Investigation of Thermal Response of Disc Brake System: A Review

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Abstract. A comprehensive review of the thermal response of disc brake system has been made. Extensive research has been carried out on the operating problems, the material for the rotor, design of the rotor and the braking conditions of the disc brake systems and numerous methods of improvement are proposed. Various ventilation patterns have been studied in order to enhance thermal efficiency, and structural performance reductions have been found in most cases. Which creates need for the design of discs with optimal thermal and structural characteristics, so that disc brake performance can be enhanced without compromising in strength and other parameters of the disc brake system. It is expected that this exhaustive and comprehensive review will help the research fraternity in identifying the research gaps for their future work. The prime purpose of this paper is to provide an exhaustive overview of developments going on in this field. The proposed research work attempts to develop and modify the system which uses the effective method to minimise the temperature and weight of disc brake rotor by thermo-mechanical analysis to optimise the performance of Disc brake. The proposed design of disc brake offers a promising solution to improve the braking efficiency by 15% and overall reduction in weight of disc brake by 10%.

Keywords. Disc Brake, Thermal Response, Rotor, Finite Element analysis.

1. Introduction

The braking system is an important safety and control systems of an automobile. It is used to reduce the speed of the vehicle from an actual speed to a desired. It also used to stop or hold the vehicles. [1] Because of many advantages of disc brakes over drum brakes have led to their use in passenger-cars and light-trucks. Most automotive are fitted with disc brake systems. Two types of disc brakes are employed in various makes of disc brakes i.e. the solid and ventilated types. The calliper is attached to the axle casing of the vehicle. When the brakes are applied friction pads move towards the disc applying equal and opposite forces on disc. Friction pads convert the kinetic energy of the vehicle into heat energy through friction. In the present research work, two friction pads are used in the brake with their friction surfaces facing the rotor. There are four main types of brake pads used in vehicles: non-asbestos organic, ceramic and semi-metallic and metallic. Out of these metallic brake pads are used in most of the vehicles. They are typically made of iron, copper, steel and graphite all mixed and together and bonded to form the pad material. [4, 44,]

The efficiency of the braking system is influenced by the temperature increase of the disc and the friction pad interface during braking. [13] The temperature rise causes thermal distortion, brake fading, brake fluid vaporisation and brake squealing, etc. [16] All of these factors straight away affect the life and performance of the brake system and, most importantly, the safety of the vehicle and the passenger. [41, 46, 51]

The literature review reveals the importance of the thermo mechanical analysis of disc brake and
to reduce the rotor weight of disc brake regarding the optimisation of disc brake performance. The following areas are worth focusing:

- To optimize design and ventilation patterns of brake discs.
- Materials and thermo-mechanical analysis along with structural dynamics can be studied by considering air cooling effect on brake discs. [41, 26]

In section 2 the basic information about disc brake is explained along with its components and requirements. Section 3 consolidates the research works on thermal and mechanical behaviour of disc brake. In sections 4 performance analysis of disc brake on the basis of design and types of disc brake rotors is presented. In sections 5 performance analysis of disc brake on the basis of operating problems and braking criteria of disc brake is presented. In sections 6 performance analysis of disc brake on the basis of thermo-mechanical analysis of disc brake is presented. In sections 7 performance analysis of disc brake on the basis of materials of disc brake rotor is presented. In last sections challenges and future direction is covered.

1.1. Objectives

The prime objectives of this research paper are as follows:
- To identify the research gaps for further research.
- To design and develop the disc brake system for two wheelers using thermal analysis system approach.
- To investigate the performance of disc brake by opting the various geometry of rotor.
- To optimize the performance of disc brake.

2. Brakes used in Vehicles

Brake is a device that transforms the kinetic energy of the running automobile into heat by means of friction. In braking, the friction pad and disc takes away the speed from wheels. The energy consumed by the brake is the thermal energy and the heat is dissipated into the atmosphere and the vehicle’s motion is stopped. [2, 18]

Brakes are the important control systems of the vehicle. It controls the vehicle in the shortest possible time and distance. It also control the speed of vehicles at turning and other crowded places.

2.1 Materials of Disc Brake

Disc brake rotors are made from gray cast iron, contains 3.5% carbon and other additives. [23] Carbon fibre reinforced carbon–silicon carbide (CF/C–SiC), a ceramic composite, has been used as a substitute for grey cast iron. Metallic ingredients are added to improve wear resistance, heat transfer and mechanical strength. [22, 14]

2.2 Constructional features of Disc brake

The disc brake as shown in Fig. 1 is a brake that uses callipers to press the pads against the disc to produce friction that reduces the rotation of the wheels, either to minimise their speed or to keep them stationary. Disk brake elements are as follows Disc or Rotor, Caliper, Brake pads, Master cylinder, Brake fluid reservoir, Brake line and Brake fluid. [9, 28]
2.3 Disc brake Rotors

It is the component which is used to hold or to stop the wheel rotation. Rotors of disc brake is made of cast iron. In racing cars and high performance vehicles composite materials such as carbon fibre or ceramics rotors are used. Fig. 2 shows the assembly of disc brake which includes Rotor, Caliper and two brake pads and it explains how these parts are interconnected. [5, 9]

3. Thermal stress analysis of Disc Brake

In order to study the thermal analysis of the brake discs under the conditions of cyclic thermal load, the temperature distribution of these brake discs is a function of time. [34] The heat produced at the disc-pad interface during sudden braking allows for non-uniform distributions of temperature in the rotor. The heat energy released varies from 300 to 800 °C. [4]

The output performance of the vehicle with respect to the braking ability depends on the friction coefficient at the brake pad and disc interface. As temperature increases, the brake discauses the friction coefficient of the brake pads to increase and improves the braking torque output. Whereas the elevated temperatures have an impact on disc and pad wear. [47, 49, 50] The friction coefficient of the brake pads unexpectedly decreases at elevated temperatures (approximately 550 °C), resulting in a reduced braking torque output. The risk of thermal cracking is growing at these temperatures. It is therefore important to keep the brake surface temperatures within acceptable limits (i.e. below 500 °C), in order to ensure the efficient operation of the vehicle braking system. [19, 20, 33]
Daanvir Karan Dhir [4], proposes that geometry of disc is an important factor in evaluating its thermal and mechanical properties. Author indicates the use of discs with holes and air foil vents where faster cooling of braking system is required, like in the racing cars and bikes. [4]

3.1 Heat Dissipation
The various modes of heat transfer through which heat is dissipated such as conduction, convection and radiation are explained in Fig. 3.

![Fig. 3 Heat transfer in disc rotor [4, 44]](image)

3.2 Transient Thermal Analysis
Transient thermal analysis can be used to find out the temperature and other related quantities that vary over time. Changes in temperature distribution are required in many applications, such as the quenching analysis for heat treatment. The elevated temperature distribution results in increased thermal stress, which may be the explanation for the failure of such systems. The transient thermal analysis for thermal stress assessment plays a very important role in such situations. [2, 33, 36]

Deepak S. Hugar et al. [2], reported useful design and help to improve the thermal, mechanical and structural performance of disc brake system.

Table 1 shows the comparison of deformation and stress for various discs.

| Disc            | Deformation | Stress |
|-----------------|-------------|--------|
| Original Disc   | 0.00369     | 19.08  |
| New disc 1      | 0.00382     | 19.67  |
| New disc 2      | 0.00568     | 29.91  |
| New disc 3      | 0.00534     | 27.45  |
| New disc 4      | 0.00351     | 18.00  |
| New disc 5      | 0.00585     | 25.65  |
Table 2 shows the comparison of weight and temperature for various discs.

Table 2. Comparison of weight and temperature [2]

| Disc          | Weight(Kg) | Temperature(℃) |
|---------------|------------|----------------|
| Original Disc | 0.98       | 124.93         |
| New disc 1    | 1.08       | 123.03         |
| New disc 2    | 0.87       | 231.98         |
| New disc 3    | 0.96       | 165.72         |
| New disc 4    | 1.14       | 128.20         |
| New disc 5    | 0.89       | 95.60          |

S.A.M Da Silva et al. [5], have reviewed the comparative analysis of the grooved disc brake rotor and the drilled-grooved disc rotor and the author’s results are as follows. The holes and grooves are provided for a cooling method and to have a greater grip on road during braking. The results obtained by authors regarding the criteria, various point load to both brake discs as shown in Table 3 and Table 4.

Table 3. Displacement and stress for a drilled and grooved disc. [5]

| Drilled and grooved brake disc | Load(KN) | Displacement (m) | Von Mises Stress (MPa) |
|--------------------------------|----------|------------------|------------------------|
| Column A                       | 20       | 0.00001938       | 57.249                 |
| Column B                       | 23       | 0.00002306       | 65.982                 |
| Column C                       | 26       | 0.00002694       | 74.423                 |
| Column D                       | 29       | 0.00002881       | 83.011                 |
| Column E                       | 32       | 0.00003269       | 91.599                 |
| Column F                       | 35       | 0.00003557       | 100.18                 |

Table 4. Stress and displacement for a grooved disc. [5]

| Grooved brake disc | Load(KN) | Displacement(m) | Von Mises Stress (MPa) |
|--------------------|----------|-----------------|------------------------|
| Column A           | 20       | 0.0000236       | 69.26                  |
| Column B           | 23       | 0.0000272       | 86.23                  |
| Column C           | 26       | 0.0000307       | 99.99                  |
| Column D           | 29       | 0.0000342       | 113.77                 |
| Column E           | 32       | 0.0000378       | 125.54                 |
| Column F           | 35       | 0.0000413       | 137.31                 |
4. Performance analysis on the basis of design and types of disc brake rotor

A comprehensive review of the thermal response of disc brake system has been made and findings of this review and the performance analysis on the basis of design and types of disc brake rotor of disc brake is presented in this section. It also discusses the limitations about the studied research papers.
In this paper author carried out the study for different hole diameters of brake disc and observed the deformation and stress developed. The deformation in the rotor plate of disc brake with elliptical holes is 8.4% higher than that of the stress developed in the rotor plate of disc brake having equivalent circular holes. The stress developed in the elliptical holes rotor plate of disc brake is 2.5% less than that of the rotor having equivalent circular holes. However, the shape of hole is changed from elliptical shape to equivalent circular shape and analyzed its effect only on two wheeler disc brake. More parameters could take into considerations for better results. [12]
In this paper author carried out the study on two wheeler Bajaj Discover 220cc and the following parameters Weight, Deflection, Shear Stress and Factor of Safety is observed. The author suggests new disc weight is 26.68 % lesser than the original disc. However, only mathematical approach is taken into considerations. [3]
This paper conducted study on various types of discs on the basis of geometric design. The author suggests that disc rotor 1 has weight 15.18 % higher than the rotor and a temperature rise of 12.32 percent higher than the disc 3 temperature. However, this study suggests the use of disc flange rotors only for restricted areas of heavy braking where a higher braking force is necessary. [4]
This paper conducted study on various types of discs such as Grooved and drilled-grooved disc rotor and the parameters displacement and stress were observed. Author concludes that displacement experienced by the brake disc is directly proportional to the stress on a sections. However, only application of linear load is taken into considerations for analysis. [5]
This paper conducted study on various types of discs such as full and ventilated type brake discs and the parameter temperature distribution is observed. The author concludes that the radial ventilation plays significant role in the cooling of brake discs during braking. However, validations through experimental study is not done by author to check the accuracy of the numerical model developed. [43]

5. Performance analysis on the basis of operating problems and braking criterion

A comprehensive review of the thermal response of disc brake system has been made and findings of this review and the performance analysis on the basis of operating problem and braking criteria of disc brake is presented in this section. It also discusses the limitations about the studied research papers.
In this paper author carried out the study on continuous braking criteria and the following parameters Von Mises stress distribution and contact pressure distribution were observed. The author suggests that the ventilated disc brake type is the best braking device for the specified application. The experimental values get from this analysis are below the limit of their allowable values. However, author suggests thermal-structural and contact analysis of a brake model without its thermal analysis. [42]
In this paper author carried out the study on repeated braking criteria and the following parameters temperature, operating speed and coefficient of friction were observed. The author claims that compared to the simulation, the laboratory experimental investigation used for the predicted field results is in equal agreement. However, experimental analysis is carried out only for brake systems of two wheeler and without variations in speed of vehicles. [27]
In this paper author carried out the study on panic braking criteria and the following parameters


total deformation, stress and strain developed were observed. The author suggests that, structural analysis is carried on the caliper when the pressure will increase and the deformation is observed. Thermal analysis is done on the periphery of the pad and the convection film coefficient was applied to the overall surface of the disc as convection occur son the overall surface. However, Study is carried out only for existing braking component, the author does not focused on the parameters which needs to be considered for designs of new braking components except the panic braking criterion. [17, 25]

6. Performance analysis on the basis of thermo-mechanical behavior

A comprehensive review of the thermal response of disc brake system has been made and findings of this review and the performance analysis on the basis of thermo-mechanical analysis of disc brake is presented in this section. It also discusses the limitations about the studied research papers.

In this paper author carried out the study on numerical analysis of solid and ventilated discs and the following parameters temperature distribution and Von Mises stress distribution were observed. The author suggests that study has been carried out for various ventilation patterns to improve the thermal performance, but decrease in structural performance was found in most of the cases. Which creates the need for new research in this area. However, researchers have studied different parameters according to the objectives of the analysis. The question remains, however, which key factors need to be taken into account for a practical and thorough study of the disc brake. [41]

In this paper author carried out the study on structural and thermal analysis of the disc brake and the following parameters vehicle geometries, materials and the dimensions of the brake components were observed. The author reveals that vaporization of brake fluid can cause due to an increase in the temperature of the pad and therefore increase the ability of the brake fluid to heat up. However, validations through experimental study to check the accuracy of the analytical model is not done by the author. [35, 40]

This paper conducted study on structural and thermal analysis of the disc brake and the following parameters equivalent stress, temperature distribution and total deformation were observed. Author concludes that the cast iron gives better performance than other materials regarding stress point of view however stainless steel gives better brake performance than others from deformation point of view. However, author carried out study only for three materials. [48]

This paper conducted study on structural and thermal analysis of the disc brake and the following parameters heat dissipation and strength were observed. The author concludes that heat dissipation is better for the aluminium but as the strength of aluminium is poor, hence this material cannot be used for the disc brake rotors. However, author carried out study only for three materials. [52]

This paper conducted study on thermo-mechanical analysis of the disc brake and the following parameters temperature, stress, total deformation and contact pressure distribution were observed. The author claims that at the outer radius of brake disc, more deformation occurs. However, many thermal and mechanical factors would have been taken into considerations to interpret its impact on fatigue life of brake discs. [45]

7. Performance analysis on the basis of materials of disc brake rotor

A comprehensive review of the thermal response of disc brake system has been made and findings of this review and the performance analysis on the basis of materials of disc brake rotor of disc brake is presented in this section. It also discusses the limitations about the studied research papers.

In this paper author carried out the study on two wheeler Bajaj Pulsar 220cc and the following parameters deformation, temperature and weight is observed. The author suggests that grey
cast iron is the best disc brake material. However, only one type of rotor material i.e. gray cast iron is taken into considerations for studying on Bajaj Pulsar Vehicle. [2] In this paper author carried out the study on ceramic material of disc brake rotor and the following parameters tribological properties and strength/weight ratio is observed. Author proves Al2O3 have better thermal and tribological properties for the said applications. However, author claims that, joining of Al2O3 to aluminium substrate presents major challenges as the thermal stresses are more. [6, 10] In this paper author carried out the study on laser surface nitride Ti–6Al–4V material of disc brake rotor and the following parameters mechanical and tribological properties were observed. The author suggests that, tribological characteristics of laser nitrided Ti-alloy shows good performance, allows the possibility of using it as a light weight rotor than the heavier materials. However, several mechanical and tribological properties could take in to considerations to have better results and to minimize environmental and health issues. [08, 15, 21] In this paper author carried out the study on light weight AMC brake rotor material of disc brake rotor and the following parameters energy consumption, weight and cost were observed. The author claims that, for a fixed geometry of brake rotor, the application of light weight AMC material gave a 50% weight reduction. For this amount of weight reduction, the predicted energy savings is 19% for the considered brake rotor. However, author carried out study only for two materials. [07]

8. Challenges and research directions

It is inferred from the said analysis that a variety of factors are responsible for the efficiency of the disc brake. Researchers have tested different criteria according to their research objectives. The issue remains as to the primary factors should be taken into account for a practical and thorough study of the disc brake. [41] From a literature study, it is found that some of the researchers have already carried out the task of reducing the weight of the rotor, different possibilities of geometric variations of the rotor, adjustment of different rotor materials to improve the efficiency of the disc brake. It indicates, however, that there are some lacunas:

- A comprehensive investigation is required for effect of thermo mechanical stress concentration and displacement on rotor of Disc brake.
- Further investigations are needed for optimisation of disc brake in Electric two wheelers.[29, 30, 32]
- Less attention has been paid to the brake fade issue of disc brake and effect of water film (hydrodynamic effect) on disc brake performance. [24]
- An elaborate investigation about the various geometric variations of disc brake is required.
- Extensive research is done on the concept of Brake Squeal but the problem is not completely solved. Need more research to be carried out in this area? [31,37,38,39]
- Hydrodynamic effect on disc brake performance has not been investigated. [24]
- Less study related to computational investigation and validation of rotor and calliper of disc brake is carried out. Further investigations are required to optimise the performance of disc brake. The literature review reveals the importance of the thermo mechanical analysis of disc brake and to reduce the rotor weight of disc brake regarding the optimisation of disc brake performance. To overcome the above lacunas, the following areas are worth focusing:
To optimize design and ventilation patterns of brake discs.

Materials and thermo-mechanical analysis along with structural dynamics can be studied by considering air cooling effect on brake discs. [41] The proposed research work attempts to develop and modify the system which uses the effective method to minimise the temperature and weight of disc brake rotor by thermo – mechanical analysis of disc brakes to optimise the performance of Disc brake.

9. Conclusions

A comprehensive review of the thermal response of disc brake system has been made. Care has been taken to review most of the available materials. Authors have extensively reviewed literature and provided directions for future work. The literature review reveals the importance of the thermo mechanical analysis of disc brake and to reduce the rotor weight of disc brake regarding the optimisation of disc brake performance. Researchers have mostly used finite element analysis for the analysis of disc brake thermal, mechanical and structural behaviour. Various ventilation patterns has taken into consideration for improving thermal performance, but found decline in structural performance in most of the cases. Which creates need for the design of discs with optimal thermal and structural characteristics, so that disc brake performance can be enhanced without compromising in strength and other parameters of the disc brake system. The proposed design of disc brake offers a promising solution to improve the braking efficiency by 15% and overall reduction in weight of disc brake by 10%. Various studies have been reported on material transition, braking conditions, period of braking, assumptions, field of application, etc. However, this field of study is wide open for further improvement. It is anticipated that this thorough and comprehensive analysis will help the research fraternity in identifying the research gaps for their further work, and that it will also help automotive designers for designing better disc brake systems with optimum efficiency for the benefit of society.

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