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Design Optimization of Automotive Disc Brake: A Review Paper

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Abstract- Disc brakes were first used in the manufacture of aeroplanes. Early in the 1950s, the Jaguar C-type, which employed loose round pads, and the D-type, the first vehicle with disc brakes on all four wheels (each disc including six round resistive pads!) were introduced to the motor industry. Owing to its increased efficiency, less weight, and better "fade" performance compared to drum brakes, disc brakes started to replace drum brakes more often in the 1970s (usually just on the front wheels, where the braking load is simpler due to the weight relocation).Drum systems had a serious issue with brake "fade"; also, with hard braking, the car would descend more slowly at the conclusion of the stop, which is an unsafe and undesirable characteristic. As disc brakes have grown in popularity, nearly all passenger cars now have them on the front wheels (drums are normally used on the back), and many high-performance vehicles also have them on every axle. Discs are also used in a variety of commercial vehicles; however, their exposed design might cause issues in some extreme conditions. Many locomotives that pull rolling stock also have disc brakes.

Keywords- Disc Brake, Thermal Analysis, Structural Analysis, Ansys

I. INTRODUCTION

1. Brake System Features:

Any braking system's main goal is to quickly, consistently, and safely slow down the car. It must be capable of immediately slowing the vehicle down from high speeds if necessary. When started, it must react quickly, and it must keep stability until it comes to a halt. There must be no differences or unevenness throughout the vehicle that might cause a loss of directional stability and, as a result, a loss of control over the vehicle by the driver.

Any respectable age or strength level must be able to operate it to its full potential. The braking system must adhere to several additional standards as well as certain legislative rules. The braking systems, whether they rely on drum or disc systems, each have unique requirements. The spinning axle must primarily receive a braking torque.

This is accomplished using a friction pair, consisting of a stationary "stator" that is indirectly mounted to the vehicle's chassis and a revolving "rotor" that rotates with the wheel. The rotor, which is frequently found inside the wheel itself, is linked to the rotating axle that has to be broken.

Its primary function is to transfer the mechanical braking torque generated by the extremely high frictional forces on the rotating rotor to the axle, which in turn causes the wheels to slow down the vehicle. As the kinetic energy of the moving vehicle is converted to thermal energy in the friction pair by braking, the high frictional forces generate enormous amounts of heat.

The rotor/stator pair's secondary function is to dissipate this heat energy, avoiding excessive heat build-up, high temperatures, and the ensuing harm and degradation of neighbouring parts.

II. SCHEMATIC OF THE BRAKE DISC

The two main categories of vehicle brake discs are solid and ventilated. The vented disc offers increased cooling capacity without increasing weight proportionally, although it is more challenging to build and not usually required. When a ventilated disc is required for high-performance vehicles to provide the needed heat transfer, the disc is often made of a cast-iron hub with two annular brake faces that are divided through radial ribs, also known as vanes. Heat is transferred away from the braking surfaces when air is allowed to flow via the air passageways between the ribs. A solid disc performs poorer at cooling because, as its name suggests, it lacks these air holes.

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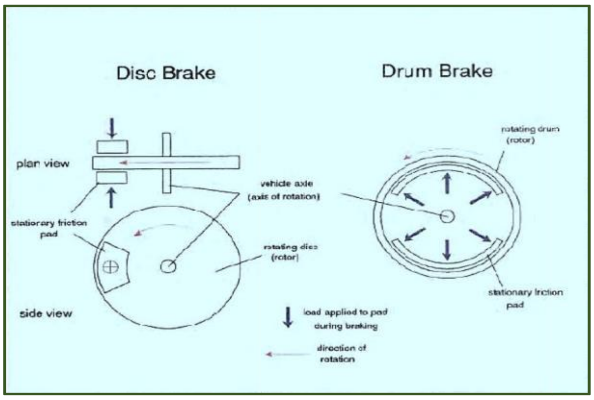

Fig 1. Drum and disc brakes are shown in this illustration.

III. BRAKE SYSTEM DESIGN

Today's disc brakes come in a variety of unique shapes. The most popular front brake disc designs come from (Pulugundla et al 2008) and include pin and vane designs, which are seen in figure 1.2 below (et. al. 2008). The pin design is often favoured from a sound standpoint whereas the vane design typically offers a more rigid construction with improved cooling performance. Straight vane designs with both a vent-in and a vent-out solution will be the focus of the current study.

IV. FAILURE MODES FOR BRAKE DISCS

A greater understanding of the numerous thermal failure types is needed to understand the need of a thorough design research of a brake disc. Judder develops when there are uneven contact forces and/or overheating between the braking disc and the brake pads. Unlike cold judder, thermal judder mostly results from thermal instabilities in the brake disc material, which is frequently caused by subpar brake disc design. Figures 1.3, 1.4, and 1.5 below show examples of geometrical deflection effects similar to butterfly effects combined with corrugated effects brought on by thermal judder.

Cracking may sometimes appear to be caused by uneven heat distribution inside the brake disc material. Hot spots are a result of the non-uniform temperature distribution that causes the brake disc to expand unevenly and, as a result, produce stress concentrations that might eventually cause a fracture to spread and injure the disc. The most efficient ways to avoid these hot patches are to modify the brake disc in order to take advantage of heat degeneracy and equal out the temperature distribution.

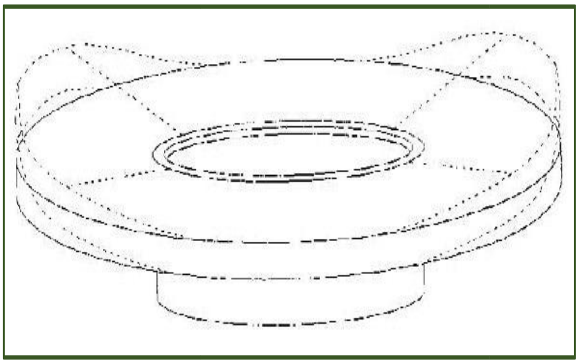

Fig 2. From Eggleston, depicts the butterfly effect caused by thermal judder (2000)

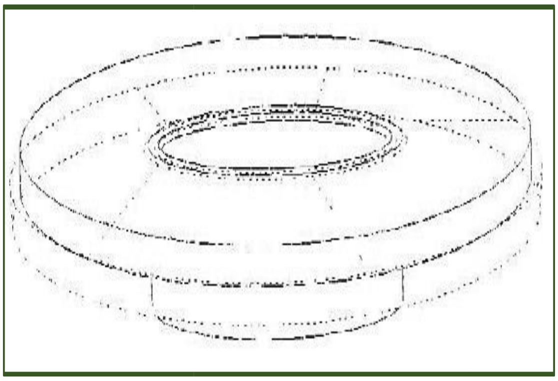

Fig 3. From Eggleston, depicts the Coning effect caused by thermal judder (2000).

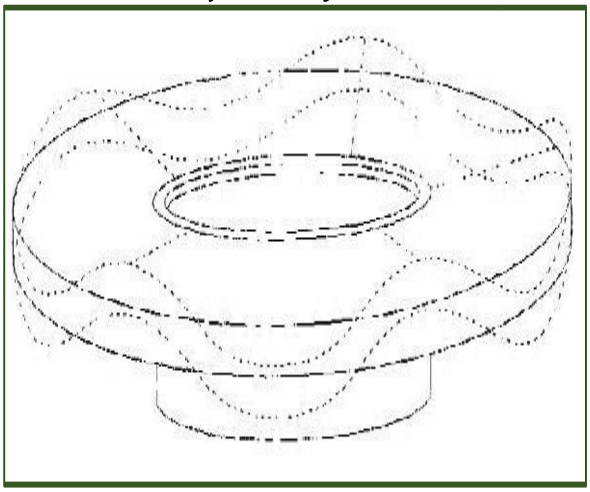

Fig 4. from Eggleston, depicts the corrugated appearance caused by thermal judder (2000).

V. REGULATING DISSIPATIVE HEAT

As shown in figure 1.6, the heat transmission from the brake disc to the surrounding air as well as other wheel house sections occurs through three distinct heat transfer modes: conduction, convection, and radiation.

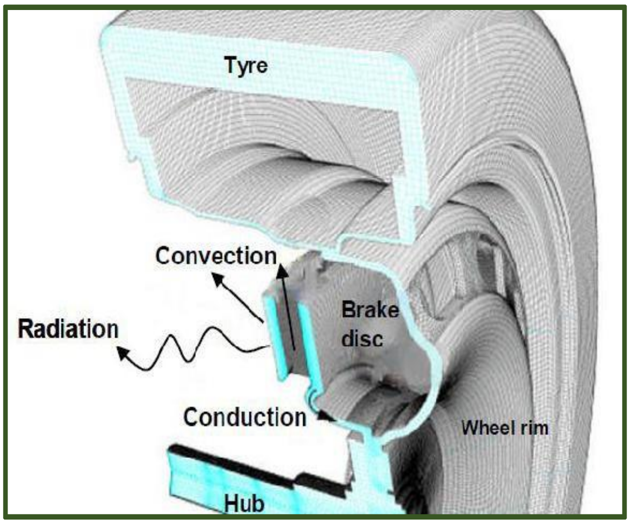

Fig 5. Disc brake heat transfer modes

1. Conduction:

The energy transmission of heat between particles in a solid is known as thermal conduction or heat conduction. The material attribute of thermal conductivity, which is utilised to transport heat, is often represented by the symbol.

When compared to another material with lower thermal conductivity, a material with a higher thermal conductivity transmits heat through the material more quickly.

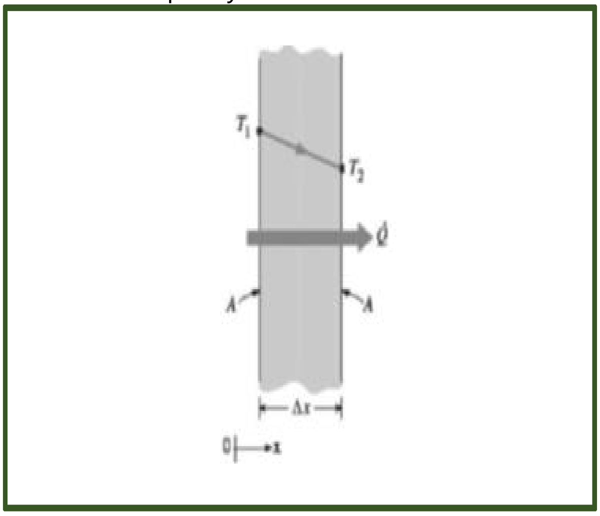

Fig 6. Conduction process.

$$\dot{Q}_{cond} = \frac{A \cdot \lambda \cdot (T_1 - T_2)}{\Delta x} = A \cdot \lambda \cdot \frac{\Delta T}{\Delta x}$$

2. Convection heat transfer:

Convective heat transfer, which is the physical behaviour of heat transfer through flowing fluids that transmits heat energy from one component to another, is a term that is frequently used to refer to the form of heat transmission known as convection. The primary source of the overall heat loss when operating the vehicle is likewise this heat loss phenomenon. Newton's law of convection may be used to describe it as

$$Q_{Convection} = h_{avg} A (T_1 - T_2) = hA\Delta T \quad (2)$$

Where (3)

$$h_{avg} = \frac{1}{A} \int hdA$$

The relationship between the area, temperature differential, and convective heat transfer coefficient, indicated by h, may be observed in the description of convective heat transfer rate. The air flow rate near the brake disc, or the flow velocity, which typically rises the heat transfer rate, the intensity of the turbulence, which typically grows the heat transfer rate over increased intensity, and the flow structure are the main determinants of the convective heat transfer coefficient.

3. Radiation Heat transfer:

Radiation heat transmission is another factor in the brake disc's overall heat loss. The Stefan-Boltzmann law, as shown in the equation below, explains radiation.

$$Q_{radiation} = \epsilon \sigma_b A(T^4_{Object} - T^4_{environment}) \quad (4)$$

Where is the Stefan Boltzmann constant, is the emissivity (0 1), A is the surface area, T objective is the object's temperature, and T environment is the environment's temperature.

VI. LITERATURE REVIEW

(Luo et al. 2022) The high-speed vehicle brake disc is a key aspect of guaranteeing the safety of the train since it is one of the crucial parts of the braking system. This study's primary goals are to thermally analyse brake discs and make accurate life predictions. The dependable life of the brake disc under various operating circumstances is anticipated using the link between the dependability of mechanical elements and the number of load cycles.

(Wang et al. 2022) For high-speed vehicles to travel safely, the stability and dependability of the braking system are crucial. In the proposed work, the tribological characteristics of BD-1, a newly designed brake disc material, were investigated. Wear debris changes in size and form when the predominant wear mechanism shifts while braking. Debris may deform at speeds between 500 and 1000 rpm and assist in the creation of an adhesive lubricating layer.

(Sawczuk et al. 2021) The findings of testing on the average and instantaneous friction coefficients of railway vehicle disc brakes are presented in this article. Independent of the different levels of wear on the friction linings and the brake disc, tests were conducted. Three categories of variables were suggested by the models: input braking parameters, speed, pressure, and mass that needed to be broken, and operating parameters. The coefficients were established using data from 384 brakes, and a further review was carried out. Regarding the acceptance of brake linings for use, the International Union of Railways' (UIC) criteria were taken into account.

(Xie et al. 2021) In order to examine the thermo-mechanical history and subsequent crack propagation of a deep fracture, EMU XFEM and Finite Element (FEM) models were utilised. Cracks tended to form near the corners of bolt holes, and an acute temperature gradient was the cause of unstable propagation along the axial direction. The results will aid in a better understanding of how braking circumstances and servicing impacts affect the behaviour of unstable cracks in EMU brake discs.

(Belhocine and Abdullah 2020) The braking phenomenon is a feature of a vehicle's stopping ability in which the friction between the brake disc and its pads converts kinetic energy from the vehicle's speed into thermal energy. In our research, we demonstrated numerical modelling utilising ANSYS software customised for the finite element method, to track the development of the global temperatures for the two types of brake discs—full and vented disc—during a braking scenario. To determine which brake disc material exhibited the best thermal behaviour, three different disc materials were investigated and the findings were compared.

(Speed 2019) The friction surfaces between the brake disc and pads produce a significant quantity of heat energy during braking, which quickly dissipates into the disc volume. The design of braking discs and connecting bolts is supported by this work. After 102 seconds of braking, the friction ring's temperature hits its maximum value of 414 °C, which is in good agreement with the bench test result.

(Kakandar, Roy, and Mehnen 2017) The brake disc is regarded as a safety-critical component in cars, which is why its service life performance is receiving more attention. Numerous factors are used to evaluate the performance of brake discs, but fatigue life and disc thermal deflection are two of the most important factors. With the use of CAE/FEA and the Taguchi design of experiment, a parametric investigation is conducted. The analysis pinpointed the geometric design elements that have a substantial impact on the performance metrics under investigation. The inboard plate thickness and the length of the effective offset are found to be two design elements that significantly affect the brake disc's thermal deflection and fatigue life.

(Belhocine, Abu Bakar, and Bouchetara 2016) A vehicle's speed can be reduced, its speed can be maintained when going downhill, and the vehicle can be totally stopped using an automotive disc braking system. The disc brake may have structural and wear problems during these braking occurrences. This work uses the commercial finite-element programme ANSYS to analyse the stress concentration, structural deformation, and contact pressure of the brake disc and pads during a single braking stop event.

(Lü and Yu 2016) For academic and commercial objectives, there has been a lot of research done on disc brake squeal reduction. The majority of the squeal reduction optimization designs now in use are based on deterministic methods that do not account for material qualities, loading circumstances, geometrical dimensions, etc. uncertainties. The time-consuming finite element (FE) simulations are replaced with the response surface methodology (RSM) in order to increase computing efficiency. The uncertainties in a disc braking system are handled using a hybrid probabilistic and interval model. The goal function used in this instance is the upper bound of the confidence interval for the design aim. Due to the consequences of the suggested optimization, the design goal and the design constraint are both interval probabilistic functions.

(Jaiswal et al. 2016) One of the most important and essential safety-critical parts of contemporary cars is the braking system. The kinetic energy of the rotating components (Wheels) is absorbed by the brake and released as heat energy into the environment. The car slows down or comes to a stop. The disc brake is put under a lot of stress when the brake is applied, which might cause structural and wear problems. The goal of this research is to simulate and analyse the temperature gradient, stress concentration, and structural deformation of a disc brake. The disc brake's design incorporates Ansys Workbench R 14.5 does solid work and analysis.

(Alnaqi, Barton, and Brooks 2015) A disc brake's thermal behaviour is a crucial issue that must be considered throughout the design stage. The thermal performance of a disc brake is evaluated at a smaller size in the current work using a scaling technique. The resulting small-scale disc brake benefits from being inexpensive and requiring less time to create.

(Ghadimi, Kowsary, and Khorami 2015) A disc brake's thermal behaviour must be considered during the design process. A scaling technique is suggested in the current research to assess a disc brake's thermal performance at a smaller size. The outcome is a small-scale disc brake with the benefit of being inexpensive and taking less time to create.

(Tiwari et al. 2014) The "Structural Analysis of Disc Brake" ANSYS project is an effort to look at how differences in disc brake rotor design, stiffness, and strength affect expected stress. A suggestion is also offered as to the optimal material and flange width to utilise in order to produce a rotor with the least amount of deformation and lowest amount of von-mises stress.

(Pevec et al. 2014) Both tension and compression are equivalent to Young's modulus, although compression has a greater value than tension by a factor of two. The cycles to failure have drastically decreased at 700 °C, which is consistent with other materials' characteristics. At room temperature (RT) and the operating temperatures of the brake discs—500 °C, 600 °C, and 700 °C—the tension, compression, and low cycle fatigue parameters were investigated.

(Li et al. 2014) After prolonged use, thermal fatigue fractures, which can include crackling, radial, and circumferential patterns, are frequently observed on the friction surface of brake discs used in railway cars. Under various braking scenarios, these fractures demonstrate various start and propagation behaviours. Brake discs' residual tensile stress distribution and crack depth are closely correlated.

VII. RESEARCH GAP AND OPPORTUNITIES

- A major issue raised in several earlier studies is the temperature stress produced on the brake disc rotor's surface.
- During braking operations, the surrounding air acts as a medium to limit the development of surface heat.
- The surface temperature of the brake disc has been lowered using a variety of methods, including improved design, different materials, and improved manufacturing processes.
- Nonlinearity not considered in previous research.

VIII. PROBLEM FORMULATION

1. General:

The methodology suggested for this study makes use of numerical methods. The thermal and structural behaviour of the disc are investigated in a basic research utilising a coupled heat transfer FE model. The finite element technique's basic premise is that you can solve a difficult issue by substituting a simpler one for it. We will be able to obtain just an approximation of the answer rather than the precise one since the real problem gets swapped out with a simpler one while determining the solution. The majority of practical issues will not have a precise solution, or even occasionally one that is approximative, that can be found with the current mathematical methods. Therefore, we must choose the finite element technique in the lack of any other practical way to determine even an approximative solution to a given issue. Furthermore, the approximate solution in the finite element approach may frequently be improved or increased by adding more computer work.

2. Nonlinearity:

Nonlinear modelling techniques are required for many mechanical engineering applications and constructions. Examples of these simulations include calculating rubber bearing capacities or forming procedures. All of them involve nonlinear constitutive equations and finite deformation analysis. The automotive industry regularly uses numerical simulation of accident concerns, which is a challenging nonlinear problem. Large numerical finite element models with tens of thousands of degrees of freedom are required for all of the aforementioned applications. As a result, effective and durable techniques of solution are also necessary, in addition to suitable formulations of the problem in the framework of continuum mechanics.

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