

Thermomechanical Stress Analysis of Vehicles Gray Cast Brake

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ABSTRACT

The main purpose of this study is to analyze the thermomechanical behavior of the dry contact between the brake disc and pads during the braking phase. The simulation strategy is based on computer code ANSYS11. The modeling of transient temperature in the disc is actually used to identify the factor of geometric design of the disc to install the ventilation system in vehicles. The thermal-structural analysis is then used with coupling to determine the deformation and the Von Mises stress established in the disk, the contact pressure distribution in pads. The results are satisfactory when compared to those of the specialized literature.

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INTRODUCTION

The braking system represents one of the most fundamental safety-critical components in modern road vehicles. Therefore, the braking system of a vehicle is undeniably important, especially in slowing or stopping the rotation of a wheel by pressing brake pads against rotating wheel discs [1]. The investigation of the localized thermal phenomena such as hot spotting and hot banding [2,3] requires a fully coupled thermoelastic analysis and thus, it is beyond the scope of the current study. This separate work is underway to include the localized thermal effects in the proposed design process and will be reported in the future. Braking performance of a vehicle can significantly be affected by the temperature rise in the brake components. The frictional heat generated at the interface of the disc and the pads can cause a high temperature. Particularly, the temperature may exceed the critical value for a given material, which leads to undesirable effects, such as brake fade, local scoring, thermo elastic instability, premature wear, brake fluid vaporization, bearing failure, thermal cracks, and thermally excited vibration [4].

Gao and Lin [5] stated that there is considerable evidence that shows the contact temperature is an integral factor reflecting the specific power friction influence of the combined effect of load, speed, friction coefficient, and the thermo physical and durability properties of the materials of a frictional couple.

Voller, et al. [6] perform a Analysis of automotive disc brake cooling characteristics. The aim of this investigation was to study automotive disc brake cooling characteristics experimentally using a specially developed spin rig and numerically using finite element (FE) and computational fluid dynamics (CFD) methods. All three modes of heat transfer (conduction, convection and radiation) have been analyzed along with the design features of the brake assembly and their interfaces. The influence of brake cooling parameters on the disc temperature has been investigated by FE modelling of a long drag brake application. The thermal power dissipated during the drag brake application has been analysed to reveal the contribution of each mode of heat transfer.

Choi and Lee,[7] presented a paper on Finite element analysis of transient thermoelastic behaviors in disk brakes. A transient analysis for thermoelastic contact problem of disk brakes with frictional heat generation is performed using the finite element method. To analyze the thermoelastic phenomenon occurring in disk brakes, the coupled heat conduction and elastic equations are solved with contact problems. The numerical simulation for the thermoelastic behavior of disk brake is obtained in the repeated brake condition. The computational results are presented for the distributions of pressure and temperature on each friction surface between the contacting bodies.

Lee and Yeo [8] reported that uneven distribution of temperature at the surfaces of the disc and friction pads



brings about thermal distortion, which is known as coning and found to be the main cause of Judder and disc thickness variation (DTV). Ouyang et al [9] in their recent work found that temperature could also affect the vibration level in a disc brake assembly. In a recent work, Ouyang et al [9] and Hassan et al [10] employed finite element approach to investigate thermal effects on disc brake squeal using dynamic transient and complex eigenvalue analysis, respectively. Braking system is the single most important safety feature of every vehicle on the road. The ability of the braking system to bring a vehicle to safe controlled stop is absolutely essential in preventing accidental vehicle damage and personal injury. The braking system is composed of many parts, including friction pads on each wheel, a master cylinder, wheel cylinders, and a hydraulic control system [11]. Disc brake consists of cast-iron disc which rotates with the wheel, caliper fixed to the steering knuckle and friction material (brake pads). When the braking process occurs, the hydraulic pressure forces the piston and therefore pads and disc brake are in sliding contact. Set up force resists the movement and the vehicle slows down or eventually stops. Friction between disc and pads always opposes motion and the heat is generated due to conversion of the kinetic energy [12]. The three-dimensional simulation of thermo-mechanical interactions on the automotive brake, showing the transient thermo-elastic instability phenomenon, is presented for the first time in this academic community [13]. Yildiz and Duzgun [14] analysed the stress of ventilated brake discs by the finite element method, three different ventilated brake discs were designed and manufactured, and their performances of braking force were investigated experimentally in addition to those of a solid disc. Afterwards, stress analyses were performed by FEA. In these analyses, a different approach, the variable loading on brake pads, was also introduced. It was found that this approach remarkably reduced the stresses on ventilated discs. Hence, this unique approach could be an improvement for eliminating crack formations in ventilated brake discs. In the study developed by Moses and John [15], fully coupled thermoelastic instability problem for a disc brake system was analysed. Thermal and mechanical model for the disc brake would be generated and solved using Comsol Multiphysics developed base on the finite element principle. The work models the heat generation and dissipation in a disc brake during braking and the following release period. The model simulates the braking action by investigating both the thermal and elastic actions occurring during the friction between the two sliding surfaces, represented by the maximum temperature on the contact surface. Brake pad and disc were selected, and parameters set to certain values from existing literatures.

In this work, we will apply modeling to the thermomechanical behavior of the dry contact between the disc and the brake pads at the time of braking phase; the computational modeling is carried out using Ansys Workbench 11 [16]. This last is elaborate mainly for the resolution of the complex physical problems. The numerical simulation of the coupled transient thermal field and stress field is carried out by sequentially thermal-structurally coupled method based on Ansys.

HEAT FLUX ENTERING THE DISC

In a braking system, the mechanical energy is transformed into a calorific energy. This energy is characterized by a total heating of the disc and pads during the braking phase. The energy dissipated in the form of heat can generate rises in temperature ranging from 300 ° C to 800° C. Generally, the thermal conductivity of the material of the brake pads is lower than on the disc ($k_p < k_d$). We consider that the heat quantity produced will be completely absorbed by the brake disc. The heat flux evacuated of this surface is equal to the power friction. The initial heat flux q_0 entering the disc is calculated by the following formula [17]:

$$q_0 = \frac{1 - \emptyset}{2} \frac{m g v_0 z}{2 A_d \varepsilon_p} \quad (1)$$

where $z = a/g$ is the braking effectiveness, a is the deceleration of the vehicle [ms^{-2}], $\emptyset$ is the rate distribution of the braking forces between the front and rear axle, A_d disk surface swept by a brake pad [m^2], v_0 is the initial speed of the vehicle [ms^{-1}], ε_p is the factor load distribution on the surface of the disc, m is the mass of the vehicle [kg], and g is the acceleration of gravity (9.81) [ms^{-2}].

The ventilated disc is lighter than the solid disc, and additional convective heat transfer occurs on the surface of the vent hall. Thus, the ventilated disc can control its temperature rise and minimize the effects of thermal problems such as the variation of the pad friction coefficient, brake fade and vapor lock.[18,19]. The ventilated disc, however, may increase judder problems by inducing an uneven temperature field around the disc. Also, the thermal capacity of the ventilated disc is less than that of the solid disc, and the temperature of the ventilated disc can rise relatively faster than that of the solid disc during repetitive braking. Therefore, thermal capacity and thermal deformation should be carefully considered when modifying the shape of the ventilated disc [20].

Figures 1 and 2 respectively shows the ventilated disc - pads and the applied forces and the geometrical characteristics of the ventilated disc.

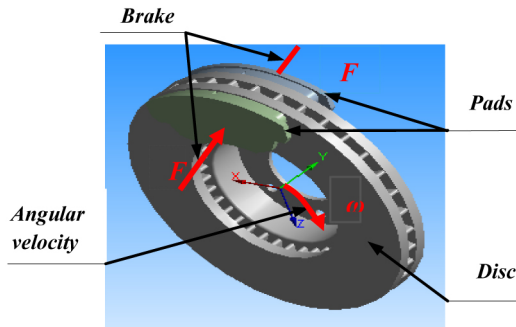


Figure 1. Disc-pads assembly with forces applied to the disc.

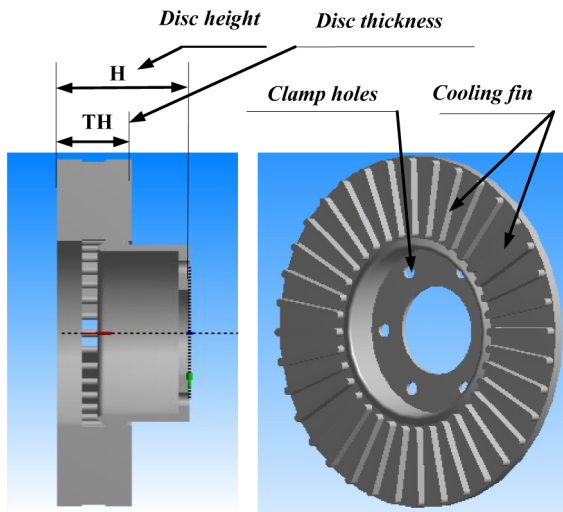


Figure 2. Geometrical characteristics of the ventilated disc.

The brake disc consumes the major part of the heat, usually greater than 90% [21], through the effective contact surface of the friction coupling. Considering the complexity of the problem and the limitation in the average data processing, one identifies the pads by their effect, represented by an entering heat flux (Figure 3).

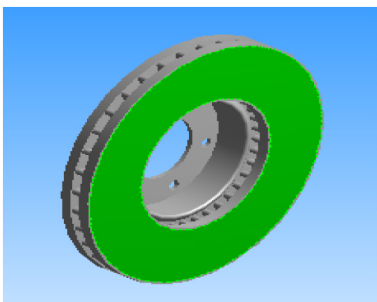


Figure 3. Application of flux.

The loading corresponds to the heat flux on the disc surface. The dimensions and the parameters used in the thermal calculation are recapitulated in Table 1.

Table 1. Geometrical Dimensions and application parameters of automotive braking.

Item	Values
Inner disc diameter, mm	66
Outer disc diameter, mm	262
Disc thickness (TH), mm	29
Disc height (H), mm	51
Vehicle mass m , kg	1385
Initial speed v_0 , km/h	28
Deceleration a , m/s ²	8
Effective rotor radius R_{rotor} , mm	100.5
Tire radius R_{tire} , mm	380
Rate distribution of the braking forces Φ	20
Factor of charge distribution of the disc	0.5
Surface disc swept by the pad A_d , mm ²	35993

Table 2. Thermoelastic properties design characteristics used in simulation.

Material Properties	Pad	Disc
Thermal conductivity, k (W/m°C)	5	57
Density, ρ (kg/m ³)	1400	7250
Specific heat, c (J/Kg °C)	1000	460
Poisson's ratio, ν	0.25	0.28
Thermal expansion, α (10 ⁻⁶ / °C)	10	10,85
Elastic modulus, E (GPa)	1	138
Coefficient of friction, μ	0.2	0.2
Operation Conditions		
Angular velocity, ω (rd/s)		157.89
Hydraulic pressure, P (MPa)		1
Design characteristics		
Volume (m ³)	8,55e-005	9,98e-004
Mass (kg)	0,620	7,238

The disc material is gray cast iron (GF) with high carbon content [22], with good thermophysical characteristics and the brake pad has an isotropic elastic behavior whose thermomechanical characteristics adopted in this simulation in the transient analysis of the two parts are recapitulated in Table 2. Rotors are made of cast iron for three reasons [23]:

- It is relatively hard and resists wear.
- It is cheaper than steel or aluminum.
- It absorbs and dissipates heat well to cool the brakes.

The thermal conductivity and specific heat are a function of temperature, Figures 4 and 5.

To simplify the analysis, several assumptions have also been made as follows [24]:

- All kinetic energy at disc brake rotor surface is converted into frictional heat or heat flux.

- The heat transfer involved for this analysis only conduction and convection process. This heat transfer radiation can be neglected in this analysis because of small amount which is 5% to 10% [25].
- In this analysis, the ambient temperature and initial temperature has been set to 20°C
- All other possible disc brake loads are neglected.

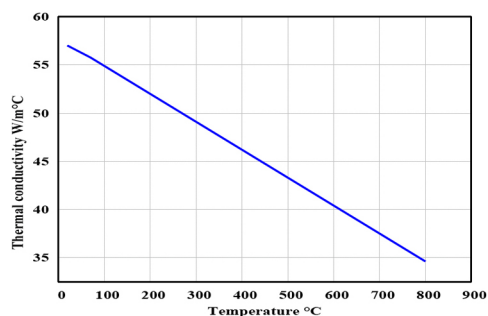


Figure 4. The thermal conductivity as a function of temperature.

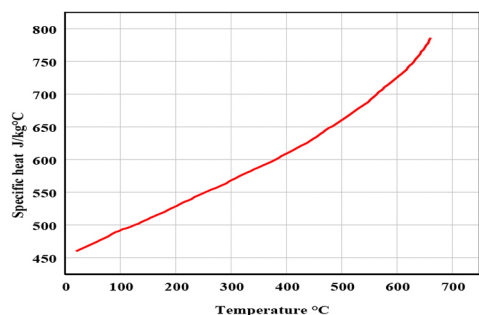


Figure 5. Specific heat versus temperature.

MODELING IN ANSYS CFX

The air flow characteristics around the brake components are highly complex and they can vary significantly with the underbody structure as well as the component shapes. Instead of using empirical equations, which are commonly used in the thermal analysis [26,27], the average heat transfer coefficients are calculated from the measured cooling coefficients by an iteration algorithm. Since the cooling coefficients account for all three modes of heat transfer, the estimated heat transfer coefficients include the equivalent radiation heat transfer coefficient.

The first stage is to create the CFD model which contains the fields to be studied in Ansys Workbench. In our case, we took only one quarter of the disc, then we defined the field of the air surrounding this disc. ANSYS ICEM CFD will prepare various surfaces for the two fields in order to facilitate the mesh on which that one will export the results towards CFX using the command "Output to cfx" [28]. After obtaining the model on CFX Pre and specifying the boundary conditions, we begin calculation on the CFX.

For the preparation of the mesh of CFD model, one defines initially, various surfaces of the disk in ICEM CFD as shown in Figure 6, we used a linear tetrahedral element with 30717 nodes and 179798 elements. In order not to weigh down calculation, an irregular mesh is used in which the mesh is broader where the gradients are weaker nonuniform mesh), (Figure 7).

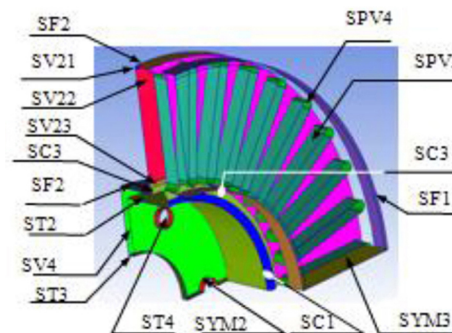


Figure 6. Definition of surfaces of the ventilated disc.

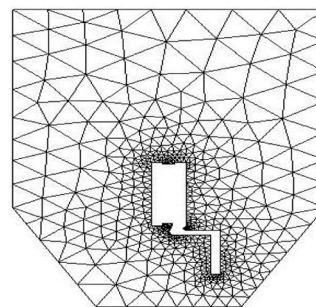


Figure 7. Irregular mesh in the wall.

The disc is related to four adiabatic surfaces and two surfaces of symmetry in the fluid domain whose ambient temperature of the air is taken equal at 20 °C [29]. An unsteady-state analysis is necessary.

Figure 8 shows the elaborate CFD model which will be used in ANSYS CFX Pre.

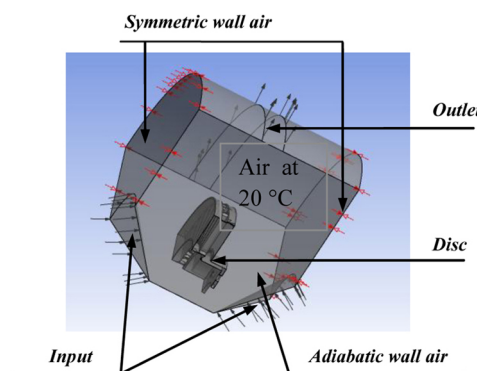


Figure 8. Brake disc CFD model.