

A Review on Heat Transfer and Thermal Analysis of Disc Brake System

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Abstract

Braking is a process which converts the kinetic energy of the vehicle into mechanical energy which must be dissipated in the form of heat. The disc brake is a device for deaccelerating or stopping the rotation of a wheel. A brake disc (or rotor) usually made of cast iron or ceramic composites, is connected to the wheel and/or the axle. Friction material in the form of brake pads (mounted on a device called a brake caliper) is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc to stop the wheel. This paper presents the review of techniques applied in optimizing the brake disc parameters. The analytical, numerical, simulation techniques and non-linear optimization techniques applied to enhance heat transfer rate and efficiency of the disc brake have been studied. In recent years the genetic algorithm and other non-linear optimizing techniques have been shows increasingly applied in heat transfer applications.

Key Words: Disc brake, natural convection, ANSYS, disc brake rotor, structural analysis, thermal stresses.

1. Introduction

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. In the process of performing this function, the brakes absorb either kinetic energy of the moving member or the potential energy given up by objects being lowered by hoists, elevators etc. The energy absorbed by brakes is dissipated in the form of heat. This heat is dissipated into the surrounding atmosphere to stop the vehicle, so the brake system should have the following requirements:

1. The brakes must be strong enough to stop the vehicle within a minimum distance in an emergency.
2. The driver must have proper control over the vehicle during braking and the vehicle must not skid.
3. The brakes must have good anti-fade characteristics i.e. their effectiveness should not decrease with constant prolonged application.
4. The brakes should have good anti-wear properties.

Based on mode of operation brakes are classified as follows:

- Hydraulic brakes.
- Electric brakes.
- Mechanical brakes.

The mechanical brakes according to the direction of acting force may be subdivided into the following two groups:

1. Radial brakes.
2. Axial brakes.

1). Radial brakes

In these brakes the force acting on the brake drum is in radial direction. The radial brake may be subdivided into external brakes and internal brakes.

2). Axial brakes

In these brakes the force acting on the brake drum is only in the axial direction. e.g. Disc brakes, Cone brakes.

a) Disc Brakes

A disc brake consists of a cast iron disc bolted to the wheel hub and a stationary housing called caliper. The caliper is connected to some stationary part of the vehicle, like the axle casing or the stub axle and is cast in two parts, each part containing a piston. In between each piston and the disc, there is a friction pad held in position by retaining pins, spring plates etc. passages are drilled in the caliper for the fluid to enter or leave each housing. These passages are also connected to another one for bleeding. Each cylinder contains a rubber-sealing ring between the cylinder and piston. A schematic diagram is shown in figure 1.

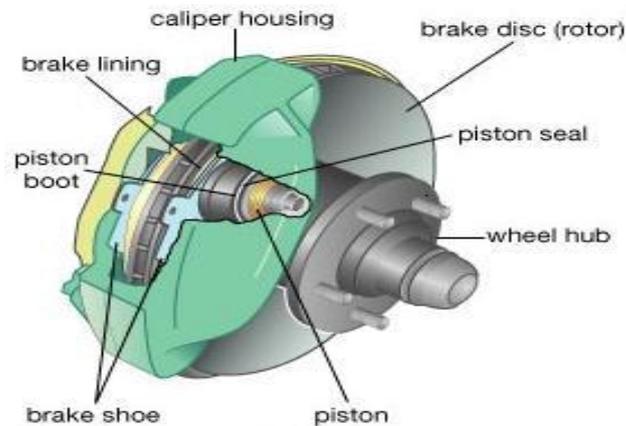


Figure 1: Disc Brake

The disc brake is a wheel brake which slows rotation of the wheel by the friction caused by pushing brake pads against a brake disc with a set of calipers. The brake disc (or rotor in American English) is usually made of cast iron, but may in some cases be made of composites such as reinforced carbon–carbon or ceramic matrix composites. This is connected to the wheel and/or the axle. To stop the wheel, friction material in the form of brake pads, mounted on a device called a brake caliper, is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc. Friction causes the disc and attached wheel to slow or stop. Brakes convert motion to heat, and if the brakes get too hot, they become less effective, a phenomenon known as brake fade.

Disc-style brakes development and use began in England in the 1890s. The first caliper-type automobile disc brake was patented by Frederick William Lanchester in his Birmingham, UK factory in 1902 and used successfully on

Lanchester cars. Compared to drum brakes, disc brakes offer better stopping performance, because the disc is more readily cooled. As a consequence discs are less prone to the "brake fade"; and disc brakes recover more quickly from immersion (wet brakes are less effective). Most drum brake designs have at least one leading shoe, which gives a servo-effect. By contrast, a disc brake has no self-servo effect and its braking force is always proportional to the pressure placed on the brake pad by the braking system via any brake servo, braking pedal or lever, this tends to give the driver better "feel" to avoid impending lockup. Drums are also prone to "bell mouthing", and trap worn lining material within the assembly, both causes of various braking problems.

2. literature Review

In the past, several authors have been applying various optimizing techniques like experimental, analytical and numerical. Some works have been carried out using genetic algorithm and particle swarm analysis.

Ali Belhocine and Mostefa Bouchetara [1]. In this paper concluded that The modelling of the temperature distribution in the disc brake is used to identify all the factors, and the entering parameters concerned at the time of the braking operation such as the type of braking, the geometric design of the disc, and the used material. The numerical simulation for the coupled transient thermal field and stress field is carried out by sequentially thermal-structural coupled method based on ANSYS to evaluate the stress fields and of deformations which are established in the disc and the contact pressure on the pads. The results obtained by the simulation are satisfactory compared with those of the specialized literature.

Aleksandar Grkic et al. [2]. In this paper, an appropriate mathematical model was developed in order to enable estimation of the sliding surface temperature values between the brake disk and brake pads throughout the entire duration of brake application. This is achieved by using the results of the temperature measurement within the brake pad and its processing, by means of an originally developed mathematical model.

Belhocine et al. [3]. The temperature distribution of rotor disc during braking operation using ANSYS Multi physics. The work uses the finite element analysis techniques to predict the temperature distribution on the full and ventilated brake disc and to identify the critical temperature of the rotor by holding account certain parameters such as; the material used, the geometric design of the disc and the mode of braking.

Hassene Djemel et al. [4]. a thermo-mechanical modelling of an automotive braking system was presented. For this purpose, three dimensional calculations are carried out in laminar, transitional and turbulent flow in ventilation ducts of brake disc. The calculations are founded on the finite volume method. Model taking into account the friction of the pad against the movable disk, developing a new so-called "Sliding Boundary Condition" technique that allowed us to take into account the spatial and temporal variability of heat flux generated by friction, and update its depending on the amount and speed of braking scenario. Indeed, we have approached the problem in two calculation phases completely independent. In a preliminary calculation phase, the speed and the temperature of the disk are maintained constant. Correlations giving the kinetics of cooling necessary for the calculation of conductive transfer in the disc are established. In a second calculation phase, we have used the equations giving the kinetics of the cooling disk for the thermal loading of the disc resulting in calculation of the transient temperature field. The results obtained by the simulation are satisfactory compared with those of the specialized literature.

Jose Luis Reyes Perez et al. [5]. The friction forces generated during braking between brake pads and discs produce high thermal gradients on the rubbing surfaces. These thermal gradients may cause braking problems such as brake fade, premature wear or hot spotting and the associated hot judder phenomenon

in the frequency range below 100 Hz. Further consequences are comfort reductions, a defective braking process, inhomogeneous wear, cutbacks of the brake performance and even damage of brake components.

Azriszul Mohd Amin et al. [6]. In this paper concluded that the method of order-of-magnitude analysis, originally proposed by Ludwig Prandtl in his analysis of fluid flow and boundary layers, could be advantageously applied to the study of temperature distribution in disc brakes. The governing equations are formulated in their entirety sans simplifying assumptions, as a 3-D transient problem, in the axial, radial and peripheral directions, also accounting for enthalpy flow and fin effect. The equations are then normalized with respect to variables of physical significance in the problem. The normalized equations are then examined for the order of magnitude of the coefficients of the terms in order to determine their relative importance. This approach has been applied with success in fluid flow, convective heat transfer and transient conduction. The results of the analysis of a disc brake based on the order-of-magnitude approach are compared with previously obtained solutions in the literature and found to have very good agreement. The value of the method is that, even without a physical understanding of the underlying phenomena, it is possible to make appropriate problem simplifications and get efficient solutions. Further, the analysis has the potential to be extended to include thermal cracking, warping and thermal stress in the disc brake.

Anup Kumar and R. Sabarish [7]. The analytical solution is not possible due to combination of loads and varying of contour of the brake drum, it is necessary to carry out finite element approach in order to evaluate the exact stress distribution and make sure that the stress values are well below the allowable limits. Drum modeled here is, of the internal expanding type brake. The shoes of this kind of brake are contained within the drum and expand outwards when the brake is applied. Such kind of brakes is used in medium heavy-duty vehicles.

Michal Kuciej and Piotr Grzes [8]. the one-dimensional analytical formulation as well as the two-dimensional FE model to study the temperature distributions in the pad/disc brake system during an emergency braking process was proposed. Both the time-dependent pressure variation and the convective cooling conditions on the free surfaces of a pad have been incorporated in the contact analytical model. The one-dimensional thermal problem of friction of the strip-foundation system during braking was formulated. An exact solution of the problem using the mathematical device of the integral Laplace transform related to Duhamel theorem was obtained. In the FE formulation to discretize the heat conduction equation for the two-dimensional problem, the Galerkin method was employed. The temperature distributions were calculated exclusively for the disc employing the heat partition ratio. Furthermore, due to the symmetry of the problem the computations were restricted to the half of the entire disc. The finite element analysis of the transient heat transfer problem for

the pad/disc system was carried out using the MSC Patran/Nastran program package. In order to confront and compare the resulting temperature distributions, equal operation parameters, the thermo physical properties of materials as well as the dimensions of the brake components were used within the numerical and analytical calculation. The obtained results from the finite element analysis reveal that both the contact temperature evolution and its values in depth of the brake rotor agree well with the analytical solution and experimental data.

Piotr grzes [9]. The aim of this paper was to investigate the temperature fields of the solid disc brake during short, emergency braking. In this paper transient thermal analysis of disc brakes in single brake application was performed. To obtain the numerical simulation parabolic heat conduction equation for two dimensional model was used. The results show that both evolution of rotating speed of disc and contact pressure with specific material properties intensely effect disc brake temperature fields in the domain of time.

Abd Rahim Abu-Bakar and Huajiang Ouyang [10]. This paper studies the contact pressure distribution of a solid disc brake as a result of structural modifications. Before modifications are simulated, four different models of different degrees of complexity for contact analysis are investigated. It is shown that the contact pressure distributions obtained from these four models are quite different. This suggests that one should be careful in modelling disc brakes in order to obtain correct contact pressure distributions. This work could help design engineers to obtain a more uniform pressure distribution and subsequently satisfy customers' needs by making pad life longer.

M. Nouby et al. [11]. Proposes an approach to investigate the influencing factors of the brake pad on the disc brake squeal by integrating finite element simulations with statistical regression techniques. Complex eigenvalue analysis (CEA) has been widely used to predict unstable frequencies in brake systems models. The finite element model is correlated with experimental modal test. The 'input-output' relationship between the brake squeal and the brake pad geometry is constructed for possible prediction of the squeal using various geometrical configurations of the disc brake. Influences of the various factors namely; Young's modulus of back plate, back plate thickness, chamfer, distance between two slots, slot width and angle of slot are investigated using design of experiments (DOE) technique. A mathematical prediction model has been developed based on the most influencing factors and the validation simulation experiments proved its adequacy.

P. Liu a et al. [12]. An attempt is made to investigate the effects of system parameters, such as the hydraulic pressure, the rotational velocity of the disc, the friction coefficient of the contact interactions between the pads and the disc, the stiffness of the disc, and the stiffness of the back plates of the pads, on the disc squeal. The simulation results show that significant pad bending vibration

may be responsible for the disc brake squeal. The squeal can be reduced by decreasing the friction coefficient, increasing the stiffness of the disc, using damping material on the back plates of the pads, and modifying the shape of the brake pads.

Rajendra Pohane and R. G. Choudhari [13]. FEM model is prepared for contact analysis. A three dimensional finite element model of the brake pad and the disc is developed to calculate static structural analysis, and transient state analysis. The comparison is made between the solid and ventilated disc keeping the same material properties and constraints and using general purpose finite element analysis. This paper discusses how general purpose finite element analysis software can be used to analyze the equivalent (von-mises) stresses & the thermal stresses at disc to pad interface.

H Mazidi et al. [14]. In this study, the heat conduction problems of the disc brake components (Pad and Rotor) are modelled mathematically and is solved numerically using finite difference method. In the discretization of time dependent equations the implicit method is taken into account. In the derivation of heat equations, parameters such as the duration of braking, vehical velocity, Geometries and the dimensions of the brake components, Materials of the disc brake rotor and the PAD and contact pressure distribution have been taken into account.

V.M.M.Thilak et al. [15]. In this work, an attempt has been made to investigate the suitable hybrid composite material which is lighter than cast iron and has good Young's modulus, Yield strength and density properties. Aluminum base metal matrix composite and High Strength Glass Fiber composites have a promising friction and wear behavior as a Disk brake rotor. The transient thermo elastic analysis of Disc brakes in repeated brake applications has been performed and the results were compared. The suitable material for the braking operation is S2 glass fiber and all the values obtained from the analysis are less than their allowable values.

Prashant Chavan and Amol Apte [16]. Gives simplified yet almost equally accurate modeling and analysis method for thermo-mechanical analysis using brake fade test simulation as an example. This methodology is based on use of ABAQUS Axisymmetric analysis technique modified to represent effect of discrete bolting, bolt preloads, and contacts within various components of the assembly.

Q Cao et al. [17]. This paper presents a numerical method for the calculation of the unstable frequencies of a car disc brake and the analysis procedure. The stationary components of the disc brake are modelled using finite elements and the disc as a thin plate. This approach facilitates the modelling of the disc brake squeal as a moving load problem. Some uncertain system parameters of the stationary components and the disc are tuned to fit experimental results. A linear, complex-valued, asymmetric eigenvalue formulation is derived for disc

brake squeal. Predicted unstable frequencies are compared with experimentally established squeal frequencies of a realistic car disc brake.

S. P. Jung et al. [18]. A simple finite element model of a disc and two pads was created, and TEI phenomenon was implemented by rotating the disc with a constant rotational speed of 1400 rpm. The intermediate processor using the staggered approach was used to connect results of two other analysis domains: mechanical and thermal analysis. By exchanging calculation results such as temperature distribution, contact power and nodal position at every time step, solutions of fully coupled thermo-mechanical system could be obtained. Contact pressure distribution of the pad surface was varied according to the rotational direction of the disc. DTV and temperature of the disc were calculated and tendency was verified by earlier studies.

Huajiang Ouyang et al. [19]. Covers two major approaches used in the automotive industry, the complex eigenvalue analysis and the transient analysis. The advantages and limitations of each approach are examined. This review can help analysts to choose right methods and make decisions on new areas of method development. It points out some outstanding issues in modelling and analysis of disc brake squeal and proposes new research topics. It is found that the complex eigenvalue analysis is still the approach favoured by the automotive industry and the transient analysis is gaining increasing popularity.

Hao Xing [20]. A disc brake system for passenger car is modelled and analysed using both approaches i.e. the transient analysis and complex modal analysis. Complex modal analysis is employed to extract natural frequencies and a transient analysis is carried out to study the thermal effects during braking. The effect of friction in complex modal analysis is investigated.

A Soderberg et al. [21]. This paper presents an approach to simulating wear on both contact surfaces at the pad-to-rotor interface in disc brakes using general purpose finite element software. It represents a first step toward a method of simulating the brake pressure needed to effectively clean the rotor of unwanted oxide layers. Two simulation cases are presented. The first addresses running-in wear under constant load and corresponds to repeated brake applications at the same constant brake load. The second studies what will happen if a lower load is applied after the contact surfaces have been run-in at a higher load level. This lower load is applied to wear off an oxide layer after a sequence of repeated stop braking at higher load levels.

Abd Rahim Abu-Bakar and Huajiang Ouyang [22]. The detailed and refined finite element model of a real disc brake considers the surface roughness of brake pads and allows the investigation into the contact pressure distribution affected by the surface roughness and wear. It also includes transient analysis of heat transfer and its influence on the contact pressure distribution. The focus is on the numerical analysis using the finite element method. The simulation results are supported with measured data in order to verify predictions. An

improved numerical methodology is presented by considering three-validation stages, namely, modal analysis at component and assembly levels and verification of contact analysis. Prior to that, a realistic surface roughness of the brake pad at macroscopic level is considered in the finite element model instead of assuming a smooth and perfect surface that has been largely adopted by most previous researchers. These two aspects have brought about significant improvement to the validation as well as analysis. Wear and thermal effects are other distinct aspects of disc brakes that influence contact pressure distributions and squeal generation in a disc brake assembly and they are also included in the current investigation. Transient analysis of disc brake vibration using a large FE model that includes thermal effects is carried out.

3. Problems in Disc Brakes

In the course of brake operation, frictional heat is dissipated mostly into pads and a disk, and an occasional uneven temperature distribution on the components could induce severe thermo elastic distortion of the disk. The thermal distortion of a normally flat surface into a highly deformed state, called thermo elastic transition. It sometimes occurs in a sequence of stable continuously related states as operating conditions change. At other times, however, the stable evolution behavior of the sliding system crosses a threshold whereupon a sudden change of contact conditions occurs as the result of instability. This invokes a feedback loop that comprises the localized elevation of frictional heating, the resultant localized bulging, a localized pressure increase as the result of bulging, and further elevation of frictional heating as the result of the pressure increase.

1. Disc Damage Modes

Discs are usually damaged in one of four ways: scarring, cracking, warping or excessive rusting.

Excessive lateral run-out

The difference between minimum and maximum value on the dial is called lateral runout. Typical hub/disc assembly runout specifications for passenger vehicles are around 0.0020" or 50 micrometers. Runout can be caused either by deformation of the disc itself or by runout in the underlying wheel hub face or by contamination between the disc surface and the underlying hub mounting surface

Scarring

Scarring can occur if brake pads are not changed promptly when they reach the end of their service life and are considered worn out. To prevent scarring, it is prudent to periodically inspect the brake pads for wear.

Cracking

Cracking is limited mostly to drilled discs, which may develop small cracks

around edges of holes drilled near the edge of the disc due to the disc's uneven rate of expansion in severe duty environments. A brake disc is a heat sink, but the loss of heat sink mass may be balanced by increased surface area to radiate away heat. Small hairline cracks may appear in any cross drilled metal disc as a normal wear mechanism, but in the severe case the disc will fail catastrophically. No repair is possible for the cracks, and if cracking becomes severe, the disc must be replaced.

Rusting

The discs are commonly made from cast iron and a certain amount of what is known as "surface rust" is normal. The disc contact area for the brake pads will be kept clean by regular use, but a vehicle that is stored for an extended period can develop significant rust in the contact area that may reduce braking power for a time until the rusted layer is worn off again. Over time, vented brake discs may develop severe rust corrosion inside the ventilation slots, compromising the strength of the structure and needing replacement.

4. Research Gap

Consequently, controlling the temperature profiles and thermo-mechanical stresses are critical to proper functioning of the braking system. CAE simulations are often used for evaluating the brake disc design using thermomechanical analysis techniques. Conventional approach is to use three dimensional FE models of the brake discs. This approach has major drawbacks of higher pre and post processing as well as solution times. Need is felt to develop a quick and reliable method to evaluate the thermal stresses in brake discs. This Project describes one such approach based on modified FEM axisymmetry analysis.

5. Conclusion

We want our vehicle's brake system to offer smooth, quiet braking capabilities under a wide range of temperature and road conditions. We don't want brake-generated noise and dust annoying us during our daily driving. To accommodate this, brake friction materials have evolved significantly over the years. They've gone from asbestos to organic to semi-metallic formulations. Each of these materials has proven to have advantages and disadvantages regarding environmental friendliness, wear, noise and stopping capability.

Since they were first used on a few original equipment applications in 1985, friction materials that contain ceramic formulations have become recognized for their desirable blend of traits. These pads use ceramic compounds and copper fibers in place of the semi-metallic pad's steel fibers. This allows the ceramic pads to handle high brake temperatures with less heat fade, provide faster recovery after the stop, and generate less dust and wear on both the pads and rotors. And from a comfort standpoint, ceramic compounds provide much

quieter braking because the ceramic compound helps dampen noise by generating a frequency beyond the human hearing range.

Another characteristic that makes ceramic materials attractive is the absence of noticeable dust. All brake pads produce dust as they wear. The ingredients in ceramic compounds produce a light colored dust that is much less noticeable and less likely to stick to the wheels. Consequently, wheels and tires maintain a cleaner appearance longer.

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