

Wear-Induced Migration of Hot Bands: Models and Comparison with Experiments

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ABSTRACT

Although the radial migration of hot bands has been frequently observed, a systematic investigation of this phenomenon has not yet been performed. The ring-shaped temperature maximum, which occurs on the brake disk, is undesirable because the focused temperatures destroy the local materials in contact. Moreover, a hot band carries a dominant portion of the frictional load. If a hot band moves radially, the braking torque is directly influenced. It is supposed that material wear influences the radial hot band migration.

New models demonstrate that wear is indeed the mechanism that triggers hot band migration. First, a minimal model including thermal expansion and a load-dependent loss of material is introduced. The simplicity of the model allows for an understanding of the impact of wear, as well as the mechanisms that lead to a periodic load distribution. This model can be analyzed in terms of complex eigenvalues, showing a periodic load distribution in the sliding plane. In fact, in some parameter cases, a nonlinear evaluation reveals hot band migrations that an eigenvalue analysis fails to predict.

Secondly, the minimal model is replaced by a model with many degrees of freedom, which is parameterized with respect to an example brake system. A numerical study shows how a hot band migrates periodically inwards and outwards over the disk, leading to braking torque fluctuations. A comparison between the model and experimental results shows quantitative agreement with respect to the amplitudes and frequency of brake torque fluctuations and operating points, where hot band migration occurs.

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INTRODUCTION

In the sliding surface between brake pad and disk, considerable amounts of mechanical energy are transformed into thermal energy. One design aim is to achieve a temperature field on the pad and disk surface, which is as homogenous as possible. Thermal localizations on a macroscopic scale typically appear in two patterns: Hot bands and hot spots [1]. The mechanism leading to local temperature maxima has first been described in [2]. "Thermoelastic Instabilities" arise as a result of the temperature field coupled with the thermoelastic field of the bodies in contact. A local temperature rise in the sliding plane leads to thermal expansion, increasing the local contact pressure. This location is then further heated by sliding friction. The resulting temperature peaks lead to an undesirable increase in material damage and wear, reducing the system's lifetime.

Furthermore, for hot bands, a slow radial migration of the temperature maximum is frequently observed [3,4,5]. As the maximum of the shear pressure, μp , appears at the radial position, r , of the hot band, the resulting braking torque, M_B , of a disk brake is directly influenced. This is made clear in Equation (1), which shows that the braking torque is calculated as an integral over the contact area, A , between pad and disk.

$$M_B = \int_A r \cdot \mu p \cdot dA \quad (1)$$

The radial migration of a hot band is frequently observed as a nearly periodic motion, progressing cyclically from a minimum radius to a maximum radius [6]. The result is a oscillating braking torque, with a typical period on the order of minutes [7].

Although models for hot bands in disk brakes are available, none of them focus on the radial migration of temperature maxima. Only [8] observes a slow change in radial load distribution, but it does not compute one full periodic cycle. A close relation between wear and the radial migration of hot bands is expected [4,9], but still lacks a systematic model-based investigation.

In the following, first a minimal model is introduced, explaining basic interaction mechanisms between wear and thermoelastic instabilities. Secondly, a model with many degrees of freedom (DOF) is discussed, which can precisely reproduce radial hot band migration, as it is observed in experiments.

MINIMAL MODEL

The model under discussion, shown in [Figure 1](#), is inspired by ideas published in [10,11]. It consists of two rods of height h and surface area A , representing two closely neighboring regions of the brake pad. Both have the same behavior with respect to elastic, thermal and tribological parameters. Each rod is loaded with a normal force, N_1 and N_2 , respectively, and slides against a rigid, nonconducting body, with velocity, v , and coefficient of friction, μ .

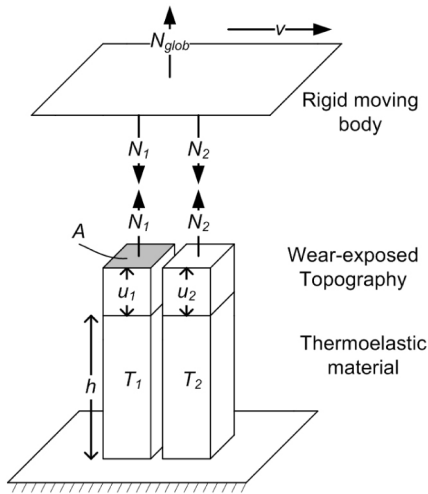


Figure 1. Minimal model consisting of two wear-exposed thermoelastic rods.

The average temperature in rods 1 and 2 can be approximated by [Equations \(2\)](#)

$$\begin{aligned}\dot{T}_1 &= \frac{1}{hA\rho c} (-\mu v N_1 - \lambda h (T_1 - T_2)), \\ \dot{T}_2 &= \frac{1}{hA\rho c} (-\mu v N_2 - \lambda h (T_2 - T_1)).\end{aligned}\quad (2)$$

Consequently, the change rate in temperature is directly influenced by the density, ρ , and the thermal capacity, c . The generated heat is proportional to the contact forces.

Compressive forces are mathematically identified by negative values for N_1 and N_2 . Furthermore, the thermal conductivity between both rods in contact is considered by thermal conductivity, λ . Thermal loss to the system environment can additionally be included, but it has the same effect as heat exchange between the rods, as demonstrated in [11]. Both rods have a wear-exposed layer, of heights u_1 and u_2 , respectively. Their wear behavior can be approximated by [Equations \(3\)](#), with wear coefficient $w > 0$.

$$\begin{aligned}\dot{u}_1 &= v w \mu \frac{N_1}{A}, \\ \dot{u}_2 &= v w \mu \frac{N_2}{A}.\end{aligned}\quad (3)$$

The unknown normal forces must satisfy

$$N_{glob} = N_1 + N_2 < 0. \quad (4)$$

The calculation of N_1 and N_2 depends on whether both rods are in contact with the counterbody, or if one of them loses contact.

If both rods contact the counterbody, they must have equal lengths. This length is a function of thermal expansion, wear and elasticity, and therefore, the following must hold

$$u_1 + \alpha h T_1 + \frac{h}{EA} N_1 = u_2 + \alpha h T_2 + \frac{h}{EA} N_2. \quad (5)$$

When only one rod, index n , is in contact, and the other, index m , is unloaded, the forces are directly defined by

$$\begin{aligned}N_n &= N_{glob}, \\ N_m &= 0.\end{aligned}\quad (6)$$

The system described by [Equations \(2\), \(3\), \(4\), \(5\), \(6\)](#) can be simplified, when only disturbances of a reference state are considered, as [Equations \(7\)](#) indicate.

$$\begin{aligned}T_1 &= T_{ref} + T \\ T_2 &= T_{ref} - T \\ u_1 &= u_{ref} + u \\ u_2 &= u_{ref} - u \\ N_1 &= 0.5 N_{glob} + N \\ N_2 &= 0.5 N_{glob} - N\end{aligned}\quad (7)$$