Design and Analysis of Brake System of a Single Seat Race Car

Rohit Kawade[1], Gaurav Pardeshi[2], Sagar Jadhav[3], Amar Jadhav[4]

[1, 2,3]BE Students, Department of Automobile Engineering, Pillai HOC College of Engineering & Technology, Rasayni, Maharashtra ,India
[4] Professor, Department of Automobile Engineering, Pillai HOC College of Engineering & Technology, Rasayni, Maharashtra ,India

---***---

Abstract:- *This paper presents the design and analysis of braking system for the FSAE race car. The basic aim of this work is to achieve the required standards for brake design and to scale through the dynamic test at the competition. This work serves as a study for developing a desired braking system for high-performance race cars. Fundamentals of vehicle statics, dynamics and previous research works are considered for designing and analyzing components of braking system. For design and analysis use of Dassault solid works 2019 and Ansys 2019R-2 is done. The considerations for designing brake system are material, ergonomics, maximum braking force, safe stopping distance lightweight, manageable temperature and reliability. The proper ratio of brake force of front to rear axle is calculated for locking all the four wheels reducing stopping distance and comply with FSAE rules. Structural and thermal stresses developed are obtained from static structural and steady state thermal analysis. The boundary conditions used for the analysis are braking torque, heat flux and convection coefficient.*

Introduction

Weber Ferreira Veloso et al. mentioned that in 2014 the Formula UFMG team chose to use the material 1020 Steel in their brake disks. After the competition it was found that there were radial cracks developed in the disc due to thermal stress non-destructive testing using liquid penetrants and magnetic particle. A comparative analysis between them and low carbon steels to choose what material would be the best for application in a Formula SAE vehicle. He stated that the maximum speed considered for braking simulation was 80 kmph. Weber Ferreira Veloso stated that the thermal cracks are fractures derived from a temperature gradient in the brake disk surface, these results in internal tension and compression which causes cracks. Weber Veloso found that, for the analysis, one could disregard the effect of radiation and conduction to the pads, leaving only the convection. Therefore for simulation, finding the accurate convection coefficient was very important, which would be possible by empirical method which would consist of a very large and expensive apparatus. Therefore, they went with the theoretical method, which was applied in conventional cars, requiring some consideration and subsequent validations.

An equation that determines the coefficient of convection was used from the known data:-

$$Air\ speed = Air\ speed\ factor \times V$$
$$Re = \frac{air\ speed \times r}{v}$$
$$Nu = 0.037 \times Re$$
$$h = \frac{Nu \times Kaiir}{r}$$

After inserting the values in the above equation, the coefficient of convection (h) as

$h = 6.655 \times Car\ speed$. [1]

Campbell Duncan Carter et al. are presenting us a design guide for vehicle, which includes considerations like vehicle dynamics and vehicle performance. The authors were qualitatively and quantitatively discussed the various aspects of vehicle design, including presentation of the relevant theory, governing equations, and design options of interest for a small race car such as a Formula SAE vehicle. According to author, the design of the brake unit involves the selection of a system and determination of the relevant geometric dimensions. Author says that while designing of the brake system, the selection was between an outboard twin caliper/disc system and an inboard single caliper/disc system. The Outboard arrangement can deliver more torque and stay cooler; however, the inboard arrangement is less expensive and does not add to unsprung weight. So the author was selected the inboard system to reduce the expenses. Author has provided us two different equations to find out braking torque, which are as follows: The torque per wheel required to stop the vehicle can be estimated by the equation:

T = W rt c (a/g)/n

Where,

rt = Tire radius

n = No. of brakes wheels

a/g = Deceleration rate in G's

It was noted that this equation assumes a constant deceleration rate. An estimated deceleration rate necessary for compliance with the Formula SAE rules can be calculated by assuming that the car decelerates at a constant rate from 20 MPH to 0 MPH in 25 feet.

The braking torque per wheel is given by:

T = Fp LNrb Cb A1/A2

Where,

F = Applied force to the brake pedal (100-125 lb)

L = Brake pedal linkage ratio

N = No. of wheel cylinder

r = Effective brae rotor disc

A1 = Caliper piston area

A2 = Master cylinder piston area

After the research author came to conclusion that, initial brake system design should include a significant safety factor since the vehicle weight is generally not precisely known at this time. [2]

According to M. S. Barakat, in order to satisfy the basic design of the braking system components the Newton law and the Pascal laws were used. A simple linear, lumped parameter model was created for initial system analysis. Author also taken into consideration this is a balance bar proportioning brake system in which the applied force is divided according to the balance bar ratio between front and rear, which will require more human efforts in case of front circuit failure to apply the rear brake and overcome at the same time the effect of the proportioning ratio. [3]

G. S. Mohd Usama mentioned that, Fundamentals of vehicle statics and dynamics and previous research works were kept in the core of designing and analysis of various components of braking system. They used SOLIDWORKS and ANSYS for analysis of brake disc, considering structural and thermal stresses. They made a 3D model of the disc in SOLIDWORKS. They kept all the discs as identical and as front wheels would be subjected for maximum braking force due to weight transfer, the analysis was done for only one disc. Further the author mentioned that, during braking process the disc has to save about 80-90% of kinetic energy of vehicle as heat, only 10% to 20% thermal energy dissipated as convection and radiation into the into the environment. After the analysis it was observed that maximum intensity of stress and strain is located at the under-cut area of brake disc and hence maximum deformation in that area. And the factor of safety was found highly reliable according to the design. The maximum temperature that can be developed in the disc was found to be 621.14o Celsius which is much lower than the melting point of the material (grey cast iron). Further they concluded that a rationalized method was developed to design or select any component, specially the dimensions of brake disc. [4]

According to Ardashir Bulsara et al. the angle θ needed to be larger so that its cosine value can be smaller, which will in return provide a larger advantage to multiply the applied force on the brake pedal without further increasing pedal height. The master cylinder angle was chosen as 70 degrees from the Authors told that, the SAE vehicle which is developed and manufacture by student engineers should be designed to be light, safe, fast and very agile as the tracks are designed to run on have a very high frequency and range of corners, so slowing down quicker is as important as accelerating faster. For that purpose student engineers have to design and fabricate a brake system comprising of an adjustable pedal box and deceleration up to 1.65G which should be able to lock all 4 wheels at the same time, hence using maximum available traction, in a straight line and validate the calculations using two brake pressure sensors.

Pedal Box Design:-

For the pedal to be in equilibrium,

$F1 = F2 \times \cos(\theta)$

Thus,

$F2 = F1/\cos(\theta)$

Horizontal after iterative 1D simulations to achieve a high enough force multiple at the master cylinders.

According to Ardashir Bulsara, after selection of the MCs, we designed all three pedals to have the same height and withstand appropriate forces which are applied to them in race conditions. Another aspect taken into consideration was the cost element of manufacturing, hence we selected water jet cutting and designed the pedals accordingly using AL 6061-T6 as the material.

Rotor design:-

In most rotor designs there are cuts or holes in the surface where the rotor comes in contact with the brake pad. The main intention of these cuts is to reduce brake fade during braking. Having cuts or holes in the rotor creates a vent or fan like effect, which flushes out this gas layer that forms. Two side effects of having these cuts in the rotor are reduced mass and an increase in the cooling. The thickness of the rotor is 4mm since it is the least value matching the caliper specifications while also satisfying heat absorption requirements. According to author, a lightweight assembly was designed, fabricated and tested to prove its performance and reliability. [5]

Promit Choudhury describes the Stress distribution of the SRM university FSAE vehicle. The main objective is to investigate and analyze the thermal and structural stress distribution of brake rotor at the real time condition during braking process and then comparing it with a modified rotor having ceramic coating. Hardened 420 stainless steel is chosen for its high strength to weight ratio and tensile strength, its availability in the local market also plays a prominent role. The zirconia-based ceramic coatings are used as thermal barrier coatings owing to their low conductivity and their relatively high coefficients of thermal expansion, which reduce the detrimental interfacial stresses.

An initial CAD model of rotor is modelled with a rotor thickness of 7 mm and rotor diameter of 240 mm. taking an initial design as reference, a modified geometry with different layers of ceramic coating has been modelled. The new model has 5 layers where the first layer is of 350 μm and the second layer is of 150 μm and the third layer is of 6 mm and again the similar coating layers of similar thickness is followed on the other side of the third layer. CAD model of rotor converted into Parasolid file. This model is imported into Ansys Workbench simulation. Geometry clean-up was performed prior to meshing of model. Finite element model was developed using Ansys Workbench Simulation. [6]

Serial Number	Material	Thermal Conductivity (W/m oC)	Thermal Expansion 10-6 (1/ oC)	Density (Kg/m3)	Specific Heat (J/kg oC)	Poisson's Ratio	Young's Modulus (Gpa)
1.	SS 420	18	6.8	7800	460	0.3	200
2.	NiCrAl	16.1	12	7870	764	0.27	90
3.	MgZrO3	0,8	10	5600	650	0.2	46

Table1. MATERIAL SPECIFICATION

Serial Number	Material	Deformation (mm)	Von Mises Stress (MPa)	Equivalent Strain	Weight (grams)
1.	SS420 Rotor (Initial Design)	0.0112	90.173	0.0004517	1.246
2.	SS420 Rotor coated with ceramic (NiCrAl-MgZrO3, Optimized Design)	0.0029	23.256	0.0001164	1.1202

Table2. POST PROCESSING ANALYSIS RESULT

Edward Lumsdaine, et al. mentioned that a two-dimensional transient heat transfer model is used to simulate the axial and radial temperature field of a disk brake rotor. The simulation results are then used as input into the Taguchi method to identify the most dominant design parameters in order to optimize the design. The disc in the disc brake system experiences severe thermal and mechanical stresses, extreme temperature gradients and stress concentration can lead to rotor deformation. Further he mentioned that the conventional methods were very time consuming and complicated and thus the objective of the study was to interface the Taguchi method with an analytic model of the disk brake system to identify the most dominant design parameters of the brake system that cause rotor failure, in order to obtain significantly reduced and repeatable results.

The Taguchi method consists of seven steps:-

(1) Selection of the control factors,

(2) Selection of the noise factors,

(3) Choice of an appropriate orthogonal array to determine the analytic runs,

(4) Analytical simulation (or experimental tests),

(5) Calculation of the signal-la-noise ratio for each control factor,

(6) Calculation 01 the analysis of variance (ANOVA) table and determination of the percentage contribution for the control factors, and

(7) Summary of results.

The steps should be repeated if results are not satisfactory or new areas need to be investigated. He then stated an equation for thermal stresses (σ) in a rotor due to the temperature difference at the center and the outer surface which is given by:-

$$\sigma = -\frac{E}{1-w}\alpha\,(Ts - Ti)$$

Where,

E =elastic modulus

W =Poisson's ratio

α =thermal expansion coefficient

Ts =temperature at outer surface

Ti =temperature at the center of the rotor disk.

And equation for heat flux was given by,

Qo(L) = (μ.p.v. / 778) x 3600 Btu/h-ft2

Where,

Qo(L) = heat of friction

μ = pad/rotor friction coefficient

z = mechanical pressure computed by dividing the normal force between pad and rotor by the friction area of the rotor in lb/ft2

v = relative sliding velocity between pad and rotor in ft. /s.

The heat transfer equation together with the boundary and initial conditions were solved using finite difference. These results combines with ANSYS stress-strain relationship results were used to tentatively determine rotor design. [7]

According to A.Belhocine et al. the main purpose of the study was to analyze the thermomechanical behavior of the dry contact between the brake disc and pads during the braking phase. The simulation strategy was based upon computer code ANSYS11. The modelling of transient temperature in the disc was actually used to identify the factor of geometric design of the disc to install the ventilation system in vehicles. The thermo-structural analysis was then used with coupling to determine the deformation established and the Von mises stresses in the disc, the contact pressure distribution in pads. The results were satisfactory when compared to those found in previous studies. [8]

K. Sowjanya, et al. stated that this paper deals with the analysis of Disc Brake. 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. Disc brake is usually made of Cast iron, so it was selected for investigating the effect of strength variations on the predicted stress distributions. Aluminum Metal Matrix Composite materials were also selected and analyzed. The results were compared with existing disc rotor. The model of Disc brake was developed by using Solid modelling software Pro/E (Creo-Parametric 1.0).Further Static Analysis was done by using ANSYS Workbench. Structural Analysis is done to determine the deformation, Normal Stress, Vonmises stress. [9]

Prof A. D. Dhale et al. The disc (Rotor) brakes are exposed to large thermal stresses during routine braking and extraordinary thermal stresses during hard braking. The aim of the project was to design, model a disc. Modelling was done using catia. Structural and Thermal analysis was done on the disc brakes using three materials Stainless Steel , Cast iron & carbon-carbon composite. Structural analysis was done on the disc brake to validate the strength of the disc brake and thermal analysis is done to analyze the thermal properties. Comparison was done for deformation; stresses, temperature etc. form the three materials to check which material is best. Catia is a 3D modelling software widely used in the design process. ANSYS was done using general-purpose finite element analysis (FEA) software package. Finite Element Analysis is a numerical method of deconstructing a complex system into very small pieces (of user-designated size) called elements. [10]

According to Rutvik H Rana the main purpose of this research includes the importance of weight reduction in Formula style racecars. This was done by using the components of a motorcycle's braking system in a FSAE car's braking system as the components are compact and light in weight. Choice of components was done by keeping the FSAE rules in mind and their ability to comply with it. A tandem type of master cylinder with diagonally split type hydraulic circuits was used to ensure stability in case of failure in one of the circuits. As a tandem master cylinder was used, proportioning valves had to be used to differentiate the pressures in the front axle and rear axle brakes (brake biasing) as a result of transfer of weight to the front axle and reduction of weight in the rear axle while in braking condition. The variation in brake pressures in front and rear wheels ensures locking of all the four wheels at the same time and reducing the stopping distance. The brake bias for their car was set to 51% for front and 49% for rear.

The calculations for selection of sizes of components like diameter of pistons inside master cylinder and calipers were done considering initial velocity of the vehicle as 60 kmph and final velocity as 0 kmph. The calculations included stopping distance, braking torque, clamping forces, brake bias, validation of the motorcycle's brake disc rotor for the FSAE car and the thermal stresses built up in the same.

The thermal analysis was done in ANSYS's WORKBENCH R15.0. This was done to obtain maximum temperature rise, equivalent stress, deformation (translations and rotations) logarithmic strain and Stress components and Invariants. The input parameters like heat flux (273333.38 w/m2), film coefficient (0.832), Reynolds number (502400) and Nusset number (36378) were obtained from the thermal calculations of the rotor. They results were found to be satisfactory.

The Hub and Upright were designed according to the inner space of the rim, dimensions of the disc and mounting points of the caliper. The weight of the whole assembly was found to be just 6kg per wheel as compared to 17kg per wheel of a commercial car with hat rotors. [11]

S.A.M Da Silva, said that the main aim of the research was to determine critical zones of different designs of disc brake system which are subjected to linear forces. The different design of disc brake rotors are smooth brake rotors, grooved brake rotors, cross drilled brake rotors and cross drilled and grooved brake rotors (combination). The required parameters to determine the different critical zones on rotor are load stress concentration and displacement. Grooved disc brake rotor and drilled and grooved brake rotor were designed according to dimensions of Renault brake system. The design was circular shaped with two parallel plates of 259 mm diameter and thickness of 6mm. Two parallel plates were present at inboard and outboard sides of plates which are the friction surfaces. Veins were provided for cooling air to enter and exit from the outer edge to center of rotor to lower operating temperature of rotor. Grooves feature was there on the grooved disc brake located on the outer edge of the inboard plate. The grooves were symmetrical. The grooves present 15 mm deep and 3 mm wide. The advantage of the grooved brake design was that it allowed the buildup gases and heat to escape through grooves. The surface of drilled and grooved disc brake rotor had both gross as well as four holes drilled precisely adjacent to grooves. The diameter of each hole was 5 mm. This arrangement increases friction between brake rotor and brake pad allowing for better grip on two surfaces. Numerical and software analysis was used to determine various parameters needed to be considered before testing would be complete. It was seen that gradual increase in the stress experienced on each section as the load was increased. The grooved disc brake rotor was found to experience a greater stress concentration and displacement as compared to drilled and grooved brake rotor. The simulation allowed the critical areas to be determined to better the required design without having to apply for destructive testing on disc brake rotor. [12]

Conclusion

After going through several research papers and articles we decided to designed and manufactured lightweight braking system to implement in SAE Supra vehicle. Also tested to satisfy its design requirement in critical operating condition. To achieve maximum potential of system the driver requires 40kg pedal force, which is very less than that of the panic braking force that can be applied by average driver. Each and every components of brake system such as brake disc, caliper, master cylinder etc. are tested under extreme condition. Various factors affecting the net heat generation and dissipation from the disc brake is determined by the generation of heat by using velocity of car. Thus, found the temperature rises in disc and have found the range of working temperature in brakes. We can use this method of finding the working temperature of brakes for many purposes. So once we know the working temperature of brakes we can select the material to be used for manufacturing components such as brake disc, caliper, brake lining, etc. as to withstand mechanical and thermal both conditions. This method is also useful while selecting the brake fluid which is suitable for required temperature ranges

References

[1] M. R. M. G. S. G. F. D. P. D. F. J. Q. G. D. A. WEBER FERREIRA VELOSO, "EXPERIMENTAL AND NUMERICAL THERMAL ANALYSIS OF BRAKE DISKS OF A FORMULA SAE VEHICLE".

[2] C. B. S. R. D. M. Campbell Duncan Carter, "Design of a Formula SAE Race Car: Vehicle Dynamics and Performance," 1982.

[3] M. S. Barakat, "ASURT Formula Student Brake Design," 2014.

[4] G. S. Mohd Usama, "Design and Analysis of Braking System for FSAE," 2018.

[5] D. L. Y. A. Y. A. Ardashir Bulsara, "Design And Testing Of An Adjustable Braking System For An FSAE Vehicle".

[6] S. R. P. P. Choudhury Promit, "Thermal and Structural Analysis of a Ceramic Coated FSAE Brake Rotor Using 3D Finite Element Method for Wear Resistance and Desighn Optimization," IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 2014.

[7] J. G. C. Edward Lumsdaine, "Design of a Disk Brake System Using the Taguchi Method," 1988.

[8] M. A.Belhocine, "Temperature and Thermal Stresses of Vehicles Gray Cast Brake," 2016.

[9] S. S. K. Sowjanya, "Structural Analysis of Disc Brake Rotor," International Journal of Computer Trends and Technology (IJCTT), vol. 4, no. 7 July, 2013.

[10] K. N. P. A. D. D. Viraj Parab, "Structural and Thermal Analysis of Brake Disc".

[11] N. H. J. A. K. S. A. K. B. Rutvik H Rana, "Optimum Design Of Braking System For A Formula 3 Race Cars With Numeric Computations And Thermal Analysis," International Research Journal of Engineering and Technology (IRJET).

[12] D. K. S.A.M Da Silva, "FEA On Different Disc Brake Rotors".

[13] "STUDENT FORMULA Rule Book 2020".