Literature Review, Spring 2020
MECE 4322-01 Finite Element Analysis
Professor: Arturo Fuentes. PhD, PE

FEA Analysis of Brake Disc for Regenerative Braking

Marcos Alipi, Hector Cuevas
Department of Mechanical engineering
University of Texas Rio Grande Valley

Abstract

A regenerative braking system (RBS) allows a vehicle to recover significant amounts of braking energy. A traditional brake system converts kinetic energy from a vehicle to mechanical energy and then released as waste heat. The RBS allows for the energy that would otherwise be converted to waste heat to be recovered as electrical energy. This system can extend the brake disc's life, minimizes the disc weight, and minimizes the brake pad wear. Regenerative braking holds many advantages for electric vehicles (EVs), and Hybrid Electric Vehicles (HEVs). The two journals that will be reviewed on this paper performed a finite element analysis (FEA) on a 3D model of a brake disc. One key component on both papers was the use of FEA to study the thermal performance of the disc brake.

1. Introduction

Conventional braking systems use 100% of the friction braking to decelerate a moving vehicle, meaning that the energy produced by the braking event is dissipated as thermal energy. Electric and hybrid vehicles use regenerative braking systems to recuperate some of the energy that would normally dissipate during the braking event [3]. An estimated 70% of the kinetic energy would dissipate through friction while the other 30% could be harvested as electrical energy [4]. This would lessen the burden of the friction brakes as an RBS would decrease the amount of kinetic energy needed to be dissipated as thermal energy by friction. [2].

Both papers identified the relationship between the weight of the disc brake and the required performance. The paper by Sarip *et al* [1] describes the initial work to establish a design methodology for lightweight discs at heavy duty. The analysis conducted by Sarip *et al* [2] focused primarily on the weight reduction of the disc brake. In the paper by Sarip *et al* the focus for weight reduction is on the materials of the brake system as well as the geometry and discusses redesigning the components using lighter materials by predicting the thermal and mechanical stresses of two disc brake sizes.

Both papers established that regenerative braking has to work in conjunction with conventional braking due to the limitations of RBSs. The energy and power produced during emergency braking are too high for a purely RBS to handle. In addition, regenerative braking cannot be utilized when the battery is either fully charged or at high temperatures.

As previously stated, the weight of a vehicle's brake disc is dependent on the expected performance. While it is possible for a lightweight brake disc to generate enough braking torque to decelerate a vehicle, the heat and power produced would overload the brake and cause failure [1]. However, because RBSs lessen the burden experienced by the brake disc, it is possible for lightweight brake discs to function in tandem with regenerative braking for passenger vehicles.

A disc brake functions by slowing the rotation of the wheel through friction caused by the contact between the brake pads and the brake disc [5]. The disc brake converts the kinetic energy of the rotating wheel into heat. Figure 1 shows the common schematic of a brake disc. If the brakes get too hot, they become less effective, this phenomenon is called "brake fade". For that reason, disc brakes have to be designed to withstand high temperatures, high amounts of heat generation and thermal loading. Traditionally disc brakes are made of materials such as iron and steel because of their tolerance for high temperatures, however they are heavier materials. A disc brake has better ability to dissipate heat due to a larger exposed friction surface.

2. Finite Element Analysis

Sarip *et al* [1] used the ABAQUS program to predict the temperature distribution of a common disc brake set up. Figure 2 shows the FE models used in their analysis. The models each consist of 3239 elements and 4720 nodes. Table 1 shows the properties of the solid and ventilated discs. The frictional behavior of the contact surface was simulated with a wheel rotational speed of 6.28 rad/sec and 10.7 rad l/sec with an initial temperature of 20C [1]. The brake pads were pressed against the discs with a uniform pressure of 4 MPa. The temperature distribution for both discs were analyzed based on the same criterion.

The results of this analysis are shown on figure 3 and 4 for the solid disc and ventilated disc respectively. The temperatures were analyzed at 3 nodes along the radial line of the disc surface [1]. From the figures it was shown that disc surface temperature increased and decreased during one complete revolution. The area in which the pads and disc are in contact causes the nodal temperature to rapidly increase. As the node leaves contact with the pads, the temperature drops.

The paper also conducted a test on brake cooling. The tests were performed with the disc rotating in still air. Each disc was run at speeds of 450 rpm, 800 rpm, and 1200 rpm with respective loads of 70 N, 50 N and 30 N. The results of these experiments are shown on figure 5. From figure 5 it is shown that cooling increases with higher rotational speeds and that ventilated disc cools faster than the solid disc.

In the Sarip *et al* [2] article a test car was used to obtain experimental values for the brake force, the brake torque in the axle, and the total kinetic energy dissipated in the brake. A Type 0 test where the engine was disconnected from the car found the brake force to be 3845 N, the brake torque was 1154 Nm, and the kinetic energy dissipated was 231 kJ; a heat transfer coefficient of 90 W/m^{2}K was also found experimentally. An initial temperature of the disc was set to 20°C, the brake disc was set to rotate at 93 rad/s to simulate a vehicle moving 100 km/hr and a rotation speed of 28.6 rad/s was used to simulate a vehicle at 30 km/hr.

Properties of the components of the disc brake system are shown in Table 2 and in Table 3 the geometries of the ventilated and prototype disc are shown.

Sarip [2] simulated for a temperature distribution vehicle moving at a maximum speed braking to a speed of 0 km/hr. The predicted temperature distribution for a ventilated disc and the solid disc on the rubbing surface was simulated in the FEA software, the results of which are in figure 6. The temperature profiles for peak temperature in the two discs are plotted in figure 7. From figure 6 it can be seen that the peak temperature will occur at the center of the friction surface, in this case node 3. From figure 7 it can be shown how peak temperatures will rise over time.

A thermal stress analysis was done using the information from the thermal distribution and a thermal stress profile was plotted in figure 8 for vehicles of 1000 kg, 1500 kg, and 2000 kg on the friction surface of the disc. In figure 8 the thermal stress over time is shown. In this figure the more mass the vehicle has the more thermal stress there is on the friction surface.

References

[1] Sarip, Shamsul , A. J. Day, Olley, P. & Qi. *Analysis of temperature and pressure distribution in brake disc for regenerative braking.* University of Bradford, 2013.
[2] Sarip S. "Design Development of Lightweight Disc Brake for Regenerative Braking-Finite Element Analysis," *International Journal of Applied Physics and Math,* vol. 3, 2013
[3] Jefferson, C.M. and Barnard, R.H: "Hybrid Vehicle Propulsion", Southampton WIT Press, 2002.
[4] M. Ehsani et al., Modern electric, hybrid electric, and fuel cell vehicles:fundamentals, theory, and design, Second Editioned. New York: CRC Press, 2009.
[5] Chowdary, Velveeta and Rao, N: "Design & Analysis of a Disc Brake Using Fea," *International Journal of Computational Engineering Research (IJCER),* Vol, 04, 2014.

Appendix

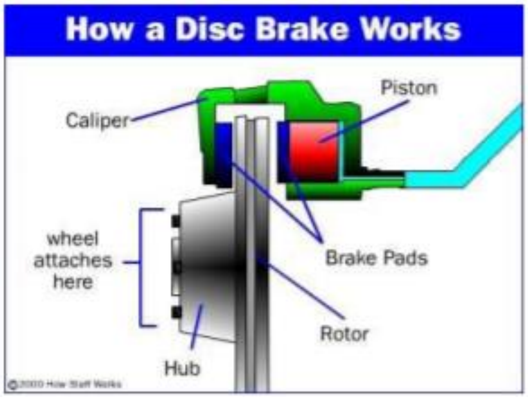


Figure 1

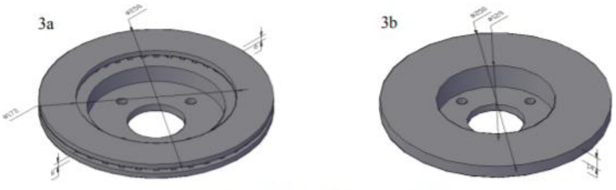
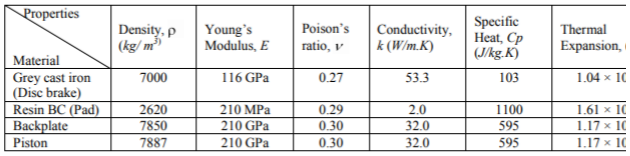


Figure 2

Table 1



Properties / Material	Density, ρ $(kg/m^{3)}$	Young's Modulus, *E*	Poison's ratio, *ν*	Conductivity, *k (W/m.K)*	Specific Heat, *Cp (J/kg.K)*	Thermal Expansion,
Grey cast iron (Disc brake)	7000	116 GPa	0.27	53.3	103	1.04 × 10
Resin BC (Pad)	2620	210 MPa	0.29	2.0	1100	1.61 × 10
Backplate	7850	210 GPa	0.30	32.0	595	1.17 × 10
Piston	7887	210 GPa	0.30	32.0	595	1.17 × 10

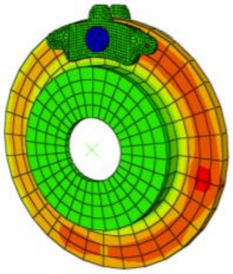


Figure 4: Solid disc

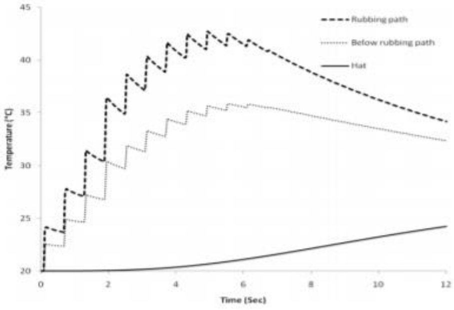


Figure 3

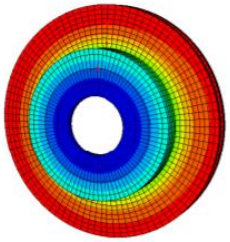


Figure 6: Ventilated disc

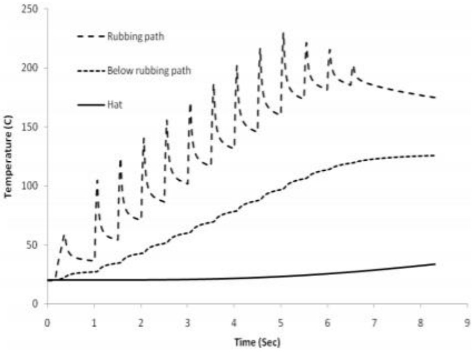


Figure 4

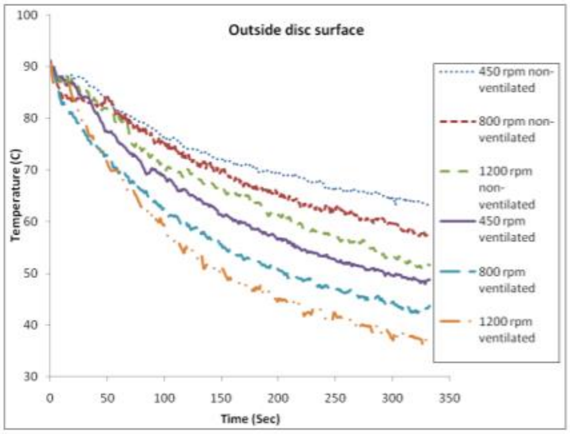


Figure 5

Table 2

TABLE I: MATERIAL PROPERTIES OF DISC BRAKE COMPONENTS ADAPTED FROM DAY [8]

Properties / **Material**	**Density, ρ (kg/ $m^{3)}$**	**Young's Modulus**	**Poison's ratio, υ**	**Conductivity k (W/mK)**	**Specific Heat, Cp (J/kgK)**	**Thermal Expansion, (K^{-1})**
Cast iron (Brake disc)	7050	116 GPa	0.27	53.3	550	11.0×10^{-6}
Stainless steel (Brake disc)	7800	200 GPa	0.29	25	460	11.0×10^{-6}
NAO friction material	2620	210 MPa	0.29	2.0	1100	16.1×10^{-6}
Backplate	7850	210 GPa	0.30	32.0	595	-
Piston	7887	210 GPa	0.30	32.0	595	-

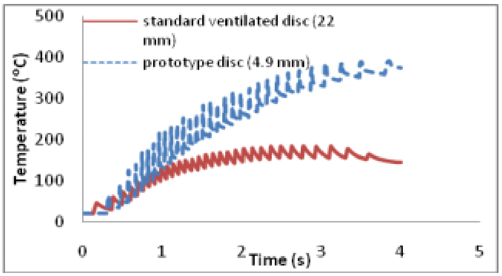


Fig. 4. Temperature profile between prototype (at node 3) and standard ventilated disc (r_{eff})

Figure 7

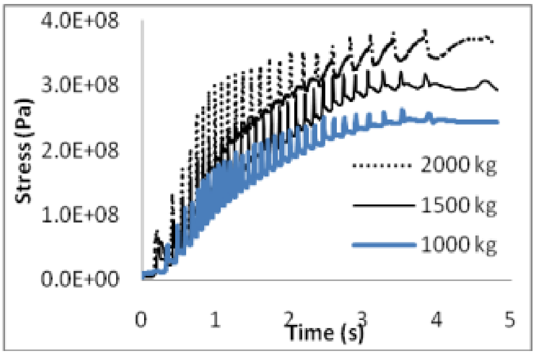


Fig. 6. Thermal stress profile on effective radius friction surface

Figure 8

Table 3

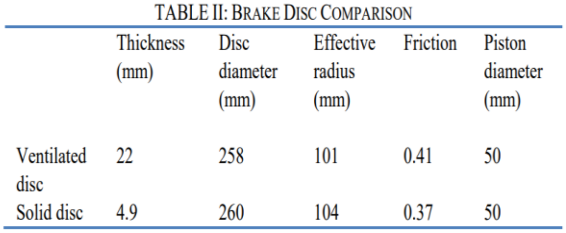


TABLE II: BRAKE DISC COMPARISON

	Thickness (mm)	Disc diameter (mm)	Effective radius (mm)	Friction	Piston diameter (mm)
Ventilated disc	22	258	101	0.41	50
Solid disc	4.9	260	104	0.37	50

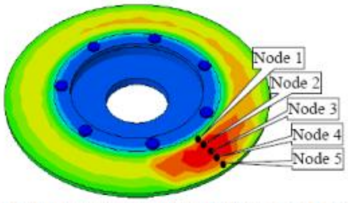


Fig. 3. FEA model of disc showing particular nodal positions

Figure 6

Problem Statement

The physical structure that will be modeled will be a brake disc for use in regenerative braking. As mentioned in the literature review, regenerative braking has the ability to make lightweight brake discs feasible in passenger vehicles, at least for electric cars. At first this was not possible as the energy and power generated during braking would cause the lightweight brake disc physical damage. However, because RBS lessens the burden the brake disc will experience, it is possible to have a smaller(lighter) brake disc.

The FEA method conducted on this model will be both a stress and thermal analysis. The reason for why these analyses were chosen is the brake pads exerts a pressure on a portion of the disc's surface and that heat is generated due to the contact friction between the brake pads and the surface of the disc. Figure 1 shows how the pads mounted on the brake caliper would be forced to press, either mechanically or hydraulically, against both sides of the brake disc to slow the rotation of the attached wheel. Figure 3 and 4 show the temperature distribution of two types of brake discs. The purpose of these analyses is to prevent yielding in the disc. As mentioned in the literature review, the stresses and the temperature will increase over time and depending on the weight of the vehicle those stresses and temperature increases can be higher in heavier vehicles. The reason this is important is that car manufacturers have acknowledged that weight reduction is a key area that can improve product competitiveness. One area that can be improved through weight reduction is the brake system of vehicles.

Problem Formulation

As stated, before the whole point of this analysis is that of weight reduction without sacrificing performance. The conditions that would be simulated in our analysis is that of braking. The model for the disc brake will use fixtures in the x, y, and z directions and will allow rotation about the z axis. We will try to simulate braking in order to study the behavior of our brake disc under these conditions. This can be simulated by giving the disc a rotational speed and pressing the brake pads against the disc to produce frictional heat. A pressure load will be applied to the disc face to show the brake pad pressing. For a thermal analysis software can be used to simulate the heat transfer, a forced convection could be simulated as well as a conduction simulation using the software. The Figure 3 and 4 show how this analysis would look like. The dimensions of the brake disc prototype are still undecided. However, the dimensions should be similar to figure 2. The material types for the disc and brake pads are still undecided. However, the brake disc should either be stainless steel or grey cast iron, and the pad should either be semi-metallic or ceramic.