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Technical Report

Transient Thermal Analysis of a Disc Brake

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1. Abstract

This project investigates the transient thermal behavior of automotive disc brakes, focusing on the temperature distributions and cooling patterns of the discs under different braking scenarios. Using provided MATLAB files and customized 3D models, we simulated and analyzed how the mechanical energy from the vehicle is converted to heat onto the disc from friction produced through braking over time. We considered three different braking cases: Case I applies constant braking power with a circular brake pad, Case II uses a ring-shaped brake pad with a linearly decreasing braking power, and Case III uses a circular brake pad with a time-dependent, linearly decreasing applied power. Two different brake disc geometries were considered, a provided grooved design with holes, and our own independent design without holes. We simulated each case with both discs to extract experimental data, particularly the maximum temperature and the simulation runtime, with identical boundary conditions. Additionally, a parametric study was conducted to understand the influence of ambient temperature on the thermal behavior of the disc. The results offer important insights into how different brake disc designs, operational conditions, and outside temperatures affect the brake's heat dissipation and cooling effectiveness, which are essential for optimizing brake reliability, efficiency, and safety in the real world.

2. Introduction

Disc brakes play a crucial role in the automotive industry as the go-to method to provide a braking system for most commercially-sold vehicles, by converting the kinetic energy of the moving vehicle into thermal energy through friction, slowing and stopping cars, motorcycles, and planes across the globe. Disc brakes are typically made from cast-iron, or some sort of composite, such as carbon-carbon or ceramic-matrix composites, and use brake pads triggered by the driver to apply a force onto the side faces of the disc. This creates a resistive frictional force that will slow the rotational motion of the disc. This disc is connected to the wheels and/or the axle, slowing down or stopping the entire vehicle completely. The thermal energy produced by the brake pad's frictional force is then dissipated through the body of the disc brake, preventing the rest of the vehicle from dealing with potential failure from overheating temperature-sensitive components, and allowing users to depend on the braking system over long distances and/or for a long period of time.

Analysing the transient thermal behavior of the brake disc is vital because the amount of friction exerted and the braking performance decreases as temperature increases, so disc brakes are typically designed to never exceed a certain temperature threshold. Under more demanding conditions, such as downhill driving, the brake disc temperature can reach temperatures as high as 700ºC, which renders the braking useless from the heat buildup. There are numerous design solutions that can prolong and improve the braking effectiveness of the discs, such as ventilated brakes, which contain ventilation gaps throughout the disc's geometry to better dissipate the heat into the surrounding air. The ventilation rings throughout the disc provide a larger surface area for heat to leave through convection, and these same gaps pull air through them as they move with the vehicle, inducing forced convection as opposed to free convection. These two factors also explain why perforated or grooved brake discs are more effective at heat dissipation compared to more basic designs. Additionally, more complex discs are less affected by wet or subpar weather conditions.

3. Methodology

3.1. Temperature Distribution Differential Equation

To simulate the different scenarios for the brake discs, we have to begin with mathematical reasoning. The amount of work needed to stop a vehicle is equal to its kinetic energy, which means the power needed to stop the vehicle is the rate of change of the kinetic energy. Assuming that our vehicle has a mass of 2000 kg, is moving at 100 km/h (≈ 62 mph), and comes to a complete stop at 2.75 seconds, the power needed to stop the vehicle is approximately 35 kW:

$$P = \frac{KE}{\Delta t} = \frac{1}{2}mv^2\frac{1}{\Delta t} = \frac{1}{2}(2000\ kg)(100\ km/h)^2\frac{1}{(2.75\ s)} \approx 35,000\ W$$

The vehicle has 2 brake pads for its 4 disc brakes, totaling 8 brake pads where power exerted through friction will stop the vehicle (4375 W of power each). It is also assumed that it will take around 0.05 seconds for a disc brake to complete a full revolution. That very same power is converted into friction through the braking system and produces heat on the pads and brake disc. The heat expansion in the disc follows the Transient Heat Equation with cylindrical coordinates:

$$\rho c_p(\frac{\partial T}{\partial t}) = (\frac{1}{r})(\frac{\partial}{\partial r})(kr\frac{\partial T}{\partial r}) + (\frac{\partial}{\partial z})(k\frac{\partial T}{\partial z})$$

The overall temperature ends up being a function of the radial component *r*, vertical thickness component *z*, and time *t*. This equation is set-up for a three-dimensional analysis of the heat conduction present in the brake disc itself.

3.2. MATLAB Simulation Setup

These calculations, as well as the necessary code to implement the disc brake models in MATLAB and simulate them with the needed boundary conditions, were done using two MATLAB .m files provided by the professor.

3.3. Cases I to III

We simulated and analyzed the transient thermal behavior of the disc brake using three cases:

- Case I - Constant power is applied to the brake discs using circular brake pads, with a radius of 25 mm. The brake pad is considered to have a heat source due to the thermal energy generated from friction, with a time-invariant heat flux of power over area. Only half a revolution (0.025 s) will be simulated to save time.
- Case II - Power linearly decreases, from 35 kW to 0 kW, as it is applied using ring-shaped brake pads with the same radius as Case I. This scenario is more realistic since the power applied will never be constant, and the brake pad power is converted into heat flux and be used in the heat source, where the heat will spike before it begins to dissipate and cool the disc slowly. The total simulation time will be 2.275 seconds.
- Case III - Power is time-dependent, linearly decreasing from 35 kW to 0 W, using circular brake pads like Case I. The total simulation time will be 0.15 seconds.

3.4. Parametric Study Methods

We chose to perform a parametric study on the effects of ambient temperature and weather on thermal behavior of the disc (Option C). The methodology for this section was to study the effects of temperature by utilizing online resources in order to gain a better understanding of how braking changes with respect to outside temperature. All sources for the parametric study can be found in the References section at the end of this report.

4. Modeling and STL Design

A perforated disc brake with ventilations was provided by the professor, and we designed a non-perforated disc brake based on the provided disc's dimensions, to analyze the effectiveness of a better optimized disc brake design. We imported the provided .STL disc file into Solidworks 2024 to convert the mesh of planes into a solid surface body to find disc dimensions, then we made our own disc before exporting it as a .STL file so MATLAB can process our model in the case simulations.

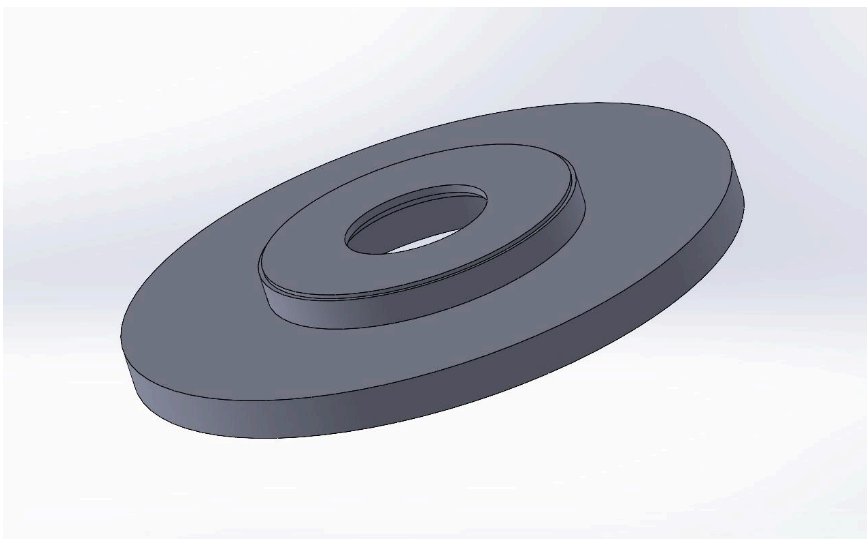

Figure 1: Image of Simplified Disc Without Holes

5. Results

5.1. Maximum Temperature

After running the simulations for both discs, we collected our data into two tables (see Appendix, Tables 1.1 and 1.2). Although we ran the program twice for each disc (to check for any discrepancies), the data was nearly identical in both trials, so we're only analyzing and plotting the data collected in the first run (see below).

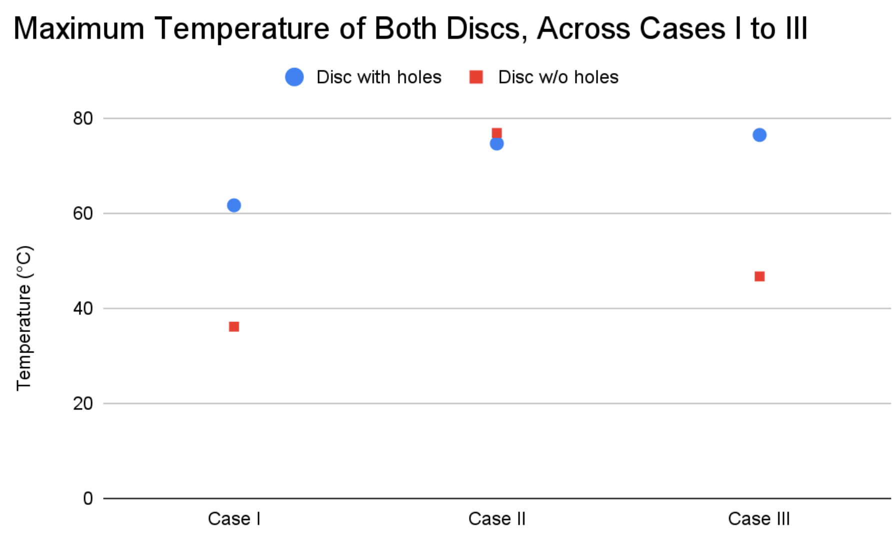

Figure 2: Graph of Maximum Temperature of Both Discs, Across Cases I to III

5.2. Simulation Time

We also recorded our simulation time (see Appendix, Tables 2.1 and 2.2).

6. Discussion

6.1 Disc Brake Comparisons

For Cases I and III, there is a significant difference between the maximum temperatures recorded, with the disc with holes having a higher maximum temperature in both cases. Meanwhile, the difference between the maximum temperatures in Case II are nearly identical. Both Cases I and III use a circular brake pad instead of a ring-shaped one to apply the braking power onto the disc brake, which could have had a small impact on the difference seen in both temperatures. Case I simplifies the problem by applying constant braking power, which compared to the two other more realistic cases, seems like an underestimation of what the real maximum temperature should be.

Maximum temperature is directly correlated to conductive thermal resistance ($R = L/kA$), where k represents the thermal conductivity of the material, L represents the thickness of the disc, and A represents the surface area of the disc that the brake pad comes in contact with. Between the two discs, the first disc had less surface area due to the holes present in its design compared to the second disc, and the thermal conductivity and disc thickness were kept the same between the two, meaning that the disc with holes has a higher thermal resistance. Given that the more thermal resistance you have, the smaller the heat rate on the disc ($q = \Delta T/R$), the disc with holes has a smaller conductive heat rate, resulting in a more prolonged heat distribution. This is why a higher maximum temperature is observed in the disc with holes, since the lower conduction rate allows for heat to build up for longer inside the brake disc, as seen in the cooling distribution for each disc in Case III:

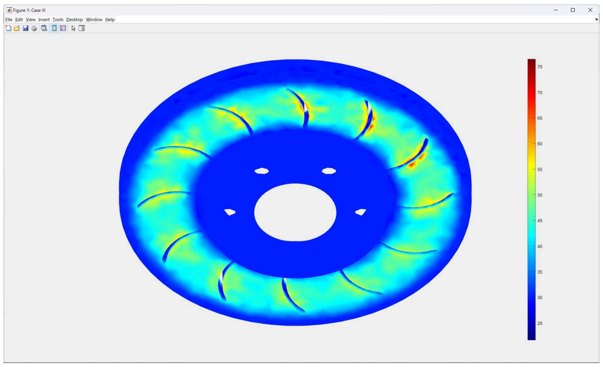

Figure 3: Case III for Disc With Holes

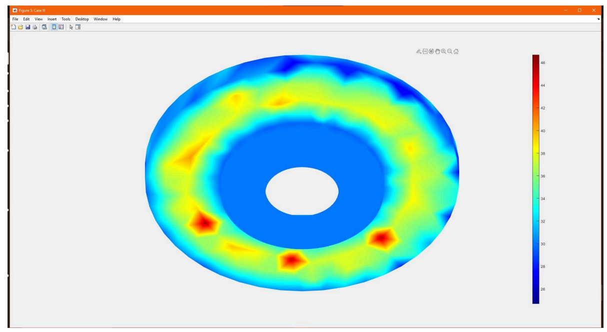

Figure 4: Case III for Disc Without Holes

As you can see, the disc with holes has a much more even cooling distribution compared to the disc without holes, which is more ideal since it allows for more efficient heat dissipation under prolonged use or suboptimal weather conditions. However, the disc with holes does reach a higher max. temperature, as seen by the small spots of red that are within the range of 65-75℃, while the red spots on the disc without holes are within 42-46℃.

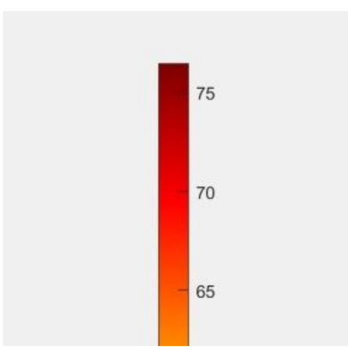

Figure 5: Zoom-in on Temperature Scale for Disc With Holes

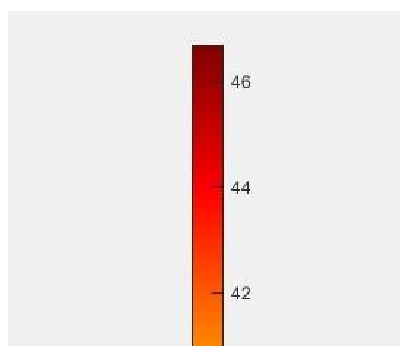

Figure 6: Zoom-in on Temperature Scale for Disc Without Holes

6.2 Parametric Study Insights

The ambient temperature in the given MATLAB code that was used for Cases I, II and III was 30℃ (86℉) with a convection coefficient (h) of 10 $W/m^2 \cdot K$. While this is slightly above a traditional average ambient temperature (~20℃), for the purposes of this study, we will be using that as a baseline temperature for comparison with more extreme temperatures. While generally a higher temperature is correlated with a higher convection coefficient, the difference in temperature between a cold/wet winter day and a hot summer day is relatively small, so we will assume h remains constant throughout this analysis.

The most obvious effect of a hot summer day on brakes will be that less heat will dissipate from the brake disc during braking through convection. This is because the change in temperature between the surface of the disc (T_s) and the ambient temperature (T_∞) is smaller on a hot day. If this lack of heat dissipation is maintained for long periods of time and the brakes exceed their maximum operating temperature, for example in stop and go traffic, it is possible for the brakes to overheat and cause a condition called "brake fade." This is when the excess heat causes the brakes to lose their ability to generate friction, which is an important factor of effective braking. Additionally, excessive heat in brakes can cause the discs to warp and/or the brake fluid to boil, both which dramatically reduce braking efficiency. These very serious safety issues are all a direct cause of brakes that are unable to dissipate heat effectively and therefore overheat, highlighting the importance of outside temperature on brakes in hot weather.

The inverse can be said for discs in cold weather, where the change in temperature between T_s and T_∞ is larger, allowing for heat to be dissipated more effectively in these conditions when compared to hot weather. In the winter, the aforementioned safety issues caused by discs overheating are less of a concern due to this increased heat transfer to the ambient air via convection. However, extremely cold temperatures can also cause the rotor to contract and therefore warp, similar to the hot weather response. This warping will cause vibrations and reduced braking efficiency as well. Additionally, on a wet day, water on the brake discs will also contribute to increased heat transfer through convection in order to keep the discs cooler. Water will also cause a decrease in friction, further contributing to less heat being transferred to the disc. However, this decrease in friction will also cause a considerable reduction in braking efficiency which is worth noting.

Overall, brake systems convert a tremendous amount of energy to heat that needs to be dissipated effectively in order for the brakes to continue working safely and as designed. Ambient temperature can have dramatic effects on how much heat can be dissipated through convection and has the ability to cause the major safety issues that were mentioned in this section. That being said, it is crucial to note the importance of outside temperature on the thermal behavior of the disc to ensure optimal conditions can be maintained throughout the system in every braking scenario.

7. Conclusion

The transient thermal analysis of disc brakes conducted in this project have demonstrated how braking scenarios, disc geometry, and ambient conditions critically affect thermal performance.

By simulating three braking cases using both a perforated disc (with holes) and a simplified solid disc (without holes), we observed that the presence of holes improved cooling distribution but also led to higher peak temperatures due to reduced conduction area and increased thermal resistance. This highlights a trade-off between localized cooling and overall thermal buildup.

The project's methodology reinforced key heat transfer concepts, particularly the importance of transient conduction and convective cooling in dynamic systems like braking. The MATLAB simulations provided valuable insight into how braking power, contact surface geometry, and heat flux behavior influence the disc's ability to dissipate energy.

Furthermore, the parametric study on weather conditions emphasized how ambient temperature variations can significantly affect braking efficiency. High ambient temperatures reduce the temperature gradient and limit convective heat transfer, increasing the risk of brake fade and damage to the disc. Conversely, colder or wetter environments enhance heat dissipation but may introduce additional concerns, such as warping or reduced friction.

Overall, this project met its objectives by applying theoretical concepts to a practical thermal challenge, utilizing computational tools to analyze complex systems, and providing insights that can inform safer, more efficient brake design in real-world applications.

8. References

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9. Appendix

Table 1.1: Maximum Temperatures for Both Discs, Across Cases I to III, Run 1

Maximum Temperature (°C)	Case I	Case II	Case III
Disc with holes	61.6418	74.6378	76.4398
Disc w/o holes	36.1247	76.8562	46.6917

Table 1.2: Maximum Temperatures for Both Discs, Across Cases I to III, Run 2

Maximum Temperature (°C)	Case I	Case II	Case III
Disc with holes	61.2088	74.8461	75.4016
Disc w/o holes	36.1247	76.8562	46.6917

Table 2.1: Simulation Runtime for Both Disc, Across Cases I to III, Run 1

Time Duration (s)	Case I	Case II	Case III
Disc with holes	248.52418	42.345071	1538.459715
Disc w/o holes	13.072401	4.001792	86.052451

Table 2.2: Simulation Runtime for Both Disc, Across Cases I to III, Run 2

Time Duration (s)	Case I	Case II	Case III
Disc with holes	353.334203	33.988122	1857.558772
Disc w/o holes	9.950492	3.979854	87.742908