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Experimental Stress Analysis

Influence of thermoelastic instabilities on thermal stresses in brake discs

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Abstract: Thermoelastic instabilities occur in frictional systems, for example in braking systems. They manifest themselves as a local intensive temperature increase, so called hot-spots, and it is accompanied by other unwanted processes, for example by vibrations or intensive wear of friction components. This contribution deals with analysis of thermal stresses in brake discs caused by occurring thermo-elastic instabilities. The analysis is based on a brake disc temperature measurement during braking. The thermal stresses are then evaluated employing the measured temperatures and numerical thermo-mechanical analysis by the finite element method. It is shown that hot-spots cause local stresses, that can achieve yield or strength limits of given material in some cases.

Keywords: Thermoelastic instabilities, Disc brakes, Temperature measurement, Stress modelling, Finite element method

1. Introduction

Thermoelastic instabilities (TEI) occur in high-speed friction systems, for example in disc brakes or transmission clutches. This undesirable effect manifests itself by non-uniform distribution of contact pressure leading to the origination of so called hot-spots, i.e. places with local intensive temperature increase. If the sliding velocity is high enough, this effect can become unstable and can result in frictional vibration, material damage, excessive wear, and brake fading. Barber has named thermoelastic instability a cause of such effects [1].

The origination and development of hot-spots is a complex problem and it is influenced by many factors - material thermal and mechanical properties, sliding velocity, contact area, size and mounting of components and others. Therefore, it is very complicated to describe and to solve this problem mathematically - experimental methods [2,3] play an important role in TEI investigation. However, mathematical modelling has brought a fundamental contribution to the understanding of TEI origination and its subsequent behaviour. Dow and Burton [4]

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introduced a mathematical model to establish critical sliding velocity for instability for two thermoelastic half-spaces. Consequently, Lee and Barber [5] brought an analytical periodical solution that involves the disc with a finite thickness, clamped between halfspaces, and Voldrich [6] proposed an approach that reduces the difficulty of intermittent contact between the disc and pads (the friction pads occupy only a part of the disc circuit). Further progress was achieved by using the finite element method and by solutions based on solving an eigenvalue problem [7,8].

We are interested in determining the influence of thermoelastic instabilities on mechanical stresses in brake disc. Due to complexity of this problem it is generally not possible to apply pure theoretical or experimental solution. However, we believe that combination of temperature measurement and subsequent finite element (FEM) thermo-elastic analysis can bring interesting information on temperature distribution, thermo-elastic stresses and brake disc deformation during braking. We have measured temperature field on disc friction surfaces during braking. The measured temperature data were subsequently used as a boundary condition for transient thermal and thermo-elastic analysis. In spite of some limitations of this approach, we can obtain useful information about thermal stresses caused by hot-spots or brake disc deformation during braking.

2. Experimental investigation of thermoelastic instabilities

A special measurement system for the investigation of thermoelastic instabilities in automotive disc brakes has been developed in the authors' laboratory. The schematic arrangement is shown in Fig.1.

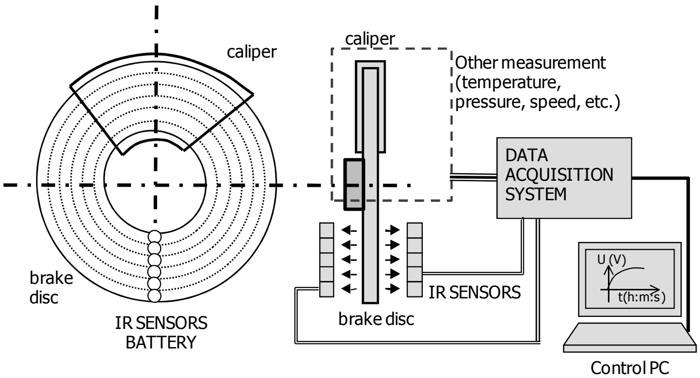

Fig. 1. Schematic arrangement of the measuring system for the temperature measurement on disc brakes.

The measurement system is based on one-colour infrared (IR) detectors used for disc braking surface temperature measurement. The sensors are equipped with a thermal barrier protection and an air supply for their cooling and cleaning and they are placed close to the disc surface. Small dimensions of the sensors enable their grouping into a battery, consisting of six sensors. The temperature is measured on both sides of the disc in various diameters from the disc rotation axis using a pair of such batteries.

The sampling frequency of the temperature measurement is up to 10 kHz and the measurement system can be used on a brake testing rig or directly on a car. The measurement system is further equipped by other sensors providing measurement of disc position and velocity, pressure in braking system, average temperature etc.

3. Thermal stresses numerical analysis

The finite element method (FEM) is used for the thermal and thermo-mechanical analysis of the brake disc. A complete three dimensional model of the brake disc was built and solved by the FEM code written in Python [9]. Using our own FEM code has brought some advantages in comparison with standard commercial FEM systems, as it allowed a more efficient processing of large measurement data (temperatures) and their use in the analysis as the Dirichlet boundary condition. The finite element model is showed in Fig.2

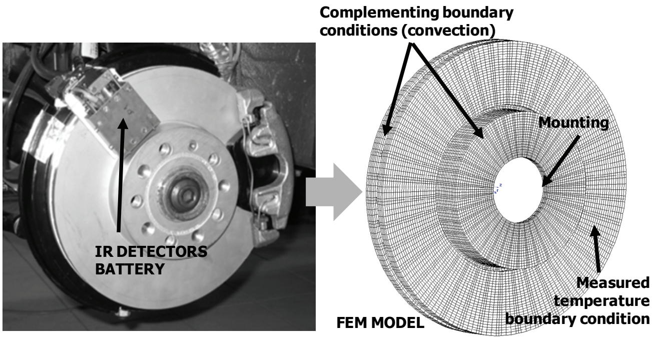

Fig. 2. Installation of the measuring system on the test car and the finite element model.

3.1. Thermal analysis of the brake disc

The temperatures are sensed at one angular position relative to the calliper. Therefore, the data are transformed first to obtain a temperature field of the brake disc surface at one evolution. The measured temperature fields are interpolated into the surface FE mesh nodes and then used as the Dirichlet boundary conditions at each time step for the numerical thermal analysis. The boundary conditions were completed by convective cooling of the brake disc and a standard transient heat transfer problem

$$\frac{\partial T}{\partial t} - \Delta T = 0 \,, \tag{1}$$

where T is temperature and t is time, was solved using the FEM.

It is necessary to point out, that it is not a true temperature field, because the temperature decrease during the pad-to-pad cooling interval is not assumed. This is the principal difference in comparison with an image of the disc temperature field provided by a fast infrared camera in one moment. However, we believe, that this approach is more suitable for the investigation of hot-spots phenomena, because the evaluated temperature field in not affected by the previously mentioned periodic heating and cooling of the disc during braking.

3.2. Thermal stresses in brake disc

The results of the previous thermal analysis, i.e. the temperature field in the brake disc at each time step, were used as the thermal-load condition for the subsequent mechanical analysis. The quasi-stationary linear elastic problem with thermal loads for each step described by the constitutive relation

$$\sigma_{ij} = D_{ijkl} e_{kl}(u) - (3\lambda + 2\mu)\alpha\delta_{ij}(T - T_0) \qquad (2)$$

was also solved using our FEM code in Python [9]. In Eq.(2) there are σ - stress, e – deformation, u – displacements, λ,μ - Lame's constants, α - thermal expansion modulus, δ - Kronecker's symbol, T - actual temperature, T_0 – initial temperature and D is the elastic tensor

$$D_{ijkl} = \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) + \lambda\delta_{ij}\delta_{kl}\,. \qquad (3)$$

Results of the thermo-mechanical analysis are stress, strain and displacement fields for each time step.

4. Results

In the authors' laboratory, an extensive research with a number of experiments with brakes has been conducted on brake testing rig, as well as on a car. The origination and further development of thermoelastic instabilities depends on many factors of braking process: components design and materials, sliding speed etc.

Two examples of the surface temperature field during braking on a standard cast-iron automotive brake discs with a diameter about 300 mm can be seen in Fig.3: "uniform" temperature field (sample A) and hot-spots caused by the thermoelastic instabilities (sample B).

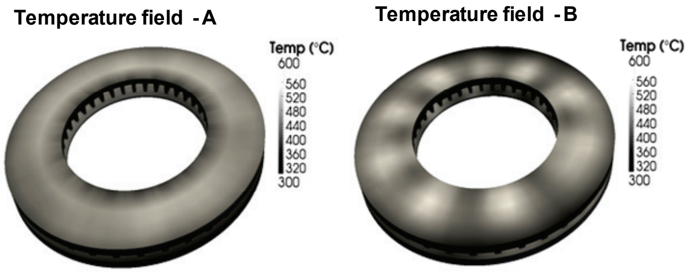

Fig. 3. Examples of brake disc temperature fields obtained by FEM thermal analysis - uniform temperature (A) and hot-spots structure (B).

No local spots with significantly different temperature in circumferential direction can be found in the temperature field of the sample A. On the other hand, local temperature differences on the sample B caused by hot-spots can be nearly 100 °C. However, some long-scale temperature differences can be found in the case of both samples A and B.

As the differences in temperature fields for "uniform" and "hot-spot" structure are evident, also the differences in stress field are observed. The radial stresses obtained by the FEM thermo-mechanical analysis are shown in Fig.4.

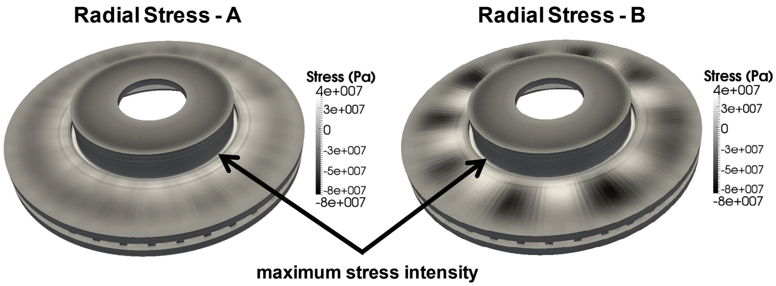

Fig. 4. Examples of brake disc stress fields (radial stress) obtained by FEM thermo-elastic analysis - uniform temperature (A) and hot-spots structure (B).

The stress field on the sample A is almost uniform in circumferential direction. In the case of the sample B, regions of higher stress corresponding to hot-spots occurrence can be found. However, the local differences of the stress field are not as high as in the case of the temperature fields, as can be also seen from temperature and von Mises stress path graphs in Fig.5.

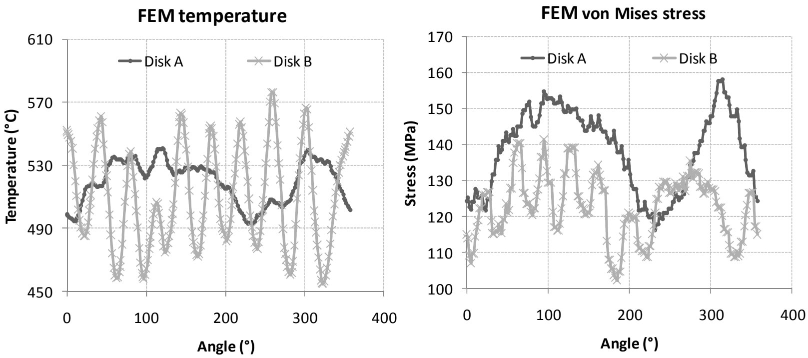

Fig. 5. Path graphs of the temperature and Von Mises stress in circumferential direction at the centre of the braking surface.

The average von Mises stress level at the braking surfaces is about 130 MPa - that is about one half of the strength limit of the cast iron at room temperature. The local stress intensity differences are about 20 MPa, however, significant long scale (the disc circumference) differences about 30 MPa are evident. The highest stress intensity can be found at the connection of the braking and mounting part of the brake disc (see Fig.4). This is caused by higher temperature of the braking part of the disc compared with the mounting part. The hot braking part tends to expand but it is fixed by the cold mounting part. Due to this, high stresses up to 200 MPa occur at their interface.

5. Conclusions

Experimental results and performed numerical computations showed, that thermoelastic instabilities can cause significant local temperature increase, so called hot-spots. The temperature of hot-spots can be higher by up to 100 °C in some cases. The thermoelastic instabilities cause also local stress deviations, although the local stress intensity differences are not as pronounced as temperature differences and long-scale stress and displacement differences seem to be more significant. However, continuing the braking process causes further maximum hot-spots temperature increase connected with a decrease of material yield/strength limits. An occurrence of nonlinear deformation processes is therefore possible.

Acknowledgements

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References

[1] Barber J.R., “Thermoelastic instabilities in the sliding of conforming solids,” *Proc. of the Royal Society of London A*, **312**(1510), pp. 381-394 (1969). ISSN 1471-2946 (Online).

[2] Panier S., Dufrenoy P. and Weichert D., “An experimental investigation of hot spots in railway disc brakes,” *Wear*, **256**(7-8), pp. 764-773 (2004). ISSN 0043-1648.

[3] Litos P., Honner M., Lang V., Bartik J. and Hynek M., “A measuring system for experimental research on the thermomechanical coupling of disc brakes,” *Journal of Automobile Engineering, Part D*, **222**(7), pp. 1247-1258 (2008). ISSN 0954-4070.

[4] Dow T.A. and Burton R.A., “Thermoelastic instability of sliding contact in the absence of wear,” *Wear*, **19**(3), pp. 315-328 (1972). ISSN 0043-1648.

[5] Lee K. and Barber J.R., “Frictionally excited thermoelastic instability in automotive disk brakes,” *ASME Journal of Tribology*, **115**(4), pp. 607-614 (1993). ISSN 0742-4787.

[6] Voldrich J., “Frictionally excited thermoelastic instability in disc brakes - Transient problem in the full contact regime,” *International Journal of Mechanical Science*, **49**(2), pp. 129-137 (2007). ISSN 0020-7403.

[7] Yi Y.B., Barber J.R. and Zagrodzki P., “Eigenvalue solution of thermoelastic instability problems using Fourier reduction,” *Proc. of the Royal Society of London A*, **456**(2003), pp. 2799-2821 (2000). ISSN 0043-1648.

[8] Zagrodzki P., “Thermoelastic Instability in Friction Clutches and Brakes – Transient Modal Analysis Revealing Mechanisms of Excitation of Unstable Modes,” *Int. J. Solid and Structures*, **46**(11-12), pp. 2463-2476 (2009). ISSN 0020-7683.

[9] Cimrman R. et.al., “SfePy: Simple finite elements in Python,” *Available from* http://sfepy.org *Accessed:* 2010-04-13.