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Efficient computation of thermoelastic instabilities in the presence of wear

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ABSTRACT

Thermoelastic instabilities in tribological systems, such as brakes or clutches, appear in the shapes of Hot Bands and Hot Spots. Focused temperatures increase as a result of an instability mechanism caused by interactions among displacement, temperature fields and friction-induced heat. To compute this phenomenon, detailed multi-dof-models, e.g. finite element analysis, and two-dimensional minimal models are currently available.

The presented approach provides a three-dimensional model that directly satisfies the field equations and relevant boundary conditions. Avoiding a spatial discretization finer than single bodies allows for an effective solution of the system. The application of this technique is demonstrated with a conventional disk brake system example, comprised a backplate, a friction material and a disk with cooling vents and vanes. For this example, a new approach is suggested to compute rigid body motions of the brake pad. The system is analyzed in terms of critical sliding velocities and thermal mode shapes. Parameter studies are performed to determine the influences of wear and friction material parameters.

1. Introduction

In brake or clutch systems, considerable amounts of mechanical energy are converted into thermal energy by friction. One design aim for such systems is a uniform spatial temperature distribution in the frictional plane, and the avoidance of thermal localizations. High peak temperatures between the two bodies can lead to friction-induced vibration and material disruption in the frictional plane, reducing the lifetime of the system. Different types of thermal localizations have been categorized in [1].

Some of these phenomena can be explained by thermoelastic instabilities (TEI) [2], where the temperature on the sliding surface rises locally, thermal material expansion leads to a small bulge. This bulge contacts the counterbody, and the normal contact stress increases, causing more regional heat generation. In the present study, two geometries of TEI-induced thermal localizations will be under investigation: Hot Bands and Hot Spots. In the case of Hot Spots, a temperature field of e.g. an automotive brake disk typically shows 5–10 temperature maxima and minima on its circumference. When come into contact with the brake pad, a noise called Hot Judder is generated, whose frequency is proportional to the number of Hot Spots and the sliding velocity [3]. When the same system shows Hot Bands, a circular ring of increased temperature is observed. The radial width of this ring is clearly smaller than the radial width of the sliding path. As the ring carries most of the frictional load, it determines the effective frictional radius. When a Hot Band migrates radially on a brake disk, the resulting brake torque is directly affected. Models mentioning influences on this radial migration can be found in [4,5]. Periodic radial motion of Hot Bands is addressed by the models in [6–8].

Typically, each brake system has a critical sliding velocity, below which, no Hot Bands or Hot Spots develop, and above which, the system shows these unwanted thermal localizations. Different models are available today to compute the occurrence of TEI. Detailed three-dimensional models can be developed using the Method of Finite Elements, e.g. [9–14]. To reduce the required computational effort, different reduction strategies are possible. The expected temperature field for Hot Spots is typically harmonic in the circumferential direction; it can be directly addressed using a harmonic ansatz. Consequently, no discretization in the sliding direction is required [15]. The numerical task is minimized further, if thermoelastic plate theories are applied [16,17]. Here, a spatial discretization is still required in the radial direction.

Whenever a discretization technique is applied, regardless of whether it is in the time or spatial domain, the required computational time exceeds the computational time of a model without such discretization. Therefore, for the process of finding optimal parameters for a brake or clutch system, models that avoid

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discretizations finer than the size of bodies of the system are valuable. Models of this kind have been suggested for brake systems in [18,19], using a single harmonic ansatz function according to the approach in [20]. These models reduce the system in question to a two-dimensional system, neglecting the influence of the radial direction. Consequently, the radial shape of Hot Spots is not addressed, and Hot Bands cannot be investigated. To address this, the harmonic ansatz can potentially be applied in the sliding direction and the radial direction. This enables a new model that covers both Hot Bands and Hot Spots, and their respective combination.

2. Model

The following model development focuses on a conventional disk brake system, in an automotive application. It is possible to apply this modeling strategy to systems of other geometries, such as drum brakes or clutches.

A computation of thermoelastic instabilities requires the solution of thermoelastic and thermal field equations, formulated as a set of coupled Partial Differential Equations. For a circular body, such as the brake disk, these field equations contain a nonlinearity in the radial direction [21]. This nonlinearity can be more readily analyzed with the help of Bessel functions, but the radial dependence of the sliding velocity in the contact prevents an analytical fulfillment of the boundary conditions in the contact.

If the curvature of the brake disk is not considered, a linear behavior in the radial direction is obtained, which allows for a periodic ansatz in the radial direction. Neglecting the curvature of the disk can lead to a system with a slightly different critical sliding velocity. An analysis of the studies published in [22] suggests that for typical brake disk geometries, the error in critical sliding velocity between the system including the curvature and the system without curvature is less than 10%. This difference seems to be acceptable in comparison with the error in critical sliding velocity between model-based predictions and experiments.

In the following, the Cartesian x-, y-, z,-coordinate system is applied, where positive x is in the sliding direction, y is the direction normal to the contacting surfaces and z is normal to x and y, as illustrated in Fig. 1. The sliding velocity, v, in the contact is assumed to be independent of the radial position. Here, the sliding path length on the disk, C, is determined by the effective frictional radius.

The fields in the system under investigation consist of displacements in all three directions and the temperature distribution. Their values form the state vector of the system:

$$\begin{bmatrix} u_x(x,y,z,t) \\ u_y(x,y,z,t) \\ u_z(x,y,z,t) \\ T(x,y,z,t) \end{bmatrix}_{\text{physical}} = \begin{bmatrix} u_x(x,y,z,t) \\ u_y(x,y,z,t) \\ u_z(x,y,z,t) \\ T(x,y,z,t) \end{bmatrix}_{\text{without TEI}} + \begin{bmatrix} u_x(x,y,z,t) \\ u_y(x,y,z,t) \\ u_z(x,y,z,t) \\ T(x,y,z,t) \end{bmatrix}_{\text{with TEI}} \quad (1)$$

here the physical displacements (physical) and temperatures are expressed by a reference state without TEI (without TEI) and small disturbances of this reference state showing TEI. In this work, only the disturbances are of deeper interest. Therefore, the index “with TEI” is not shown in the following model development.

The system can be divided into two regions: One, where the disk is contacted by the friction material, and a second, where the disk is uncovered. First, we focus on the region where the disk is in contact. If the boundary conditions limiting the system in the x- and z- directions have a minor influence on the TEI-susceptibility, and if the system is assumed to be linear in time and space, a solution in the form

$$\begin{bmatrix} u_x(x,y,z,t) \\ u_y(x,y,z,t) \\ u_z(x,y,z,t) \\ T(x,y,z,t) \end{bmatrix} = \begin{bmatrix} \tilde{u}_x(y) \\ \tilde{u}_y(y) \\ \tilde{u}_z(y) \\ \tilde{T}(y) \end{bmatrix} \left(e^{j(b_x x + b_z z + Dt)} + e^{j(b_x x - b_z z + Dt)}\right) \quad (2)$$

can be found. Here, j is the imaginary unit, and the behavior in time is determined in the complex variable D. The purely real variables b_x and b_z determine the geometric shape of the field. In the present investigation, it is assumed that Eq. (2) reasonably approximates the real displacement and temperature field. This will later be verified in discussions of Figs. 6 and 7.

For the dependency on the variables in the sliding plane, x and z can be simplified by a coordinate transformation to two rotated coordinate systems, (ξ, y, ζ) and (ξ', y, ζ'), where the axial coordinate y remains unchanged. This is a transformation of two intersections in the contact, where the intersection for $+\varphi$ is shown in Fig. 1. These intersections are rotated around the y-axis by angles $+\varphi$ and $-\varphi$ with respect to the sliding direction.

When the two new parameters φ and β satisfy

$$b_x = \beta \cos(\varphi)$$
$$b_z = \beta \sin(\varphi), \quad (3)$$

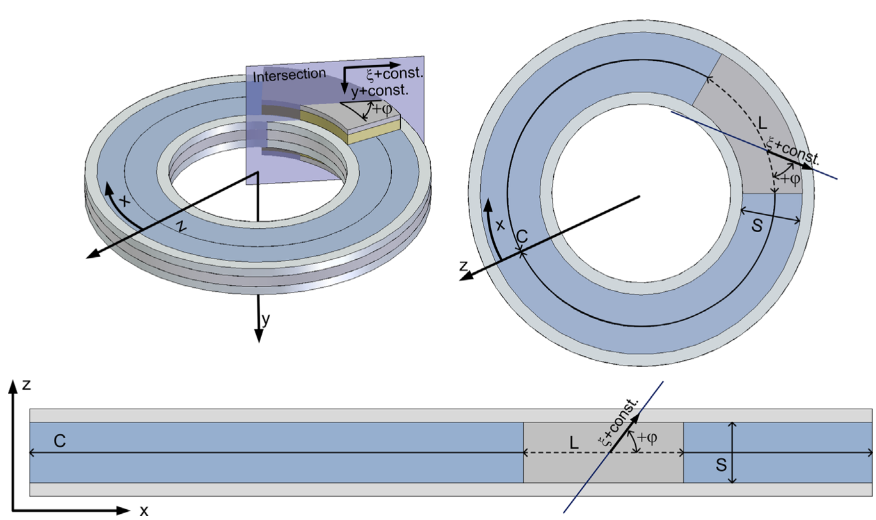

Fig. 1. System in Cartesian coordinates. Visualization as a closed ring indicates periodic boundary conditions in the x-direction. Intersection introduced in the contact at angle $+\varphi$. Not shown: Intersection at angle $-\varphi$.