Design of Brake Disc for Hydraulic Brakes.

Vivek Singh Negi[1], Amit Deshpande[2], Nayan Deshmukh[3]

[1,2,3] Department of Mechanical Engineering, Sinhgad Academy of Engineering, Kondhawa

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Abstract: *The most important safety feature of any vehicle is the braking system. Fundamental requirement of any braking system is to decelerate a vehicle precisely in variable condition. The kinetic energy possessed by a retarding vehicle, which is proportional to its mass and square of its speed, needs to be safely dissipated in form of heat. Driver applies force on brake pedal and by a series of force manipulations, a clamping force is applied on rotor and wheels are stopped. The paper is concerned with design of brake rotor. After a vehicle's tyre, its brake disc is perhaps most abused component. The disc has to sustain great friction and heat combined with clamping force exerted by brake calliper. Therefore, careful consideration of material for brake disc and its design plays key role in design of braking system of vehicle. The paper presents methodology of design, various considerations made during design and the logic behind them. The validation of design is done via calculations as well as finite element analysis of model of brake disc. The FEA serves purpose of analysis as well as that of optimisation in terms of weight reduction.*

Keywords: **Braking system, disc-type rotor, waterjet machining, heat treatment, FEA, ANSYS**.

1. INTRODUCTION

Braking system is at heart of every vehicle's control and safety. Apart from serving as a mechanism of retarding the vehicle, brakes are essential in navigating vehicle as per driver's intention. This is achieved by a series of force transmitting members, which convert, amplify and apply the force, offset to wheels' centreline, generating torsional moment in opposite direction to that of motion.[1] This mechanism is assembly of multiple components, and each component is carefully specified to achieve optimum braking in all foreseeable conditions. Brakes are broadly classified as follows: firstly according to source of application of force as – mechanical brakes, hydraulic brakes and pneumatic brakes and secondly according to geometry as drum-type brakes and disc-type brakes.

Some of the advantages of hydraulic brakes are that they have quick response, greater force generation capacity, compact size, reduced weight, non-dependency on power unit and greater feedback [2]. The necessity of replacing mechanical brakes, which are even more compact, arose from the fact that as vehicles became faster and faster, the force required generating required braking effort, increased significantly. Thus, automotive industry developed a more elegant solution to above problem in form of hydraulic brakes. The principle of operation remains same as that of every other type- conversion of kinetic energy of vehicle into heat energy by virtue of frictional resistance.

The hydraulic brakes can be implemented in both ways- drum and disc. The latter of the two being more favourable due to its benefits, which are explained throughout the paper. The drum brake is still one of preferred designs for automobile engineers, especially at the rear of passenger cars and heavy vehicles due to its advantages. Still, the drum brakes are complex assemblies compared to disc brakes and allow little area of modification for high performance.

The racing car, be it formula or off-road buggies, requires high performance brake assembly.[3] This need is justified by the fact that these vehicles need to perform extreme conditions and hence, the components need to be durable and robust. Therefore, the system is designed to withstand higher demand of performance and conforming to safety standards set by safety governing body. As a result, the system use higher-grade materials than normal cars and quality conformance is even greater than normally required.

Custom rotors are introduced in system to reduce weight and achieve required output, compromising between performance and economical value of system. They provide benefit of sizing as per designer's specifications against OEM rotors, which limit designer's scope in terms of size of disc. The design of brake rotor is concerned with developing a disc, capable of withstanding braking torque, high clamping force, high wear and extreme temperature.

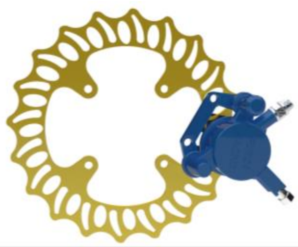

Fig-1: Brake assembly with disc-type rotor.

Disc-type rotors are extremely efficient in terms of heat dissipation. The friction generates tremendous heat, which raises temperature of disc itself along with calliper pads. The rise in temperature is undesirable since it induces creep in disc material. Another adverse effect of the temperature is heating of brake oil, which is important to prevent. A disc has greater contact area with surrounding medium. It is also provided with vanes or holes for increasing turbulence along the surrounding medium.[4] This increase in turbulence causes rising in heat transfer coefficient, which in turn helps in cooling the disc faster. In this way, disc-type rotor has advantage of better thermal dissipation over drum-type setup.

2. CONSIDERATIONS IN DESIGN OF BRAKE DISC

Design of brake disc is heavily influenced by space available for mounting. The type of wheel selected defines the space limitation for brake disc. In BAJA vehicle it is essential that the wheel should sustain over high bumps and pitfalls. The DWT rims with 10" diameter were selected as wheels because of their low weight and good design. The wheel selection affects the procedure in terms of space availability and mean wheel radius, which translates torque applied on disc to the braking torque at ground. The rotor has to fit properly in packaging space available. For current BAJA vehicle, maximum allowed size for disc was 7" diameter, after considering size of calliper and clearance space.

The diameter of brake disc is decided by considering maximum amount of braking torque that would be applied on disc. The area of application of clamping force by calliper and thereby frictional force generated on disc is the major factor in design. The disc is designed considering above two factors. The diameter is finalised after multiple iterations, which was 175 mm for both front and rear.

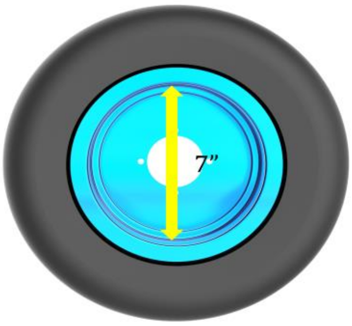

Fig-2: Space available in rim

The thickness of brake disc is limited by a certain fixed distance between calliper pads. Another parameter taken into consideration is the matter of sustainability of disc under high temperature. Therefore, thorough thermal analysis of disc is done to test its ability to sustain high heat. The thickness, therefore becomes function of thermal diffusivity of material, heat transfer coefficient, thermal stability. This is validated using Finite Element Analysis of disc, since mathematical computations of such complex scenario is difficult. The FEA also provides simple yet effective method of optimisation of thickness of disc. The final value of thickness is 4mm for front disc and 3.5 mm for rear disc.

3. SELECTION OF MATERIAL FOR BRAKE DISC

The rotor has to withstand high heat, generated due to friction, simultaneously with high clamping forces. Therefore, the material of rotor should have high toughness and thermal stability. Brake rotor is one of the parts, subjected to high wear. Hence, the material should be highly resistance to wear and thereby to corrosion that occurs due to pitting.

Effect of higher temperature on disc material is explained by phenomenon of creep. The thermal stability becomes important characteristic wile selecting the material, which will reduce unnatural behaviour of metal at higher temperature.[5] The material should also dissipate the heat quickly. This will prevent overheating other braking components. Temperature is of vital importance in performance of braking; too low temperature is also undesirable for high performance race cars. In such vehicles, high strength aluminium alloys and Carbon-Carbon matrix is used for making brake disc.[6] The carbon-carbon matrix is excellent in withstanding wear, loads at extremely high temperatures, and has very low weight. However, it is very expensive.

The wear and corrosion resistance of selected material should be sufficiently high, though it can be enhanced by subjecting it to heat treatment. Material with excellent wear resistance will prevent scratching of disc under extreme forces from pads and will prevent pitting corrosion that occurs due to such surface deformities. The formation of abrasives is inevitable since brake pads are made from granular material, which wears out in form of small particles. The disc brakes have another advantage in this account over the drum brakes for easier removal of such particles.

The materials finalised for selection were Stainless steels of grades 321 Or 420 Or 410. Finally, SS 410 was selected. It is highly resilient to wear and corrosion and is ready to be heat treated and easily available in market. The grade 410 has added advantage of being magnetic. Even though magnetism has no direct influence on operation, it is helpful in manufacturing process. The magnetic disc is easy to clamp on magnetic chuck and does not require any additional clamping method. Grinding equipment are often provided with electromagnetic chuck and hence surface finishing becomes easier by use of 410 grade.[6].

4. MANUFACTURING AND POST PROCESSING OF BRAKE DISC:

The brake disc is manufactured from a plate of 4.2mm thickness of stainless steel 410. The cutting operation is carried out by using waterjet machining process. It is debatable; whether to use lasercut machining or waterjet machining, since lasercut machining is less costly and faster than waterjet. However, the lasercut machining process uses high temperature laser for cutting the metal and hence residual thermal stresses are induced in the component. These stresses affect in the long run as they are responsible for premature fatigue failure. Therefor, it is wise to use waterjet machining for cutting the required shape.

The scrap generated is used as test specimen for conducting Vickers's hardness test. The test is carried out to inspect hardness of disc material, which is compared with OEM brake rotor. The hardness was found to be nearly half that of OEM rotor and hence needed to be heat treated for increasing the same.

The brake disc is subjected to heat treatment as follows: Material is heated up to temperature of 975°C. It is held there for a period of about 14 minutes for 4mm thickness. Then, it is oil quenched to room temperature. The disc is reheated for tempering up to 250°C. It is held there for a period of two hours and then air cooled to room temperature.

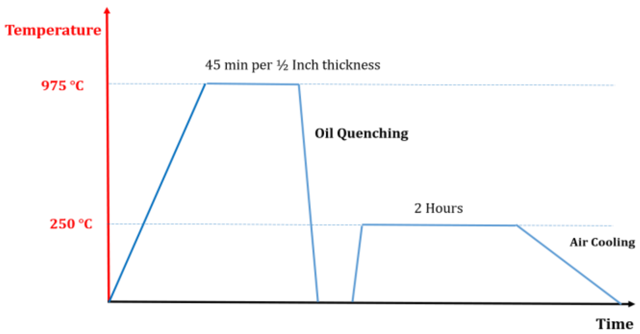

Fig-3: Heat treatment cycle for Brake disc.

The brake rotors are surface finished to have a certain surface roughness. This roughness is important, as too high value will cause excessive wear and noise, whereas too low value will make brake disc ineffective and cause slipping under calliper pads. Therefore, grinding operation is carried out to set the R_a Value. The value of surface roughness is kept within range of 30-60 micro-inches Ra or 100 micrometre R_a. This value is also implemented in most commercial vehicles.

Fig-4: Measurement of surface roughness

5. PREREQUISITE DATA FOR CALCULATIONS:

Following data is essential for carrying out the calculations of stopping distance and disc dimensions:

Table-1: Prerequisite Data for Calculations

Sr. No.	Parameter		Value
1	Gross weight of vehicle		236 kg
2	Wheelbase		56"
3	C.G. height		17.14"
4	Weight distribution Ratio		45:55
5	Static Weight Distribution	Front	105.75 kg
		Rear	129.25 kg

It is also necessary to clarify following terms, which are often used in design of brakes:

- Dynamic Weight transfer:

When a vehicle travelling with certain speed is suddenly stopped, the front suspension goes into jounce whereas rear spring experiences re-bound. The reason behind this is that a portion of rear axle's weight gets transferred to front axle and sums up to gross front axle weight. This is known as dynamic weight transfer. Following expression gives value of dynamic weight transfer:

$$Wt = \frac{h * m * g}{b}$$

Here,

W_t – Dynamic weight transfer

h- Height of CG from ground

m- Mass of vehicle in kg

b- Wheelbase

The dynamic weight transfer of current vehicle is 36.211 kg.

- Clamping force on rotor:

The clamping force is the force exerted by brake calliper on disc. The frictional force is developed because of this clamping force, which is normal to disc surface. The force is given by following expression:

$$F_c = F_d * M.L * H.L * 2$$

Here,

F_c- Total clamping force

F_d- Force applied by driver

M.L- Mechanical leverage

H.L.- Hydraulic leverage

- Stopping distance:

Stopping distance is measured from point, where driver applies brakes, to the point where vehicle comes to full stop.

- Stopping time:

It is the time span required for vehicle to come to full stop after brakes are applied

- Braking torque requirement:

The required braking torque is dependent on dynamic weight transfer and wheel dimensions. It is used in calculating diameter of brake disc. Following expression gives required braking torque:

$$Tb = \frac{Wt}{2} * \frac{Dw}{2} * g$$

Here,

T_b- Braking torque

W_t- Dynamic axle weight

D_w- Diameter of tyre

g- Gravitational acceleration

Required brake torques for current vehicle are:

Table-2: Required Braking Torque

Front	127.89036 Nm
Rear	83.8177 Nm

6. CALCULATION OF STOPPING DISTANCE

The stopping distance of vehicle is calculated as follows:

6.1 Simplified Calculations:

$$S_{total} = (V_{tr} * t_r) + \left(\frac{V_{tr} * t_s}{2}\right)$$

Also,

$$\frac{V_{tr}}{a} = t_s$$

So,

$$S_{total} = (V_{tr} * t_r) + \left(\frac{V_{tr}^2}{2a}\right)$$

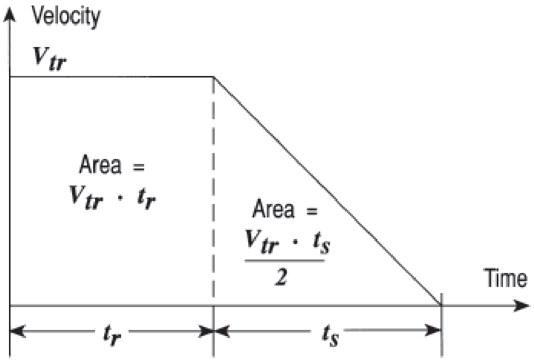

Fig-5: Simplified stopping distance and time period.

Here,
V_{tr}- Initial vehicle velocity

t_r- Driver reaction time

t_a- brake system application time

t_s- braking time

a- deceleration

Now,
V_{tr}= 40 km/hr

t_r= 1 Sec.

t_a= 0.25 Sec.

t_b= 0.3 Sec.

a=μ*g
= 0.7*9.81

Therefore,

$$S_{total} = (11.11) + \left(\frac{11.11^2}{2 * 6.867}\right)$$

S_{total}= 20.097 m

6.2 Detailed Calculations:

Total stopping distance is given by:

$$S_{total} = V_{tr}\left(t_r + t_a + \frac{t_b}{2}\right) + \frac{V_1^{\ 2}}{2 * a_{max}} - \frac{a_{max} * t_b^{\ 2}}{24}$$

$$S_{total} = 11.11 * \left(1 + 0.25 + \frac{0.3}{2}\right) + \frac{11.11^2}{2 * 6.867} - \frac{6.867 * 0.3^2}{24}$$

$$S_{total} = 15.554 + 8.9873 - 0.02575$$

S_{total}= 24.5155 m

$$Total\ Time = t_r + t_a + \frac{t_b}{2} + \frac{V_{tr}}{2 * a_{max}}$$

Total Time= 2.2089 Sec.

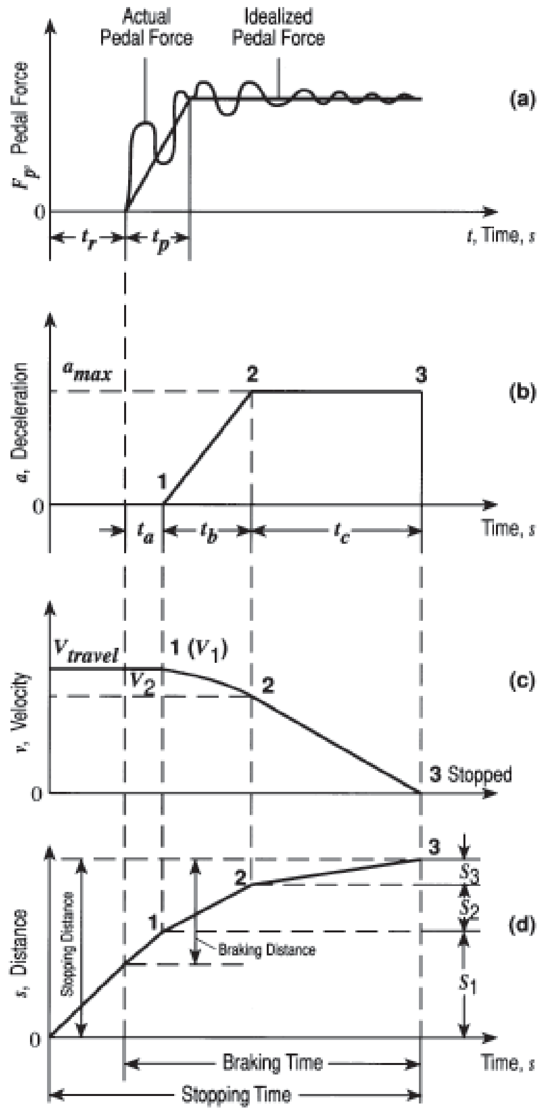

Fig-6: Detailed stopping distance and time period

7. FINITE ELEMENT ANALYSIS OF BRAKE DISC.

Since multiple parameters are associated with design of brake disc, it is difficult to obtain mathematical expression for such process. Therefore, FEA serves as validation as well as optimisation method for disc design. The structural and thermal analysis is performed on CAD model of disc. CAD model is generated using CREO© Parametric 2.0. The FEA is performed on ANSYS© 14.5.

7.1 Static Structural Analysis:

The structural analysis of rotor is performed to validate its strength under stresses. It is expected that rotor is strong component and should not deform under clamping loading. Any deformation may lead to failure of disc and thereby braking system. For structural analysis, the surface of calliper pads is imprinted on both sides of disc. Forces are applied on these areas.

This force is applied on both sides and magnitude of this force is given by following expression:

$$F_x = \frac{Total\ clamping\ force}{2}$$

Another force that act on rotor is the frictional force. This force is created due to combined effect of clamping force and coefficient of friction between pad and brake disc. Following expression gives the value of frictional force:

$$F_r = \mu * F_x$$

The results of static structural analysis are given below:

- Front Disc:

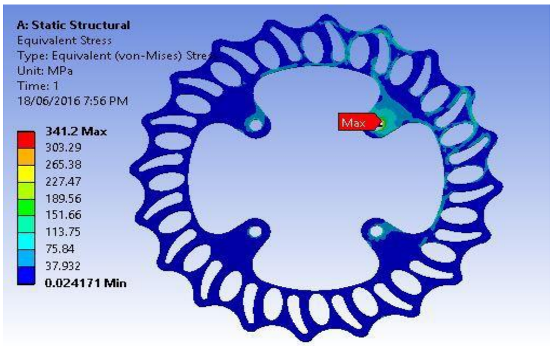

Fig-7: Von-mises stresses in front disc.

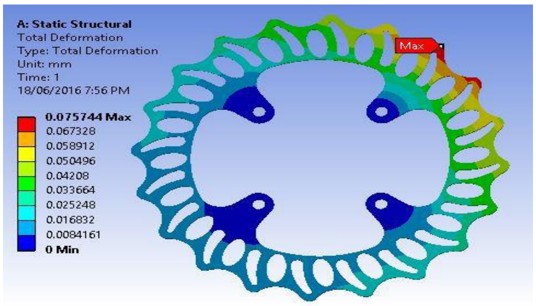

Fig-8: Deformation in front disc

- Rear Disc:

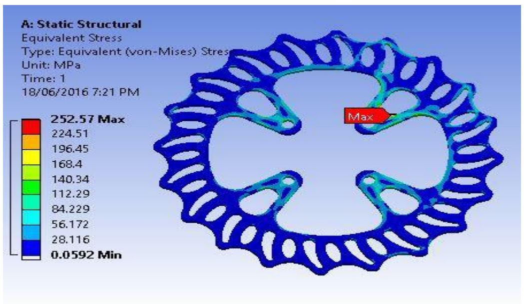

Fig-9: Von-mises stresses in rear disc

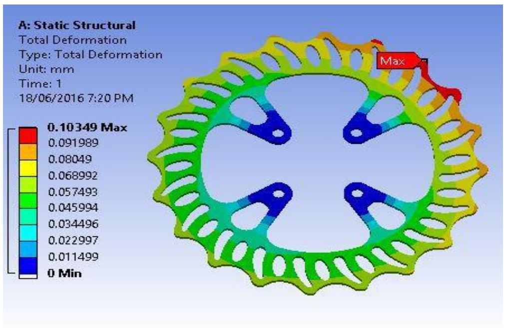

Fig-10: Deformation in rear disc

Table-3: Results of Static Structural Analysis

Von-mises Stress	Front Disc	341.2 N/mm²
	Rear Disc	252.57 N/mm²
Deformation	Front Disc	0.07574 mm
	Rear Disc	0.10349 mm

7.2 Thermal Analysis:

For thermal analysis of brake disc, an annular surface, whose radial width is equal to width of calliper pad is imprinted on disc. The heat flux is transferred through this surface. Results of thermal analysis are given below:

- Front Disc:

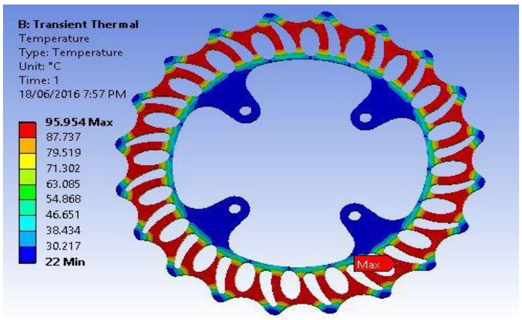

Fig-11: Transient temperature of front disc.

- Rear Disc:

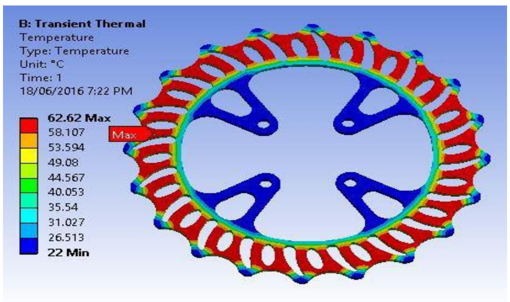

Fig-12: Transient temperature of rear disc.

Table-4: Result of Thermal Analysis

Front Disc Temperature	95.954 °C
Rear Disc Temperature	62.625 °C

8. RESULTS:

The results obtained from design and specifications are given below:

- Front Disc diameter = 175 mm
- Rear Disc diameter = 175 mm
- Front disc thickness = 4 mm
- Rear disc thickness = 3.5 mm
- Calculated stopping distance = 24.5155 m
- Calculated stopping time = 2.20 seconds.

It can be inferred that design of brake disc is heavily dependent on choice of wheel, dynamic weight transfer, choice of brake callipers and master cylinder. The objective of design of tough and durable brake rotor is achieved.

9. CONCLUISION:

The brake disc, after implementation in BAJA vehicle, satisfies the design requirements. It proves to be durable on rough terrain and critical operating conditions. Thus, we can conclude that initial objective of designing brake rotor for braking system of BAJA vehicle is satisfied and serves as ground for further research on said system.

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