

Simulation of Fully Coupled Thermo-Mechanical Effects in a Disc Brake Rotor

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Abstract: *The frictional heat generated during braking of a vehicle can cause numerous negative effects on the brake system, such as brake fade, premature wear, and thermal cracks causing the brake to have inherent noise and vibration issues under braking, called rumble. An opportunity therefore exists to eliminate brake rumble from the vehicle, thus providing a quality improvement opportunity.*

In this paper, a fully- coupled, temperature- displacement analysis using Abaqus/Standard was carried out to take into the account both thermal and structural effects on the brake rotor. The effect on thermal performance of rotational speed (corresponding to V_{max} braking conditions) and rotor temperature, due to the rotating heat source, has been evaluated. Disc thickness variations are shown to arise from the temperature profile across the disc cheek surface.

The scenario simulated considers the thermal effect of braking a vehicle which was prone to generating an audible rumble noise. The simulation measured the thermal and geometric changes in the disc, demonstrating the disc thickness variation and thermal banding of the rotor, and the location of these on the disc surface due to the effect of the thermo-mechanical loading.

Using this simulation technique, design changes to the pads to eliminate the rumble by moving the hottest band of the disc to a more central location, were assessed and verified on a vehicle.

Future developments will include further investigation of the sensitivity of the rumble noise to pad friction material compressibility and profile and to the internal vane pattern of the disc.

Keywords: *Fully-coupled simulation, Brake System, Brake disc design, Heat power distribution, Braking, Pad/disc system, Frictional heating, Moving heat source, Heat conduction, Finite element method, DTV(disc thickness variation).*

1. Introduction

In the current automotive world there is a high standard of customer expectation regarding brake noise. This is having a large impact on the technical design and virtual development of braking components and systems. This leads to engineers having a greater focus on the product development in terms of testing, design and analysis to satisfy these customer requirements.

The main benefit in using simulation is to be able to assess the large numbers of design iterations often required to achieve a good design in a cost effective manner. This helps design teams to perform the design changes and analyses efficiently by changing the designs and meeting the structural targets early during the design phase minimizing the effects later in the delivery of a vehicle program.

These restrictive demands, in terms of the NVH and thermal performance, push the vehicle manufacturers to find ever more innovative technologies and hence new design options to increase the refinement of the car whilst working towards cost and weight reductions of those systems and in overall reduction in the weight of the car.

During the virtual product development process the key technical targets are fatigue, thermal, brake pedal feel, service life, brake cooling, NVH e.g. brake squeal, rumble etc.

The critical aspects of the brake design are in meeting all these performance requirements and often there is conflict in meeting them.

Currently dynamometer and vehicle tests are carried to evaluate the NVH and thermal performance physically. This will determine the Disc Thickness Variations (DTV) and temperature of the disc surface under the varying contact pressures between the pad and disc. The non-uniform contact pressure also leads to non-symmetric temperature profile on the disc cheek surface.

Virtual simulation can play a significant role in the identification of the non-symmetric temperature profile on the disc cheek surface leading to development of efficient brakes that meet the performance and NVH targets, whilst reducing the need for testing of physical prototypes.

This paper mainly focuses on the noise resulting from the thermal effects on a disc during braking.

2. Thermo-mechanical simulations.

Thermal simulation of the problem defined above can be managed by uncoupled and coupled simulations in Abaqus, where separate and simultaneous calculations are made for the temperatures and mechanical loading respectively.

In order to consider the simulation of the above case, Abaqus/Standard Coupled Temperature-Displacement Analysis is used to capture the effect of the structural performance under the thermal and mechanical loadings in braking simulation. The advantage of the above simulation procedure is that the thermal contours developed take into consideration the caliper effects, pad geometry effects, and contact pressure effects that will vary during the braking. See figure 1.

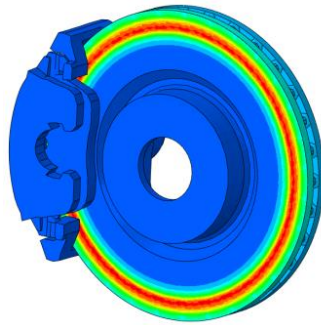


Figure 1. Thermal Contour of a disc surface.

3. Thermo-mechanical CAE process.

A detailed CAE process has been developed to capture the effects due to thermal and mechanical loading due to the high-speed braking. This process helps in predicting temperatures, thermal hot band location, disc thickness variations (DTV), brake torque variations (BTV) , etc. which are contributing factors in the generation of unwanted brake noise and vibrations.

Why we need to use this “Analysis” procedure?

- Because the mechanical and thermal solutions affect each other strongly and, therefore, must be obtained simultaneously.
- For prediction of the temperature profile of the disc surface due to the varying contact pressure between the disc and pad during braking.
- Taking into account both thermal and structural effects leads to a more representative finite element model in which the geometric distortion of the brake system, as a consequence of the heat generation, can be predicted throughout the full braking event.
- Capture the effect of brake caliper stiffness on the brake disc and pad positions or movements during the high-speed braking.
- To study the effect of the “consequence of friction and imposed rotational motion”.
- To study the effect of ‘rotating heat source’.
- To explore the behavior of the temperature dependence of material properties.
- To predict the transient thermal and structural behavior of the brake system.

4. Brake System Finite Element Model.

A braking event under a particular deceleration is simulated by rotating the disc at an appropriate angular velocity and applying the braking pressure through the brake fluid. This brake simulation is done by simulating the brake dynamometer boundary conditions e.g. pressure, speed and deceleration. The model includes all contacts between the relevant components e.g. between the pad and disc, caliper and piston, anchor and pad abutment.

The pad and disc are defined as two deformable bodies, and sliding friction between them is proportional to the normal force on each element. The friction coefficient is made further dependent upon the surface temperature.

The brake disc, pad and pistons are modeled with C3D8T, C3D6T brick elements, caliper and anchor with higher order C3D10MT tetra elements.

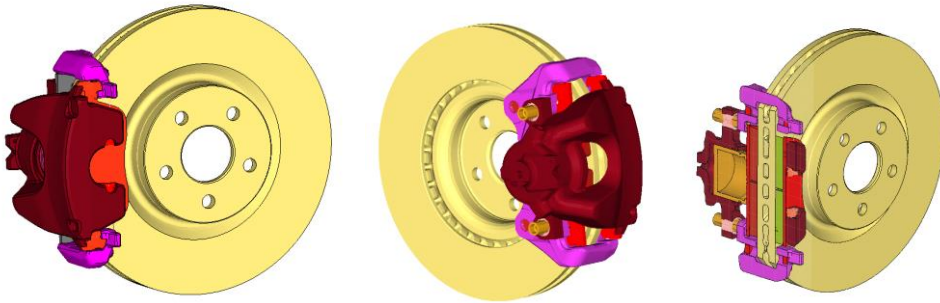


Figure 2. Finite element model of a brake assembly used for thermal simulation.

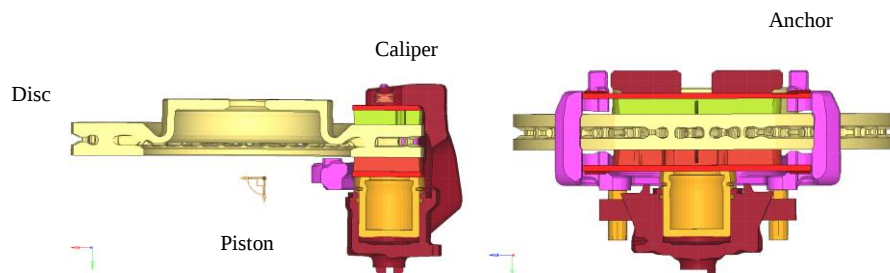


Figure 3. Finite element model of a brake assembly showing the cross section.

5. Results discussion.

A finite element model was used to conduct a study to minimize the brake DTV by simulating the braking event under deceleration with two differing designs. The results of the braking simulation are presented below showing the disc temperatures and the disc thickness variations (DTV). It was observed that good combinations of the disc and pad design have a great influence in minimizing the temperatures in the hot band and at the same time the disc distortions.

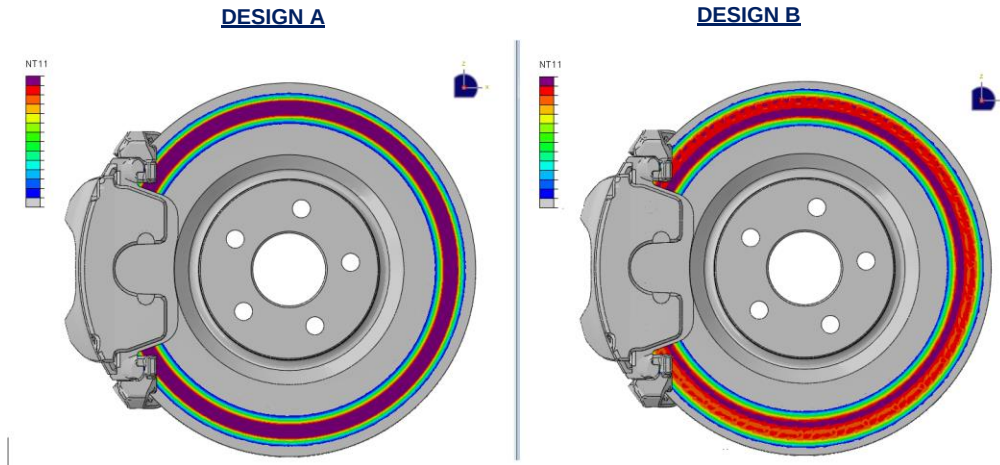


Figure 4. Contour showing the disc temperature (Outboard face.)

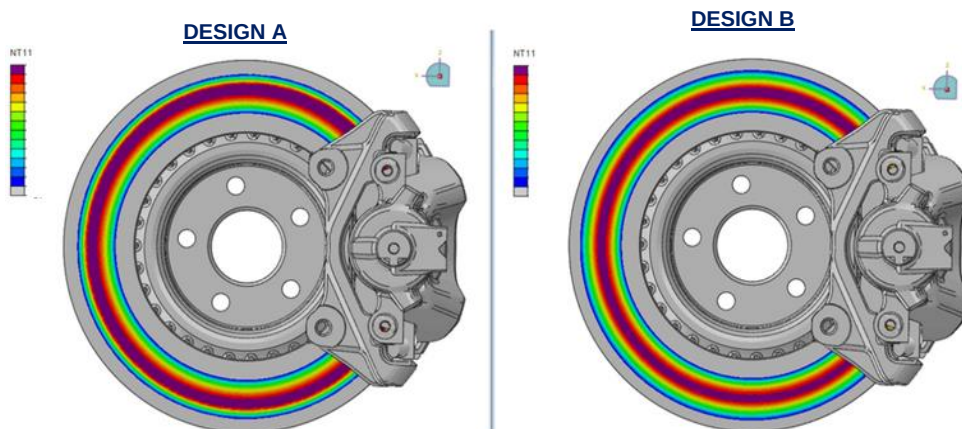


Figure 5. Contour showing the disc temperature (Inboard face.)

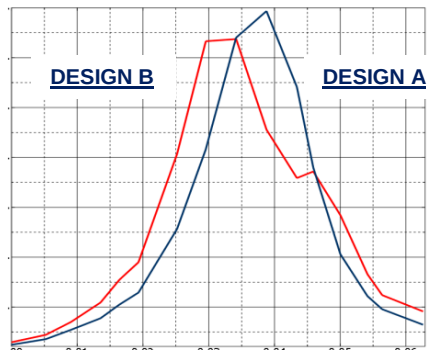


Figure.6 Temperature profile across the cheek surface.

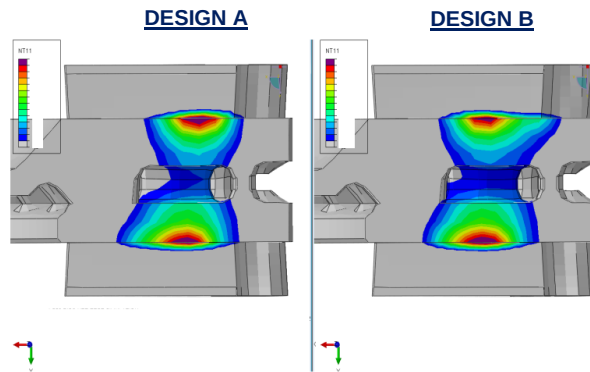


Figure.7 Contour showing the temperature²s across the disc.

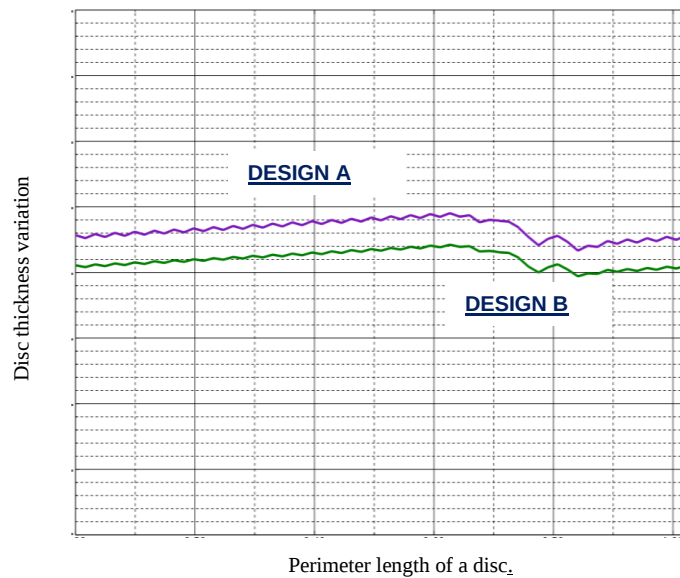


Figure 8. Contour showing the disc thickness variation.

Vibration measurements made in the vehicle at the seat rail and at the steering wheel under the two designs highlighted showed that Design B made contributions in reducing the vibration experienced due to the thermal distortion of the disc.

6. Conclusion and future work.

In this paper, the braking event is simulated by using the Abaqus/Standard Coupled temperature-displacement analysis. This methodology captures the mechanical and thermal behavior of a disc during braking under varying contact pressures. Caliper stiffness affects the disc temperatures and distortion; however, effects due to geometrical change in the disc and pad have a greater influence. This process will give a better understanding of the disc and pad behavior under different braking events during the design process. This method has great potential for disc design in terms of temperatures and thermal fatigue.

Further study of disc thermal fatigue and distortion of different brake assemblies in various braking scenarios and under variation of pad compressibility with respect to temperature, using multi-physics simulation analysis incorporating brake cooling using CFD is recommended.