Design and Analysis of Single Piston Floating Brake Caliper

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***Abstract* - The safe operation of a motor vehicle requires continuous adjustment of its speed and direction according to the variation of traffic on the road. Steering system, tyre tread, and braking system generally govern the control of the vehicle on the road. The basic function of a braking system is to reduce the speed of the vehicle or to bring it to halt, whichever is needed. Braking system must be designed to perform safely in all the conditions including smooth and rough roads, wet, dry or slippery road, a lightly laden or fully laden vehicle, braking on turning or braking in a straight path, etc. The following work studies an optimized design of a single piston floating disc brake caliper. Disc brakes provide better braking force, lightweight, simpler design and better maintainability. This caliper is designed to improvise the braking system in the Mini Baja vehicle and in two-wheelers. The best available brake caliper in the market is the Wilwood braking system. This design is aimed at reducing the weight of the brake caliper assembly with increased strength of the caliper body and also reducing the deformation due to operation at high temperature as compared to the OEM available in the market.**

The brake caliper is modeled and analyzed considering all the drivable conditions. The modeling is done in SolidWorks 2016 and analyzed via FEA in ANSYS 19.2 Academic. The resultant caliper is tested for pressure and loads on the caliper and its effect on the motion of the vehicle and the results are studied for the displacements/deformations and stresses on the caliper.

Keywords: Braking System, Disc Brakes, Brake Caliper, Weight Reduction, Increased Strength, FEA Analysis.

I. INTRODUCTION

The braking system in a vehicle plays a crucial role. It is required for lowering the speed of the vehicle or to completely stop the moving vehicle. This is basically done by dissipating the kinetic energy of the vehicle into heat by friction. Nowadays, braking systems are of various types. Major used braking systems are mechanical braking system, hydraulic braking system, and air braking system. Drum Brakes comprises of drum brake shoe actuated with a pedal system in the rim of the vehicle. When the pedal is pressed, the drums are pushed against the circular walls of the rim. Friction is produced between the brake shoe and the rim, and the speed of the vehicle is lowered. In the disc braking system or hydraulic braking system, a metallic alloy or carbon composite disc is fitted with a wheel hub and a caliper is fixed across the disc to hold it. The caliper is comprised of brake pads in between the jaws to hold the moving disc. This type of braking system is more powerful than the mechanical braking system. Air braking system works the same as the hydraulic braking system, the only difference is that the fluid used is compressed air for braking. This system is generally used in heavy-duty vehicles.

The following braking system relates to a hydraulic braking system. This paper aims at the design of the single piston floating brake caliper. Brake calipers are of two types- Floating brake caliper and fixed brake caliper. Floating brake calipers have single side piston(s). Fixed brake calipers have both side piston(s) of the disc. Floating brake calipers is called so because it moves or floats to another side when brakes are applied in order to maintain smooth braking without distorting the disc. In fixed brake caliper, when brakes are applied pistons on both sides of the disc presses against the disc to apply brakes. Fixed brake calipers are more complex in design and heavy as compared to floating brake calipers. Components of a brake caliper are (1) Caliper Body (2) Caliper Piston (3) Retraction Seal (4) Friction Pads (5) Bleed Port and (6) Fluid Inlet Port. The main function of the caliper is to support to brake pads and the clamping force applied by the piston. An important aspect of the caliper is high stiffness and strength, but at the same time, it should be lighter in weight.

Hydraulic Braking System - Single piston floating brake caliper
As we know, the braking system is used to stop the vehicle by dissipating the kinetic energy of the vehicle into heat via friction. In the hydraulic braking system, a disc or plate is connected with the wheel using a hub. This disc passes through a set of jaws called caliper which holds the disc while the brake pedal is pressed. When the pedal is pressed, the force is transferred to the piston of the master cylinder which injects the brake fluid into the brake caliper piston(s) with enormous pressure. Caliper piston, in turn, pushes the brake pads against the disc. When both pad and disc come in contact, the frictional force is produced the vehicle stops. In case of floating type brake caliper, when brake pad moves toward the disc and stick to it, there is no space left for more actuation, so the caliper floats away from the wheel on the floating pins. This results in the total actuation of the disc and brake pad.

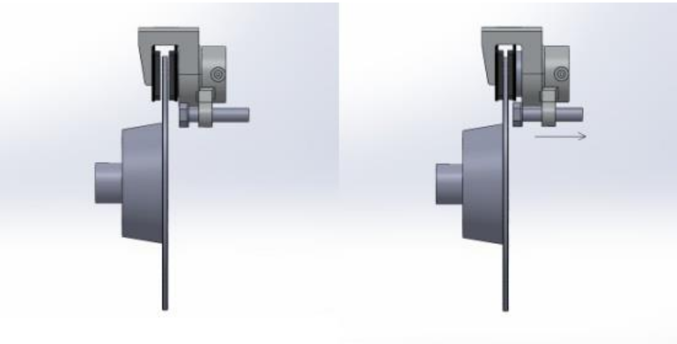

Fig. 1. Floatation of brake caliper while applying brakes

II. RESEARCH METHODOLOGY

The main aim of the research is to develop a brake caliper which must be highly optimized with respect to weight and at the same time must have enough strength and stiffness to withstand the forces and pressure. This section includes the steps needed to develop such a brake caliper.

1) *Project Planning*
As there are plenty of brake calipers available in the market, it is very important to set certain objectives for designing. It is observed that there is mainly the use of double-piston brake calipers in two-wheelers and BAJA vehicles. But the force required can be easily acquired by single pistons. So, it is decided to design the caliper with single piston system only. It has to be decided whether a fixed caliper must be used or a floating caliper. It was observed and calculated that the forces required for stopping the vehicle can be generated using a floating brake caliper. Also, the use of floating brake caliper reduces the weight of the whole system. Generally, OEM brake calipers use two seals in the piston caliper assembly. One is used for pulling back the piston when brakes are released and others for preventing water, dirt or other foreign substances. These functions can be done using a single O-seal. Brake calipers are mounted using a mounting plate and float on the floating pins separately. SO, a system had to be developed to exclude this complex mounting. After considering all the constraints offered by the existing caliper, we came across the objectives of the design of the caliper.
All of the tasks required to achieve the project's scope are sequenced according to their dependencies for each other. It is started by the study of the vehicle dynamics followed by the calculation of the bore diameter of the brake piston with respect to the piston diameter of the master cylinder. Once the forces and bore diameter is calculated, the modeling of the caliper is started. Jaws are designed so as to resist the forces exerted by the piston on the pads and disc. The whole assembly is designed and modeled in SolidWorks 2016. The modeled caliper is then analyzed structurally in ANSYS 19.2 Academic. The analysis and stimulation are done using Finite Element Method.

2) *Force Considerations and Calculations*
For the safe application of the braking system in a vehicle, proper calculation of the vehicle motion is necessary. Improper forces calculation would result in under-braking of vehicle or over-braking of the vehicle which is hazardous in both cases. Therefore, braking forces and torques on front and real axes should be calculated considering all parameters and constraints. The mechanics of braking system is calculated using fundamentals of rotations, forces and moments. Consider a vehicle of weight W acting downwards from its center of gravity 'c' at height h and at the center of wheelbase b as shown in the figure. Two reaction forces act on the front axle and rear axle R_1 and R_2 respectively. The sum of these reaction forces is equal to the weight of the vehicle. It is implacable that there must be friction between the ground and the tyre. Let the frictional force resisting the front tyres and rear tyres to be f_1 and f_2 respectively. At 60 km/h, when hard brakes are applied, the vehicle must stop within 5 seconds and less than 10 meters of braking distance. If we consider 1 second as reaction time of the driver, the total timing of halt of the vehicle must be within 6 seconds and under 10 meters. The retardation rate 'a' using laws of motion comes out to be 4.905 m/s^2. The braking system is being designed for Baja vehicle or two-wheelers, so the weight of the vehicle including the rider is 250kgf or 2500 N. Using the fundamentals of mechanics, all forces in a direction/axis must not disturb the stability of the vehicle. Therefore, $\sum F_x = 0$, $\sum F_y = 0$ and $\sum F_z = 0$. Also, the moment produced along the center of gravity of the vehicle while braking should not topple the vehicle, so, the summation of all moments should be zero. In the figure below, f_1 and f_2 are in the x-direction. Sum of f_1 and f2 would be equal to the force exerted by the engine of the vehicle. Therefore,

$$\Sigma Fx = f1 + f2$$

But, the force exerted on a body is equal to the product of its mass and acceleration,

$$\Sigma Fx = f1 + f2 = ma = \frac{W}{g}a$$

Finally,
$$f1 + f2 = \frac{W}{g}a \quad (1)$$

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Similarly, the summation of all forces in y-direction must be zero. In this direction, the only weight of the car and the reaction forces are acting. Therefore,

$$\Sigma Fy = W - R1 - R2 = 0$$
$$R1 + R2 = W \qquad (2)$$

Now, when all the forces have been considered, the moment also plays an important role in the stability of the vehicle. It will be very convenient to sum the moments produced by all the forces been exerted on the vehicle while braking if it will be calculated at centre of gravity; only for the sake of ease in calculation. Therefore, at the centre of gravity, if anticlockwise moment is taken as positive and clockwise moment taken as negative according to the figure, then moment equation will be,

$$\Sigma Mx = 0$$
$$f1.h + f2.h + R2.\frac{b}{2} - R1.\frac{b}{2} = 0$$
$$(f1 + f2)h + (R2 - R1).\frac{b}{2} = 0 \qquad (3)$$

On simplification of this equation using equation 1 and 2, the formula for reaction forces will pop out.

$$R1 = \frac{W}{2} + \frac{h}{b}\frac{W}{g}a \qquad (4)$$

$$R2 = \frac{W}{2} - \frac{h}{b}\frac{W}{g}a \qquad (5)$$

Both the reaction forces are calculated putting all the relative values and the values for R1 and R2 came up to be 1788.8 N and 711.2 N respectively. Using these values, frictional forces on front axle and rear axle are calculated and results to be f_1=670 N and f_2=266 N.

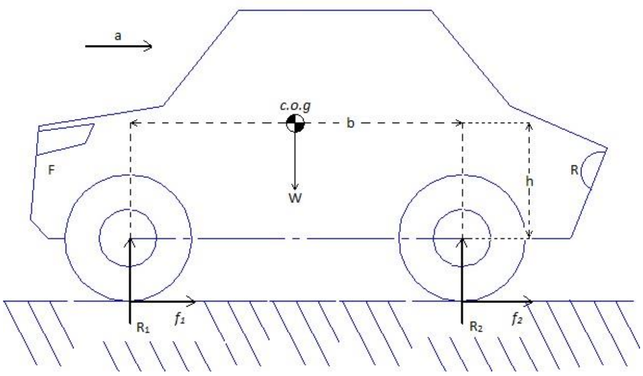

Fig. 2. All the forces and moments exerting on the vehicle

3) Bore Diameter calculation

After the calculations of the frictional forces which are responsible for the motion of the wheels of the car, the bore diameter of the caliper piston needs to be calculated. The mechanics behind the calculation starts with the application of force on the brake pedal by the driver. It is observed that the normal force applied by the 95th percentile male is 350 N. the force is multiplied by the leverage of 5 provided by the pedal. This force then increases to 1750 N and bifurcated to 875 N to each cylinder (we are considering separate master cylinder for both front axle and rear axle). The master cylinder which is required must produce enough pressure so that the force can be generated within a feasible size of the brake piston. In this case master cylinder with bore diameter of 19.05 mm (0.625 in) is used. Using this master cylinder, the pressure generated from inside the cylinder is 3.071MPa. This pressure will be uniform within the whole system and transmitted to the brake caliper. For the dimensions of the piston-mainly diameter of the caliper piston, brake force exerted on the disc is required.

When the vehicle is moving on the ground, the tyres are getting torque from the engine to move it in forward direction. This torque on each tyre is produced by frictional force between the tyre and ground. While braking, this torque is needed to be counteracted. This can only be done by another torque equal and opposite in direction. This is done by the action of brake pads on the brake disc as shown in figure. The friction produced between the disc and brake pads must be enough to produce same torque as that in the tyres. But the wheel size is one of the constraints for the size of disc. The diameter of the tyre used is 22 inches (558.8 mm). Therefore, the disc to be used should be optimum in size to fit inside the wheel along with the calipers. It is decided to use 170 mm diameter disc for this scenario. On equating the torques, we get

$$f_{tyre} \times r_{tyre} = f_{disc} \times r_{disc}$$
$$\mu_{tyre} \times R_1 \times r_{tyre} = \mu_{disc} \times F_b \times r_{disc}$$

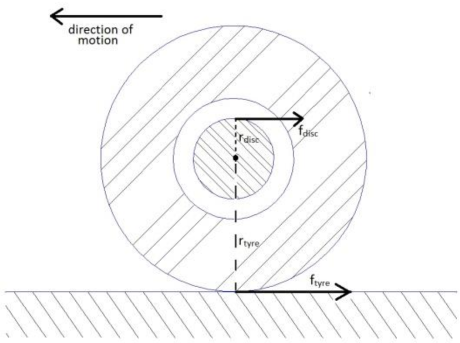

Fig. 3. Toque exerting on the disc and tyre must be equal and opposite in direction

From the above equation, force exerted by the brake caliper on the disc can be calculated. The value for this force came out to be 2856 N. This force on the surface area of brake piston will exert the same pressure as exerted by the master cylinder. From this relation, diameter of the piston can be calculated. So, force per unit area is pressure, then the value of the diameter of the circular cross-section of the piston came out to be 34.42 mm. After getting this value, the 3D model of the brake caliper is made using CAD software like SolidWorks 2016 and would be analyzed using ANSYS 19.2 Academic.

4) 3-D Modeling of the brake caliper

After all the required calculations which are needed to be processed, 3-D modeling of the caliper started. This is carried out on SolidWorks 2016. SolidWorks is a solid modeling Computer-aided Design (CAD) and Computer-aided Engineering (CAE) computer program that runs on Microsoft Windows. SolidWorks is published by Dassault Systèmes. The basic design structure of a conventional brake caliper is modeled. The final model of the caliper is then to be analyzed structurally to check whether it could bear the loads and stresses exerted while the braking operation. Some of the views of the model are given below.

5. *Structural Analysis of the brake caliper*

The analysis of a component is a very crucial step to perform as it will predict the performance of the component. In today's world, these simulations on the components are carried on by using a method known as Finite Element Method. The Finite Element Method is a numerical method for solving the problems of Engineering and Mathematical Physics. Typical area of interests includes structural analysis, heat transfer, fluid flow, mass transfer etc. The analytical solution of these problems generally requires the solution to boundary value problems for partial differential equations. The finite element method formulation of the problem results in a system of algebraic equations. The method approximates the unknown function over the domain. To solve the problem, it subdivides a large system into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function. Studying or analyzing a phenomenon with FEM is often referred to as finite element analysis (FEA). The FEM analysis of the brake caliper body and brake piston is carried out on ANSYS Workbench 19.2 Academic.

The FEM analysis is performed in various steps. These steps are in ordered manner and the later step cannot be done before the former step. The analysis is started by the study of the 3D model of the component, followed by deciding the material of the component and specifying various relevant properties of the material which are needed for the analysis. The process is then followed by subdividing the component into smaller and simpler units in a matrix called 'meshing', then specifying the points or surfaces of all the supports, displacements, forces, pressures, moments etc. on the meshed component geometry, these steps till here are called 'preprocessing' of the component. Using these data, the software automatically generated second or third order differential equation totally dependent on the structures and boundary conditions and solve these equations. The information from the solution of these equations are then determined and represented graphical or in tabulated format as per the user's requirement of the information such as deformation, equivalent stress/strain, factor of safety etc. On the basis of these results, the weak portion of the components are reinforced and the over-designed portions are optimized. We follow the similar steps to perform the structural analysis on the brake caliper body and the brake piston. It was necessary to find out the effect of the forces and pressure on the designed components. The detailed analysis of the caliper body and piston are below.

A. Material Selection

Material selection of the caliper body and the brake piston is one of the main factors which would affect the durability and strength as well as the weight of the caliper. It was decided from beginning to use Aluminium alloy for the caliper body because of its light weight as compared to Cast Iron alloy. Various grades of aluminium alloys are examined for the caliper body. The final selection was to be done between Al 6061 (T6), Al 6063 (T6) and Al 7075 (T6). These three alloys are already having more strength and third the weight of OEM grey cast iron grade EN-JL 1060. Al 7075 (T6) is selected when all properties are compared from other two. The relevant properties are tabulated below. Similarly, SAE AISI-1026 Carbon steel was chosen among two selected carbon steels for the brake piston.

	Al 6061 T6	**Al 6063 T6**	**Al 7075 T6**
Density (kg/m^3)	2700	2700	3100
Poisson's Ratio	0.33	0.33	0.32
Young's Mod (GPa)	69	68	70
Yield Tensile Strength(MPa)	370	270	480
Ult Tensile Strength(MPa)	410	300	525

Table 1. Properties of the Aluminium alloys selected

	AISI 1018	**AISI 1026**
Density (kg/m^3)	7900	7900
Poisson's Ratio	0.29	0.29
Young's Mod (GPa)	190	190
Yield Tensile Strength(MPa)	400	470
Ult Tensile Strength(MPa)	480	550

Table 2. Properties of the Carbon steels selected

B. Meshing of the brake caliper

Meshing process of the brake caliper body and the piston is done by the workbench software by itself. There are four types of meshing element – bricks, prism, tets and pyramid. Brick and Prism mesh element are used in the caliper body because they are used when the direction and quantity of parameters are known to the user and it can be pre-defined. The size of the mesh element is of $1x10^{-4}$m and total of 28722 nodes are made by the software on the body. For the brake piston the size of the mesh element is same and the total of 10117 nodes are made by the software.

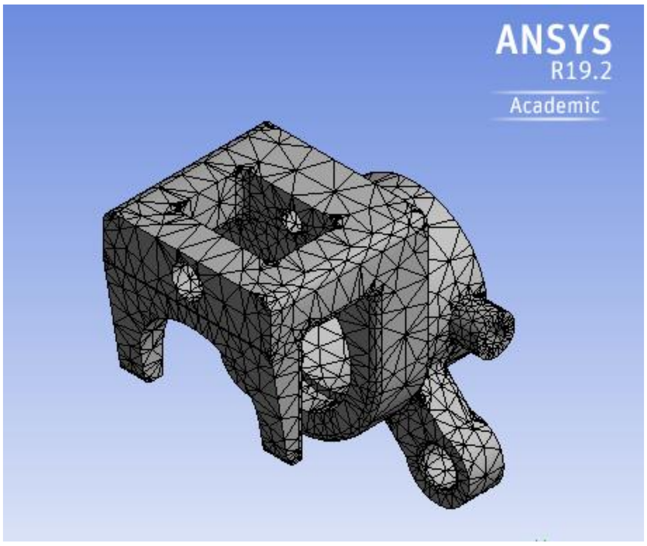

Fig. 4. Meshing of the caliper body

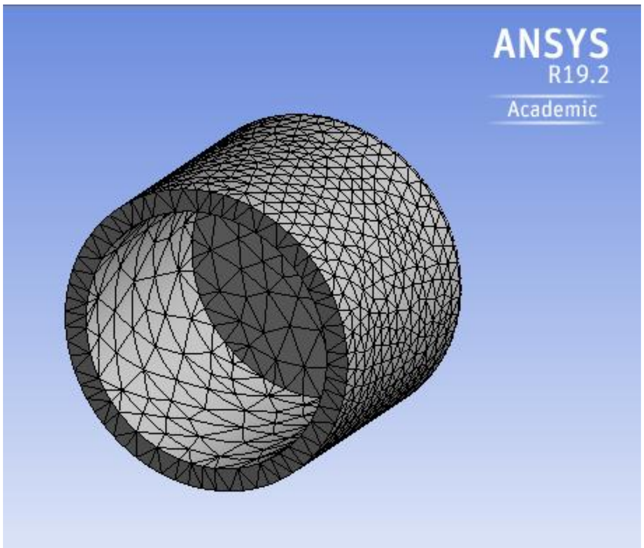

Fig. 5. Meshing of the brake piston

C. *Result of the Structural Analysis*

After the meshing of the caliper and the piston, boundary conditions are set on the appropriate surfaces and the parameters are applied on them. The primary concentration is given to the total deformation and the Factor of Safety of the caliper and the piston body. The weak areas of the body are then verified and reinforced. This took around a couple of iterations on the caliper body and the brake piston. The caliper body and the brake piston are finalized which should work in the rigorous conditions for which it is made. The deformation and safe contours are shown by the software. The maximum deformation shown by the body came up to be 5.02 x 10^{-3} m with the Factor of Safety of 2.62. As far as the brake piston is considered, the maximum deformation came up to be 1.01 x 10^{-5} m with the Factor of Safety of 8.855.

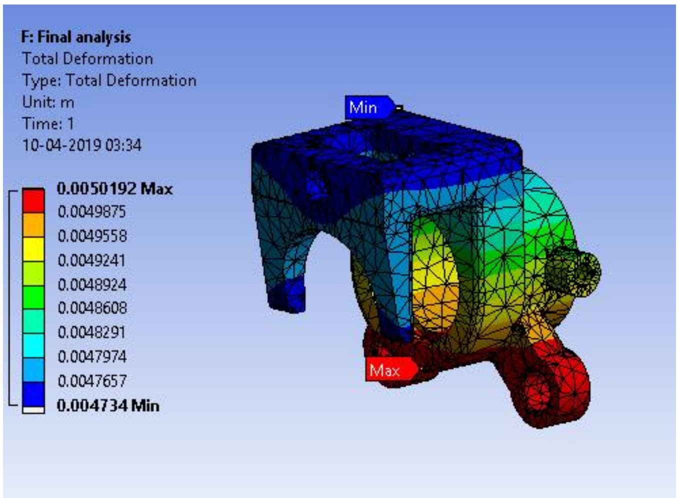

Fig. 6. Deformation contours of caliper body

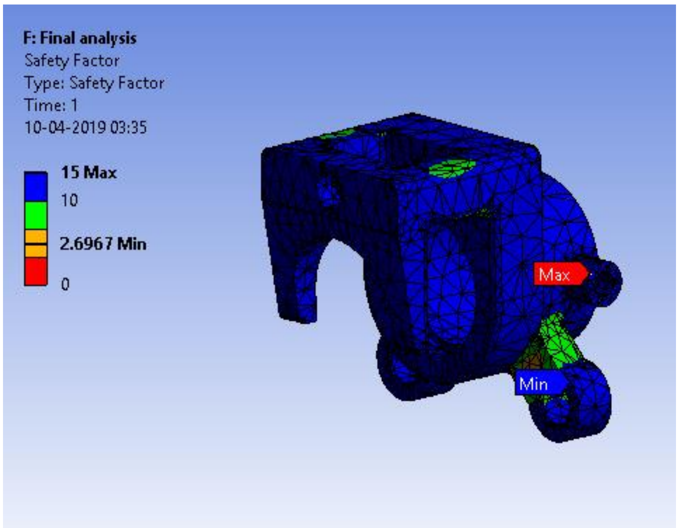

Fig. 7. Factor of Safety contours of caliper body

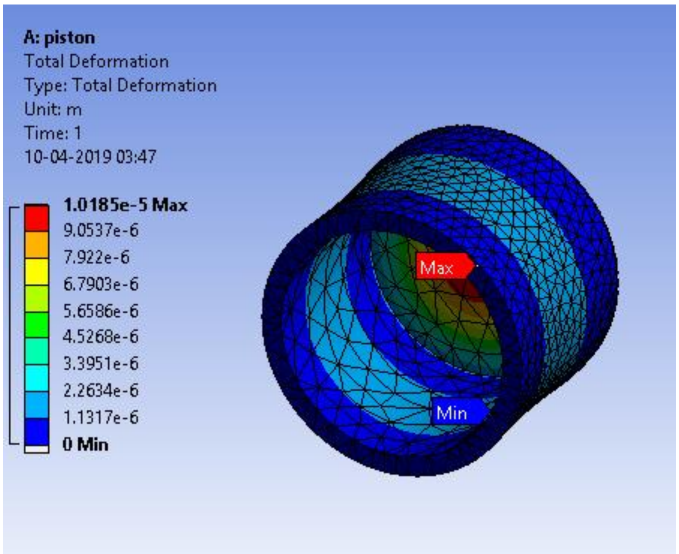

Fig. 8. Deformation contours of Brake Piston

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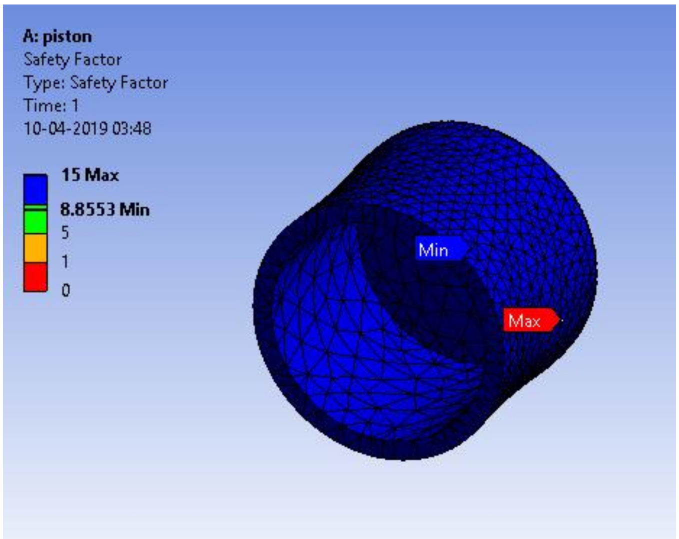

Fig. 9. Factor of Safety contours of Brake Piston

6. Seal Groove of the Brake Caliper

Seal groove in the inner lining of the brake caliper is used to fit a rubber seal in order to prevent the brake oil from leaking while application of the brakes. While deciding the material for seals inside the caliper bore, various factors are considered. Its compatibility with brake fluid, temperature operating range, fluid pressure range, hardness, working conditions (static or dynamic), tensile strength, compressibility and failure modes. Various materials available for seals are Thermoplastic elastomers, Rubber, Rigid thermoplastics, etc. Rubber seals such as nitrile rubber (NBR) and hydrogenated nitrile rubber (HNBR) are proposed to be used as the material for seals and can operate up to 150 bars.

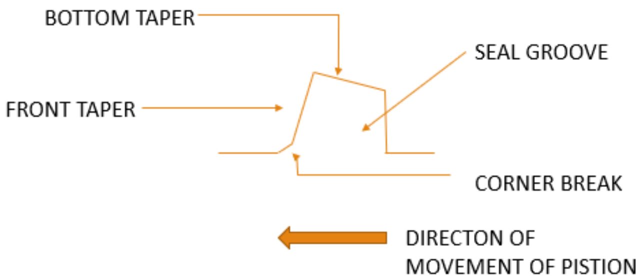

Fig. 10. Seal Groove Geometry mechanics

It is necessary to understand the seal groove mechanics before counterboring the brake caliper cylinder wall. With the actuation of brakes, piston moves out, which needs to be retracted from the brake rotor surface after releasing the brake pedal so that there will not be any piston drag. Also, the brake fluid must not leak. The seal performs both the functions of piston retraction and leakage prevention. With release of the pedal, it pulls piston back, releasing the energy. It indicates that the amount of retraction depends upon the deformation of seal, and should be considered while selecting the seal groove. Piston drag and piston displacement are directly dependent on the piston retraction. If the piston retraction is small, piston drag is induced. Greater the piston drag, greater is the energy loss and fuel consumption. Considering the factors of the deformation of the seal, the groove geometry must be selected. In this case, an O-ring seal is selected from SKF. O-rings maintain sealing contact force by radial or axial deformation in the seal housing between two machine components. The most important criteria that influence the maximum operating pressure at which O-rings in static radial sealing can be used are the following: (1) extrusion gap (2) material (3) sealed fluid (4) temperature. Therefore, the O-ring seal used here is **OR 34.2 x 3.0 - N70.**

7. Final Rendering of the Brake Caliper

The final caliper body, the brake piston, O-ring seal, inlet and outlet nipples, all the pins - floating and pad pins and brake pads are assembled with each other. The finalized caliper is designed by keeping in mind that there will be no requirement of mounting plate for it on the upright of the wheel. The rendered image of the assembly is shown below.

Fig. 11. Rendered image of the Brake Caliper Assembly (1) Caliper body, (2) Retraction Seal, (3) Brake piston, (4) Brake Pads, (5) Pad Pins, (6) Floating pins

III. CONCLUSION

This paper studies in detail, the design and analysis of the brake caliper. The brake caliper is analyzed and optimized up to the limit such that the weight of the caliper is reduced up to 274 grams which is 65% as compared to OEM brake caliper. But the weight factor doesn't affect the strength, durability and stiffness of the caliper body. Appropriate material has been used to enhance the strength, stiffness and durability of the caliper. Also, other important factors have been considered such as complex mounting. There will be no requirement of the mounting plate to mount the caliper. Mounting points on the uprights are sufficient for it. The caliper is corrosion resistant, therefore, there will be no rust formation on the caliper which increases is life and service period.

Piston drag and retraction is studied and it is found that the use of two seals is not required. The tasks of both the seals can be done by only one seal. Furthermore, other components are modified to reduce the weight, increase the strength and reduce the manufacturing and procurement cost.

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