Thermo-mechanical assessment in three auto-ventilated disc brake by implementing finite elements

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Abstract. During the braking process of a vehicle, temperature rise caused by friction between the brake pads and the disc is not quickly dissipated. This depends on the disc’s geometrical features, cooling channels and manufacturing material. Therefore, when there comes a sudden braking, immense amounts of heat may build up in a brief time, which cause elevated temperature gradients to rise within the disc. Under these conditions, brake system’s functionality and safety might be jeopardized. The objective of present research seeks to simulate temperature performance and mechanical properties in three ventilated brake discs, through Finite Elements Analysis and by means of ANSYS Software and SolidWorks Simulation. Brakes temperature and geometrical structure was noted by using a specialized design software. Results and conclusion: The results obtained prove that discs can be effectively used at extreme work conditions, at a speed of 800 Km/h and at a 20 °C room temperature. However, it is important to select the right geometrical features, so heat loss process is efficient and higher safety standards are guaranteed, ever since maintenance and cleaning of all system’s components are adequately performed. It was found that brake systems efficiency evidently depended on discs geometrical features, work conditions in which they are operated and the distinct types of available brake discs, as it was proved through software-made simulations.

1. Introduction
Brake system has an impact on the dynamic performance of a vehicle during braking stages, throughout which rotor can reach 900 °C. Such a temperature rise might cause a system loss or breakdown. To reduce this overheating within disc rotors problem, it becomes necessary to design brand new geometrical features in ventilation shafts and cooling channels allowing boosting air flow. Bearing in mind the research conducted by Jiménez, it is also needed to study different channel geometrical features, so successful systems operation is assured [1-2]. In view of the foregoing, it is precise to understand brake systems transitory and nonlinear effects, road undulations and driving dynamics of tires lateral performance, which mainly jeopardize the microstructure of these systems. On the purpose of accurately simulating these nonlinear effects during dynamical maneuvers in vehicles, it is necessary to implement a dynamics software, which allows to validate analytic results with the ones that were extracted from the state of art [3]. To optimize mechanical and microstructural properties of brakes, carbon fiber can be used as it allows reaching a lower coefficient of friction and
far more stable curves. This is mainly due to the toughness of the application exerted on such types of materials meant for brake manufacturing purposes. [4]. In other research works, reinforced polymeric composed materials were used, which boast excellent mechanical and tribological properties, given that such properties are often used in several engineering systems applications for transmission and brake manufacturing purposes. For these reasons, researchers analyzed wear mechanisms of some linen fiber reinforced Phenols in a disc brake under distinct conditions, by using electron microscopy. In addition to this procedure, a wear map was correlated with previously taken pictures [5-6]. Brake pads and malfunction discs were used in mixture of asphalt to analyze its properties and features as it became a type of solid waste, which results in a grave environmental problem. In this regard, through the different tests based on current standard, researchers got to boost asphalt conditions output [7].

Likewise, metallic brake pads for train wagons have polymeric designs with metallic elements exposed to corrosion, a reason why these systems are treated to avoid such performance. As well, they were used as samples in a study on speed kinetics of corrosion on all metallic parts of pads [8]. A similar performance, but in several types of brake, such as: ventilated brakes, auto-ventilated brakes, ABS brakes, etc., was analyzed in a research project conducted by Stewart [9]. In Mexico some researchers studied and described wear mechanisms that are implicit in discs pads and brake shoes. For that matter, a brake disc was subjected to real service conditions in elevated temperature zones, which allowed proving that in such case there is a sliding wear. On the purpose of corroborating those results, gathered data was validated through scanning electron microscopy, X rays spectroscopy and Atomic force microscopy [10]. In addition, it is important to analyze physical-chemical features of systems, with the intent of optimizing their mechanical components through Finite Elements Analysis, as well as of having a broader view on the performance that might be different according to the operation [11]. In the light of the above, 3D-CFD simulations are currently of great assistance, given the fact that they constitute a crucial toolkit to assess, not only the global amount of heat transferred to the environment, but also its punctual heat distribution upon the systems. As well, in the research conducted by Berni, it is proved that two heat transference models, broadly adopted, are effective to foretell heat flows [12-13].

2. Materials and method

With the intent of assessing these brake systems performances, the search of several bibliographical sources allowed to obtain the following features:

2.1. Brake disc

Disc brake is the element that, whether is united to the wheel axle or makes part of it, turns along with the wheel and constitutes, therefore, the mobile element of every braking system. Brake pads work upon the surface of the disc on the purpose of stopping the vehicle. Friction established between the brake pads and the disc turns the kinetical energy, built-up by the vehicle due to speed, into caloric energy, which consequently elevates systems temperature. Discs own geometrical conditions, in the shape of dishes with a vast; exposed and ventilated surface, allows continuous cooling and the possibility to evacuate all heat generated due to friction. If this did not happen, systems would break down [14-15].

2.2. Brake discs geometrical features

Brake discs geometrical features constitute a circular and perfectly mechanized surface, which is made up of the following parts (see Figure 1). They are characterized by a flat circular surface to which several manufacturers have continuously provided modifications and solutions meant to improve, as far as possible, heat dissipation, which evacuates heat generated within the disc when braking. Some of them are the following:

2.2.1. Friction Surface or rotor. It is the surface upon which the pads and the disc come into friction. In this way, it is dimensioned, so dissipation power reaches 250 W/cm². Nonetheless, power might
increase as everything depends on the geometrical features of the disc. Given that the latest is ventilated, dissipation power values might be close to 750 W/cm$^2$.

2.2.2. Brake pad. It is situated at the center of the disc, inside of which there is a hole where the hub is set. At the rear of it, a bevel was set to perfectly support the disc on the steering knuckle. Around the hole where the hub is housed, some other smaller holes have been opened with the intent of allowing the passage of anchor pins within rims.

2.2.3. Hub. The hub is a cylinder that joins the belt, supported by a rotor, to the axle of a vehicle.

2.2.4. Thermic filter. It deals with a mechanized channel that sets the rotor apart to reduce heat flowing from there to the hub. By means of these kinds of channels, excessive heating within rims and tires is avoided.

2.2.5. Cooling channels or ducts. It is a zone created to improve disc heat evacuation, so overheating is avoided. These channels or ducts are found in ventilated discs. Ventilated discs are made up of two rotors separated by channels or ducts internally set. Such ducts guarantee disc cohesion, which allows air flow inside. Thanks to these blades, disc cooling is not only generated on both external and internal surfaces of the disc. Energy exchange largely depends on the way and guiding of blades, as in some cases these blades block air flow in a certain thermic filter. If air flow section is reduced, thermic gradient increases, which means that the difference of temperature between both sides of the channel is considerably elevated. This causes hub temperature to lower. Such process is vital as heat transferred to the rim, and consequently to tire rubber, is low, which results in protecting tires carcasses. In addition, a decline in disc deformation is achieved, by reducing hub temperature and its respective thermic tensions [17-18].

2.3. Chemical formula

Brake discs material formula is a nodular grey melting of flake graphite containing 92-93% iron (Fe). This ferroalloy is generally made up of more than 2% carbon, more than 14% manganese, less than 0.6% silicon and other elements determining specific properties of braking systems, as it is noted in the following Figure 2 [19]. The material used to manufacture brake pads must have an elevated coefficient of friction, so that its contact with disc surface gets to reduce rim tour speed (See Table 1). In addition, this coefficient of friction must be kept steady as far as possible at any temperature rate or pressure during its operation, as it is noted in the following Figure 2 and Figure 3.
Table 1. Physical-mechanical properties of brake discs.

| Property                                      | Value                                      |
|-----------------------------------------------|--------------------------------------------|
| Full load vehicle weight                      | 1250 Kg – 1950 Kg – 2250 Kg               |
| Forward/backward distribution                 | 70% - 30%                                  |
| Pad surface                                   | 3546.03 mm²                                |
| Vehicle speed                                 | 80 km/h                                    |
| Braking deceleration                          | 0.6 m/s²                                   |
| Pressure within the disc                      |                                            |
| Pressure exerted by centrifugal force         | 0.73 N/mm²                                 |
| Compressive strength                          | 2205 N/mm²                                 |
| Braking performance at the thrust center.      | 9626 N – 15016 N – 17326 N                |
| Pulling stress exerted by friction            | 122 N/mm²                                  |
| Physical properties                           |                                            |
| Drive resistance                              | 240 N/mm²                                  |
| Hardness                                      | 170 GPa – 250 GPa                          |

2.4. Major problems linked to brake discs
The study of distinct problems in brake discs prove that most of them can be prevented, if hook-up gets more attention and simulations by finite elements are conducted, on the purpose of improving systems and their components. Such tasks are not only carried out through quantifiable or measuring controls, but also by means of a strict visual test on the components.

3. Results and discussions
With the intent of having a broader view of disc brake performance, three (3) types of samples of distinct vehicles were selected. From these samples, vehicle models exposed to distinct load-carrying capacities, such as: a Renault private car, a Toyota pickup and a Mitsubishi public transport bus were likewise selected. Their thermic properties (specific heat, thermic conductivity, thermic dilatation coefficient, inter alia) were analyzed on the purpose of comparing them with those which were mathematically calculated. Besides thermic analysis, geometrical features and the effect of their performance were sketched by using computer-aided design software.

3.1. Static structural analysis
Static analysis of brake systems is conducted based on the calculation of motionless particles to estimate conditions of strength, deformations and safety factors; to which these discs are subjected. For this analysis’ purpose, mathematically obtained calculations for an average speed of 80 Km/h and 20 °C temperature were carried out [21-23]. Geometrical features and flat discs were drawn by using SolidWorks software, which were imported to ANSYS Inc. software with the scope of carrying out the analysis, as it is shown in the followings Figure 4(a), Figure 4(b) and Figure 4(c):

Figure 4. Geometrical features, (a) Disc 1, (b) Disc 2, (c) Disc 3.
Through this static analysis applied to three sample-discs, it is possible to note, with a broader view, the performance of strength, deformations and safety factors of discs in the distribution of their highest and lowest geometrical values. In the following Figure 5(a), Figure 5(b) and Figure 5(c), the deformations do not exceed 0.00015 mm which can be considered as depressible what is shown at the ends of the braking track, what there is no occasion any failure, this depends of the type of geometry of the disk and its capacity of operation.

![Figure 5](image)

**Figure 5.** Entire deformations, (a) Disc 1, (b) Disc 2, (c) Disc 3.

In the following Figure 6(a), Figure 6(b) and Figure 6(c) the elastic stress in each of the discs is depressible, generating a negligible value on the braking track, and in the fixing track there is a value not greater than 0.0027 that does not affect the safety of the braking system.

![Figure 6](image)

**Figure 6.** Elastic deformation, (a) Disc 1, (b) Disc 2, (c) Disc 3.

The following Figure 7(a), Figure 7(b) and Figure 7(c) present the safety factor for each of the discs that are of different geometry, where it can be seen that the discs Figure 7(a) and Figure 7(b) have a safety factor greater than 0.5 but in the disc 7c due to the geometry this value is less than 0.5 so it is out of range but these values guarantee the correct functioning of the braking system.

![Figure 7](image)

**Figure 7.** Safety factor, (a) Disc 1, (b) Disc 2, (c) Disc 3.
3.2. Numerical analysis of heat transfer.
The model analysis was carried out on ANSYS Inc. software, by importing geometrical features from SolidWorks Software where the following temperature distribution results. Through thermic analysis on the three discs concerned, it is possible to note, with a broader overview, temperature distribution performance of the discs concerned by covering all their geometrical features. This represents a significant interest for this research. Considering starting conditions of 80 Km/h and different temperatures of functioning previously were 80 °C, 107 °C and 95 °C respectively for each disc calculated mathematically and through Finite Elements software, was possible to spot the areas that experience thermic stress when stopping, as shown in the followings Figure 8(a), Figure 8(b) and Figure 8(c):

![Figure 8. Temperature distribution, (a) Disc 1, (b) Disc 2, (c) Disc 3.](image)

The distribution of temperature on the disc is reflected in the braking track which is where the tribological torque of the disc and the pastille interact, this heat generated by friction is promoted to the bell and therefore to the braking system when performing repetitive braking and therefore the disk does not have a correct geometry in order to quickly dissipate the heat by convection.

4. Conclusions
The system considered as a study and calculation item by the authors of this research was the most suitable, since the elements considered are easily accessible and nowadays almost every vehicle has ventilated disc brakes on four rims because of its effectiveness in braking process. Conversely, vehicles that still use drum-brakes are affected by heat loss problems, moisture and corrosion due to ineffective braking caused by closed zones, which delay heat evacuation, and therefore, damage structural properties of the material used. Likewise, excessive usage of brakes can cause brake liquids to boil, as well as a total or partial loss of brake system. On average, most of drawbacks related to these systems, such as: heat loss, corrosion and cracks, stem from braking inefficacy, as heat generation zones are closed and delay heat evacuation.

Thanks to the analysis carried out via ANSYS software on the three discs under study, it was possible to validate their performance regarding deformations, tensions and safety factor of the static analysis. Through thermic analysis it was noted the temperature levels distribution performance and heat flow direction on the discs’ geometrical features. Besides, it was possible to prove that disc 2 (Toyota) is the one that shows major effectiveness during heat transfer process subjected to mathematically calculated conditions. Design software is key to visualize and analyze conditions, to which brakes are subjected, a reason why mechanical systems can be optimized on the purpose of improving resources, safety and braking process efficiency.

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