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Coupled thermomechanical computation method for a virtual design process of brake discs

F. JUNGWIRTH*, A. DORNHEIM* AND C. FRIEDRICH♦

* Dept. Driving Dynamics
BMW Group
80788 München, Germany
email: frank.jungwirth@bmw.de,
email: arne.dornheim@bmw.de,
www.bmw.de

♦ MVP Machine Elements, Fastening Systems, Product Innovation
Dept. of Mechanical Engineering
University of Siegen
Paul-Bonatz-Str. 9-11, 57076 Siegen, Germany
email: christoph.friedrich@uni-siegen.de,
www.mb.uni-siegen.de/mvp/

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Abstract. *In this paper a thermomechanically coupled simulation in order to design brake discs and calipers is described. Regarding the demands of the development process a more detailed model with improved forecast quality is developed. The extended simulation model implies the brake dynamometer and the brake caliper assembly. Mechanical interactions between caliper and brake disc are focused reagrding the influence of heat power distribution on the brake disc.*

1 INTRODUCTION

On the one hand the weight of vehicles is increasing caused by larger dimensions, higher safety standards and more comfort features. On the other hand the environmental awareness increases concerning the CO_2-Emissions. Regardless of this target-conflict the level of driving dynamics should increase. These opposed demands push the automobile industry to find alternative and innovative designs to increase efficiency and reduce car weight, particularly in the chassis. Weight reduction is very efficient if it is done by reducing the unsprung mass, especially at the rotating brake disc.

The brake disc as a safety-related component needs to be reliable, high performant and damage-tolerant under all circumstances. In the brake disc development, these targets regarding functional safety have to meet the other essential demands such as weight, cost, development time, manufacturing feasibility, quality and comfort.

Considering the aspects above, the development process is determined by the following technical objectives:

- fatigue strength
- thermal stability
- comfort regarding the brake pedal feeling
- long service life
- brake cooling
- comfort regarding NVH-requirements, e.g. brakesqueal
- stable friction coefficient

The first three objectives listed above are strongly mandatory for the brake disc design regarding thermomechanical behaviour. The key aspects of thermomechanical behaviour are tested on a brake dynamometer to determine the deformations and its fatigue strength. The results of the dynamometer show a high sensitivity to the parameters of the entire brake system. In addition to the design concept of the caliper (floating or fixed caliper) the inherent rigidity of the caliper has a major impact. This leads to a non-uniform contact pressure between brake pad and brake disc, and in consequence, to an inhomogeneous distribution of the applied heat power to the brake disc.

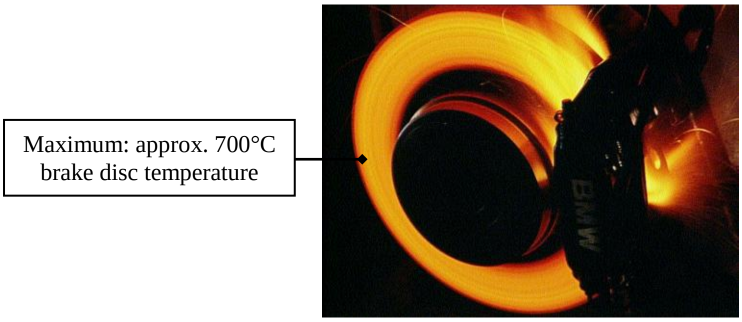

Figure 1: Heated brake disc

In order to that, several iterations in the development process are needed to find the ideal brake disc design for a brake system. Hence, the simulation plays a major role regarding the improvement of the development efficiency and reduction of hardware prototypes. The standard simulation is limited to the single component brake disc. Considering the other objectives mentioned above, geometry could change in late development phases, e.g. due to NVH-issues. In these late development phases, there is no time for several hardware design loops of the disc. Thus, a changed disc design needs to be virtually confirmed as good as possible. To reach this goal regarding strength, a more detailed simulation method is required, taking into account the whole brake system and the thermomechanical interaction.

2 APPROACHES FOR THERMOMECHANICAL SIMULATIONS

There are two main methods to approach a thermomechanical problem: the fully coupled thermal-stress analysis, which carries out the thermal and mechanical calculations simultaneously and the sequentially coupled thermal-stress analysis, which performs both operations one after the other. For the first case in Abaqus/Standard the heat transfer equations are integrated using a backward-difference scheme, and the coupled system is solved using Newton's method. This enables investigation of problems with strong impact of the thermal on the mechanical solutions and vice versa. The second case is performed by first solving the pure heat transfer problem, then reading the temperature solution into a stress analysis as a predefined field. Hence, the coupling between thermal and mechanical solution is limited to a one-way investigation [1].

Calculating a brake assembly the fully coupled method takes the influence of the changing pressure conditions into account, which are caused by the heated brake disc. In consequence, the pressure conditions combined with the friction coefficient determines local heat energy generation directly. The sequentially coupled method is limited in this respect.

In order to reduce the complex reality problem several investigations have been made. Former studies emphasize the major role of the contact pressure between the brake disc and pad as a key parameter of wheel brakes. Experimental studies were made using pressure sensitive films to identify the distribution of contact pressure in static cases [2]. In reality, dynamic effects are dominant, respective to wear and friction laws in the thermomechanical contact. Loemba introduces a measuring technique at a dedicated test bench to indicate local confined areas with homogeneous friction coefficients in a disc-pad configuration [3]. One step further Degenstein used a divided brake pad with force sensors under each part. This enables a detection of the point of load incidence and the distribution of contact pressure during the braking process. A great advancement is that the application works under real conditions [4,5].

For the basic understanding of brake disc design characteristics, many researchers focuse on numerical simulations of disc-pad systems. A fully coupled thermomechanical method with a three-dimensional FE model was developed in [6], taking into account wear due to the contact pressure. The aim was to predict hot judder in a brake disc. In order to predict fatigue strength of disc brakes a fully coupled thermomechanical simulation method was developed [7]. Main improvements were the varying distribution of heat flux entering the brake disc, by using the contact pressure distribution. In [8] a sequentially coupled thermomechanical finite element analysis of disc brakes under repeated braking conditions is performed. Herein a small segment of the disc and a uniform heat flux were assumed. Söderberg [9] introduces a simulation method with the target to predict wear and contact pressure distributions in brake pads. Another approach using Eulerian algorithm is upcoming for coupled thermal-stress analysis. Nguyen [10] performed a sequentially coupled thermal-stress analysis by first performing a transient heat transfer Eulerian analysis followed by a steady-state mechanical analysis. Strömberg developed a finite element approach using an Eulerian framework for simulation of frictional heating in sliding contacts and implemented it for simulation of frictional heating in disc-pad systems [11,12]. Here, the key approach is to decouple the simulation in one mechanical contact problem and a frictional heat problem.[13]

The investigations described above show varying possibilities to simulate thermomechanical interactions in a brake system with different levels of detail. Nevertheless there is no method with a high level of detail combined with computational efficiency.

3 DEVELOPMENT OF A THERMOMECHANICALLY COUPLED CAE PROCESS

The described shortcoming of the methods shall be handled through an advancement of the CAE process. In consequence of the described requirements (chapter 1) and methods (chapter 2) the following challenges must be met in a new approach:

- Determination of the influence of the brake caliper to the brake disc (mechanical – thermal coupling)
- Performance prediction of the complete wheel brake, taking into account all interacting components with their mechanical and thermal behaviour.
- In contrast to the fully coupled method the calculation time should be significantly reduced.

According to the challenges a decoupled simulation for the thermal and the mechanical problem is preferred. The new approach consists of divided calculations using Abaqus/Standard (Version 6.11) that are carried out sequentially in a plurality of time steps with updated heat power distribution input. Firstly, a pure thermal analysis at a brake disc segment will be used (described in chapter 3.1). Secondly, an extended mechanical system model is employed, consisting of the brake disc, dynamometer setup and the brake caliper with brake pads (described in chapter 3.2).

3.1 Investigation of a brake disc segment

The current used simulation method at BMW for the early and main development phase is restricted to investigations of the brake disc as a single component with a sequentially coupled method. Thereby a segment of the brake disc with cyclic symmetry is modelled. Additionally the dynamometer setup is included. For the transient thermal analysis a dedicated heat power distribution is proposed (randomized distribution shown in Fig. 2, left). One of the key assumptions is the heat power distribution on the brake disc.

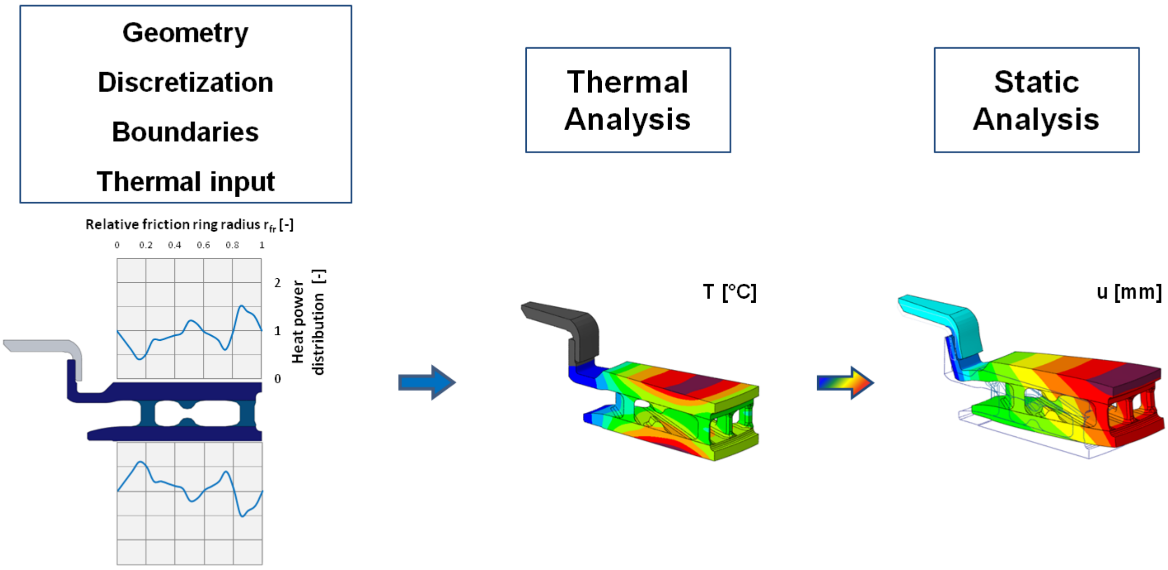

Figure 2: Sequentially coupled thermal-stress analysis (method A)

The distribution has been derived from experimental tests. In the following a static, mechanical analysis uses the resulting temperature fields as external load. Figure 2 shows compressed the main properties of this method - named as method A in the following. In the early and main development phase, the method described is a very powerful, fast tool.

Regarding the fact that caliper geometry is not available in this phase, the prediction of temperature and deformation as well is quite good. Further discussions will be made along with the results in chapter 4.

3.2 Stress analysis with a brake system model

The system boundary has to be chosen carefully to detect the relevant phenomena, although the calculation efficiency should not be influenced. Hence, for the static, mechanical analysis the dynamometer setup is modelled, the brake pads and the brake caliper. Here the temperature fields are regarded as external load. The main parts, except the dyno, are shown in figure 3.

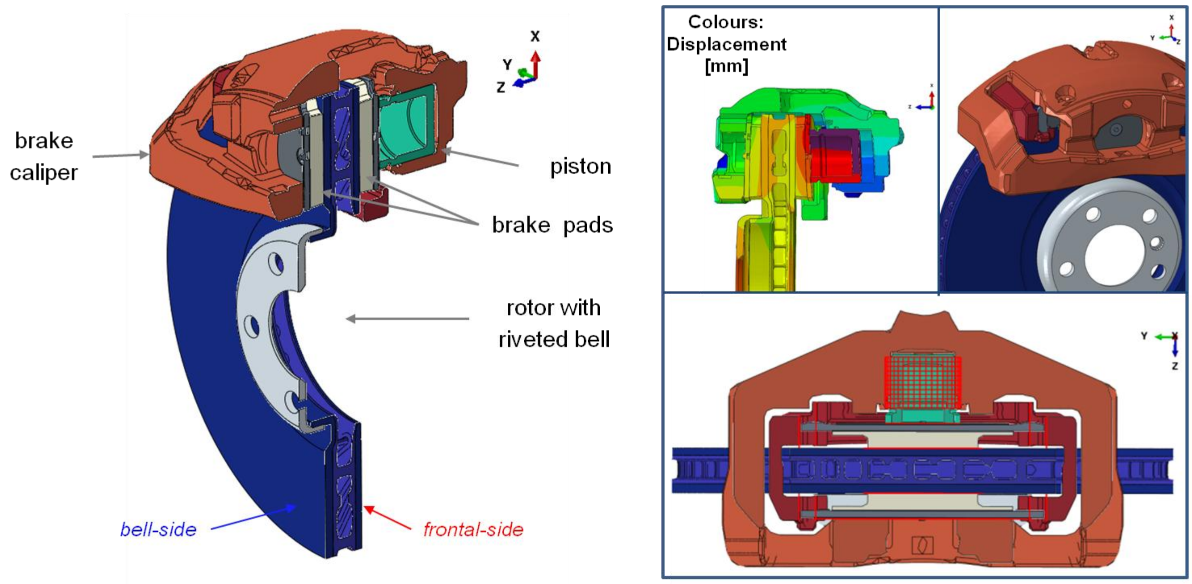

Figure 3: Brake system model in FE (overview and details)

The model includes many contact pairs, e.g. between (red lines in Fig. 3, details at the bottom):

- piston vs. brake caliper
- piston vs. brake pad
- brake pads vs. brake disc
- brake pads vs. brake caliper

In the key contact pair between brake pads and brake disc is assumed that the rotation of the disc is specified as a predefined field on the disc surface, with a controlled amplitude. In this case it is assumed that the slip velocity follows from the difference in the user-specified velocities and is independent of the nodal displacements [1]. The frictional sliding between the two deformable bodies is defined by the Coulomb friction. The friction coefficient as key feature is velocity-, pressure- and temperature-dependent. Therefore a complex measurement process was developed at reduced pads [14]. Additionally a preconditioned pad configuration is considered using a wear simulation. The brake pressure is applied at the piston bottom and leads to a specific contact pressure distribution at the pads, due to the system boundaries (see

Fig. 3, on top left in the details). That pressure in combination with the friction coefficient and velocity at each node results in a global brake moment. Because of the decreasing friction coefficient at high temperature an unsteady moment is expected. Thus, a feedback control of the brake pressure is implemented. Further assumptions are the temperature-dependent material properties with thermal and elastic/plastic behaviour are taken into account.

3.3 Normalized power distribution derived from contact pressure distribution

Concerning the mechanical-thermal interaction the key link is the heat power distribution. The stress analysis, as described in the previous subchapter, supplies the results needed. In particular the contact pressure distribution is used to generate a new heat power distribution. Figure 4 shows the principle procedure.

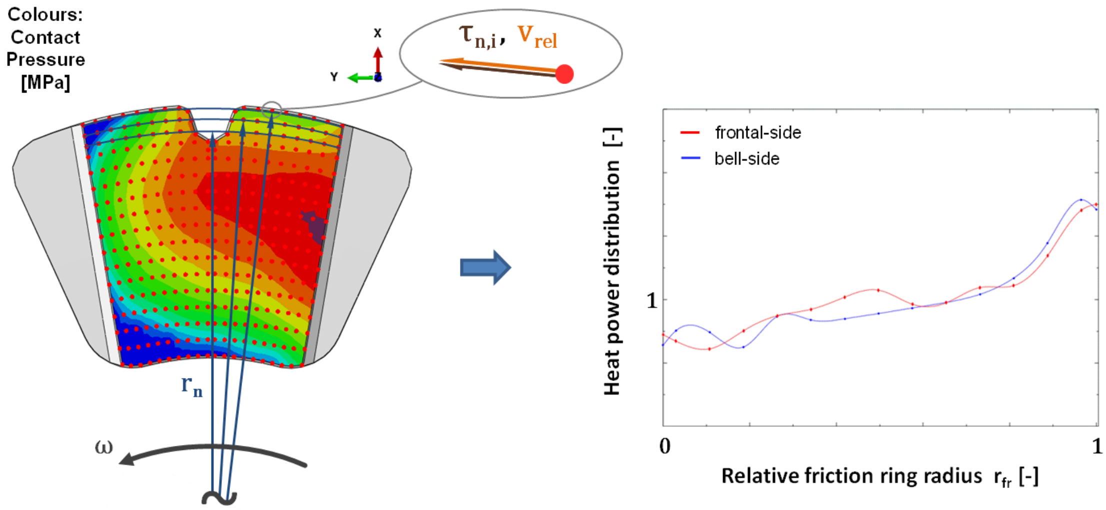

Figure 4: Postprocessing procedure leading to heat power distribution

The specific power per node is calculated by:

$$P_{spec,n} = \vec{\tau}_{n,i} \cdot \vec{v}_{rel} \tag{1}$$

Because of the collinear vectors of the shear stress and circumferential velocity their absolute values can be multiplied [15]. Then a postprocessing uses the following mathematical relations, concerning the specific power for a node row in circumferential direction.

$$P_{spec,n} = \sum_{i=1}^{j} \tau_{n,i} \cdot \omega \cdot r_n \tag{2}$$

This calculation needs to be done for the bell- and the frontal-side of the brake disc. Afterwards a normalized heat power distribution is determined, by assuming that the included area of both pad side curves is two (see Fig.4, right). Considering that the shear stress is dependent on the pressure and the friction coefficient, the heat power distribution is found as a function of the friction ring radius [15,16]. Hence, the key assumptions and procedures are described, that are used for the new approach.

3.4 Approach of the incremental, sequentially coupled thermal-stress analysis

The described simulation parts are combined into a new simulation method (method B). The brake system model as described in chapter 3.2 is used for a static, mechanical analysis with temperature fields as external load. The pure thermal analysis is performed at the brake disc segment. Both of this analysis processes alternate and are carried out as an incremental sequentially coupled thermal-stress analysis. In order to calculate an entire brake event ten incremental steps are proposed. This method has been performed in automated operations, by using several scripts.

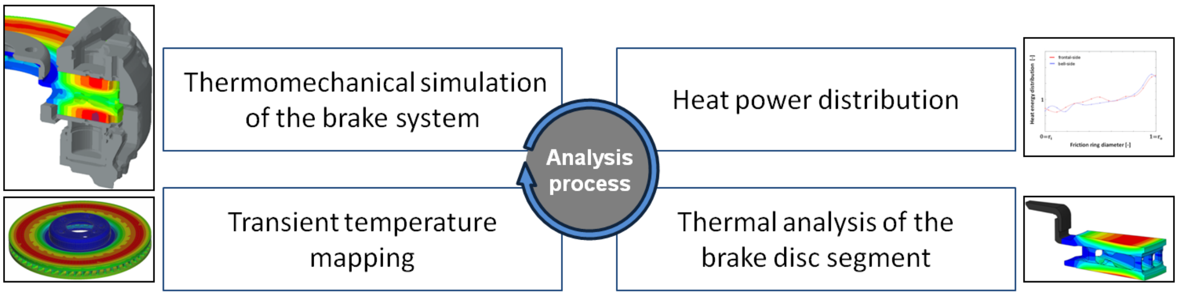

Figure 5: Incremental, sequentially coupled thermal-stress analysis

On the one hand the updated power input distribution takes the brake system characteristic into account, resulting in a differentiated temperature field in the brake disc. On the other hand, a complete thermal-stress analysis is generated, taking the thermomechanical interactions into account.

4 COMPARISON OF SIMULATION AND TEST RESULTS

In the following chapter the comparison of deformation and heat power distribution of the brake disc is focused.

4.1 Resulting deformations and stresses

Method A, assuming the cyclic symmetry, has a good agreement concerning the maximum deformation value.

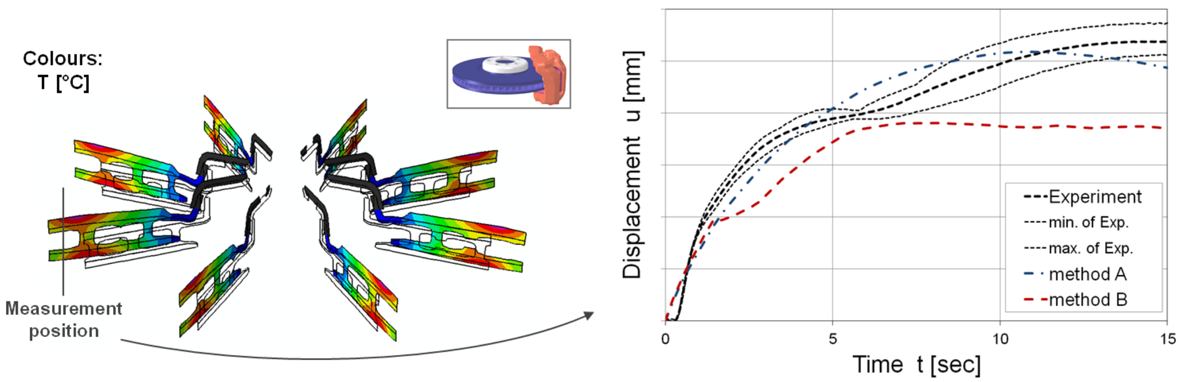

Figure 6: Distribution (method B) and maximum results of the deformation

In comparison, the analysis at the brake system (method B) shows the specific deformation behaviour (see Fig. 6, left). In opposite of the caliper the location of maximum disc deformation value is found. This is in good agreement with test results.

Figure 6 shows the deformation distribution and the maximum results of method A and B in comparison with dynamometer results. The inflection of the experimental deformation curve at 5 seconds brake time, can be explained by the dynamic interactions during the brake event. The new simulation method B enables a more differentiated investigation of the deformation behaviour. However, it is supposed to enhance simulation parameters concerning the dynamometer setup, due to a better prediction of absolute values.

The location and type of the maximum stresses is very well known and investigated [16,17,18]. Circumferential compression occurs in the brake disc during the brake event, leading to residual stresses in the cooling phase. These are highly influenced by the highest temperature, which both methods could indicate. Additionally, method B shows a mechanical, superimposed stress, caused by the alternating deformation under the brake caliper.

4.2 Heat power and temperature distribution

The heat power distribution can hardly be measured by a test method. Hence, the results have to be compared regarding the temperature distribution. Therefore a dynamometer test with eight thermocouples at each side (bell- and frontal-side) has been made (randomized thermocouple distribution, see figure 7, top on the right). Two heat power distribution diagrams (see figure 7, left) show the development during the first incremental steps of the coupled process. On the right, the resulting temperature distributions of the brake disc surfaces are shown, depending on the brake disc radius.

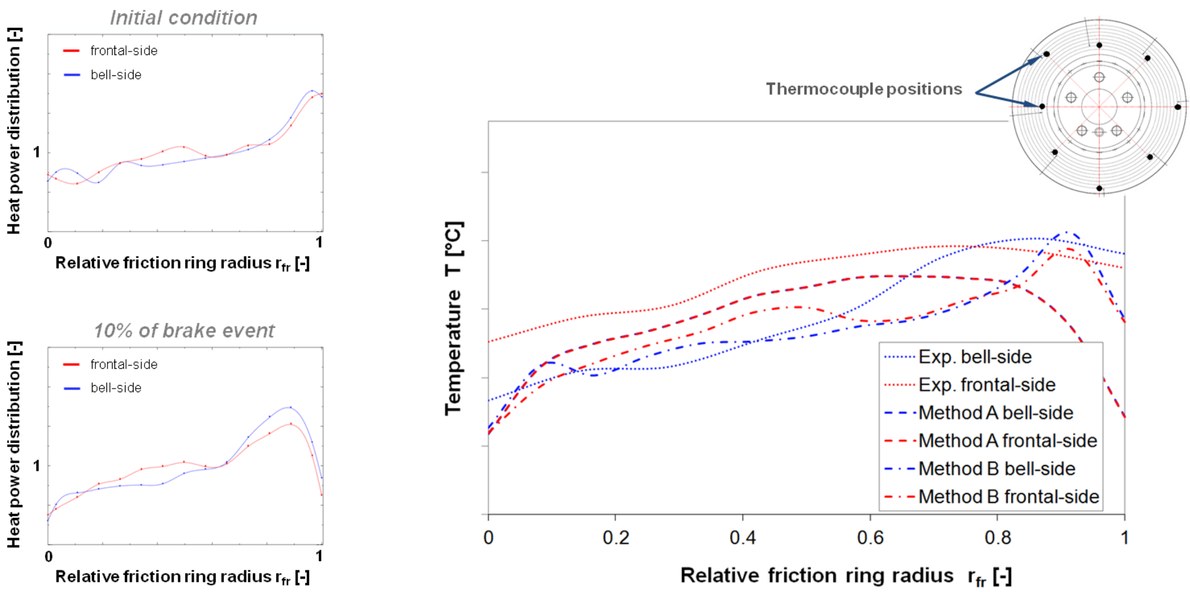

Figure 7: Heat power and temperature distribution of the brake disc

Due to the incremental, sequentially coupled analysis the power distribution, differs between the frontal- and bell-side of the disc. With method B it is possible to determine the higher impact on the outer radius. For further improvement of the validation the measurement process has to be reviewed. Some researchers introduced new measurement methods with extra sensitive thermocouples in application at brake pads, so that the highly dynamic temperature distribution could be indicated [5,19].

5 CONCLUSIONS AND FUTURE WORK

In this paper the development of an incremental, sequentially coupled simulation method is introduced. In order to fulfil the demand of the development process, the method enables the comparison and performance prediction regarding the influence of brake calipers. In addition the mechanical loads are taken into account, due to the brake pressure and the brake moment. In conclusion, the incrementally updated normalized power distribution is derived from contact pressure distribution of a complex system model. That leads to a new temperature distribution in the brake disc, depending on the system boundaries of the thermal calculation.

The new simulation method reveals high potential, concerning the thermal and mechanical behaviour of the brake disc regarding the thermomechanical influence of the entire brake system. That leads to an improved understanding of the basic mechanical characteristics of brake discs and thus gives the knowledge for a straight forward development of new brake disc concepts. Also an assessment of varying caliper geometries is possible. However, the method has potential for development concerning the prediction of absolute values. Consequently this process has to be advanced and more verified regarding the following subjects:

- thermomechanical stresses under repeated braking (settled stress-strain behaviour)
- fatigue analysis with dedicated material model

With this CAE process further potential to reduce weight, or increased performance of brake systems can be utilized.

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