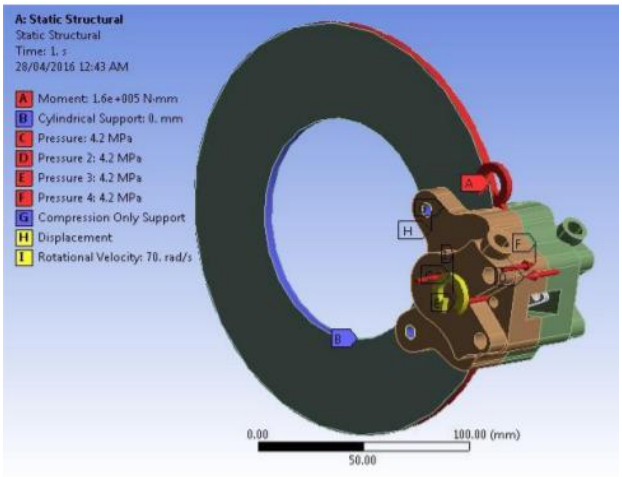


Figure 6:-Loading conditions for Brake Caliper

The piston diameter and the bore diameter are calculated according to required braking torque. This magnitude of clamping force is applied on the rotor by the piston. T e diameter and number of pistons can be iterated according to equation depending upon the rim size i. e. space availability. The piston diameter was selected to be 28 mm as per availability of rubber seal. The piston diameter is nothing but the bore diameter of caliper. There is clearance fit between the piston and the caliper bore in absence of any seals. A step is provided at the bottom of bore to prevent the back side of piston from touching the bottom surface of caliper and to increase the space for fluid to apply pressure.

7. Results and Discussions

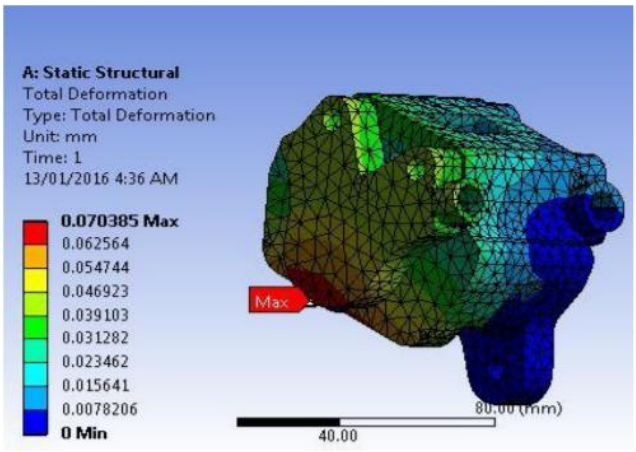


Figure 7:-Total Deformation of Brake Caliper

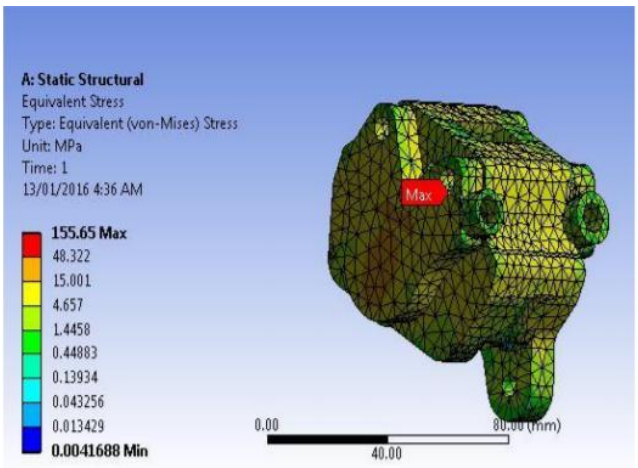


Figure 8:-Equivalent stress (von-misses) of a brake caliper

δ_{max}mm	0.070385
σ_{max}(MPa)	155.65
FOS	3.25

Table 2:-Deformation & Stress variations

The stress results show that factor of safety for the designed model is within limits Thermal stresses were neglected as their effect is negligible. The parameters decided could help in further lowering the manufacturing cost and weight.

8. Conclusions

The following comments could be concluded:

1) Determination of the braking force is the most crucial aspect to be considered while designing any braking system. The generated braking force should always be greater than the required braking force.
2) The calculation of required clamping force helps us to decide the diameter and the number of pistons to be used. Space and assembly constraints are also an important factor while designing the caliper body.
3) The seal groove geometry is pivotal to the operation of the caliper as it allows the piston to retract after the required clamping force has been applied.

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