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Spatio-temporal identification of heat flux density using reduced models. Application to a brake pad

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ABSTRACT

The identification of the spatio-temporal variations of a heat flux density field is addressed in this paper. The developed technique combines the use of reduced models (BERM method) with an iterative method of conjugate gradient descent, for which the gradient is estimated by the adjoint method. The application relates to the identification of the heat flux received by a brake pad in a braking situation, for which the mechanical deformation and the phenomena of wear cause the appearance of hot spots that one seeks to locate. The use of two different Branch bases, one for the temperature field and the other for the heat flux, enable to identify rapidly the time-space variation of the heat flux, without any hypothesis on the spatial form on it.

1. Introduction

In the field of transportation, braking is a major problem. The goal is to acquire a systematic reliability with an acceptable cost.

A difficulty of this type of problem is knowing the heat flux generated at the interface between the pad and the disk, and the way in which it is distributed. With the actual computing resources, numerical studies concerning thermomechanical coupling have been carried out [1–5], and show that the mechanical deformations generate a spatial distribution of the pressure which is not regular, and which varies according to the time and the scenarios of load and speed.

Moreover, to these mechanical deformations are added phenomena of rupture (tearing of particles), physicochemical reactions (phase changes), and the presence of adhesion forces (attraction forces of the atoms of the two surfaces in contact with each other). The characterization of the coefficient of friction is generally done empirically, from tribological or chemical analyzes during experimental tests [6–9].

Finally, the particles which are torn off the pad during the braking contain some of the energy generated by the friction and can be trapped between the disk and the pad, and form a bed of debris that is ejected from the friction interface according to a speed whose profile can be complex [10,11].

So the experimental observation is particularly important, but then, major difficulties arise, related on the one hand to the movement of the disc, and on the other hand to the non-accessibility of the contact zone between the disc and the pad. The attempts made preferentially pass through the pad. Thus, Qi et al. [12] propose to insert thermocouples through the pad to reach the contact zone. Tests using a glass disk to visualize the phenomena of friction have been conducted [7]. Following the same idea, Majcherczah et al. [13] perform an experimental setup in which a metal ring abrades a sapphire ring. The interface temperature measurements produced, although imprecise, showed the appearance of hot spots on the surface of the rotating disc.

All these solutions remain very difficult to implement, and finally, the most common solution is to make temperature measurements in the brake pad at a well-defined distance from the contact zone, then to go up by inverse procedure to the zone of contact. Saric et al. [14] therefore implant 15 thermocouples at 7 mm from the surface and 5 thermocouples at varying depths of 2–10 mm from the friction zone. Siroux et al. [15] perform temperature measurements at different depths (2, 5 and 7 mm). Wong [16] implants up to 36 thermocouples in the brake pad.

With regard to the inverse problem, many studies have been carried out. From artificial measurements simulated by a numerical model, Bauzin et al. [17] go back to the estimation of the coefficient of friction and the parameters which characterize a model of distribution of the flux generated. Chen et al. [18] proceed to the estimation of the flux generated by friction between two

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cylindrical bars. Yang et al. [19] identify the distribution of the flux received by the disk. The data is obtained from direct simulations by fixing a radial evolution of the flow proposed by Choi [2]. The use of the inverse technique allows Quéméner et al. [20] to find the temporal evolution of a heat flux generated by the friction of a pawn on the edge of a rotating disk. Quéméner et al. [21] also propose the experimental identification of the heat flux received by a brake pad and the flux received by the disk for a real-life configuration of a car braking system.

Nevertheless, all these studies remain a simplification of the reality, because one fixes a supposedly known spatial evolution of the heat flux density according to a simple law (often a linear evolution according to the radius of the disk), and where only the temporal evolution of this field is sought. But in reality, given the thermo-mechanical deformations and the phenomena of wear and tearing of materials on the brake pad, the distribution of the generated flux density is complex and difficult to predict. The idea is then to seek to identify the spatio-temporal evolution of the flux density received by the brake pad, from simple temperature measurements. The method of identification used in this study is the Adjoint Method and a reduced modal model (Branch Eigenmodes Reduction Method) is used to overcome the large sizes of matrices related to the three-dimensional geometry of the brake pad.

2. Physical problem

We consider a car brake pad for which the complexity of the geometry is respected (Fig. 1). It is composed of two materials: the brake lining and its metallic support, whose characteristics are presented in Table 1. This brake pad undergoes three types of boundary conditions (Fig. 1):

- The surface Γ_1 in contact with the disk receives a heat flux density $\varphi\,[\mathrm{W}\cdot\mathrm{m}^{-2}]$ which varies in space and time.
- On the boundary Γ_2, we consider a convective exchange with the external environment whose temperature is $T_{ext} = 0\,°\mathrm{C}$, with a stationary exchange coefficient $h = 20\,\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}$.
- For the back Γ_3, the brake pad is considered perfectly isolated from the brake caliper and piston assembly.

The system of equations describing the thermal problem is then written (with $\Omega = \Omega_1 \cup \Omega_2$):

$$\begin{cases} \forall M \in \Omega,\, t > 0 & c\frac{\partial T}{\partial t} = \vec{\nabla}\cdot\left(k\vec{\nabla}T\right) \\ \forall M \in \Gamma_1,\, t > 0 & k\vec{\nabla}T\cdot\vec{n} = \varphi(M,t) \\ \forall M \in \Gamma_2,\, t > 0 & k\vec{\nabla}T\cdot\vec{n} = -hT \\ \forall M \in \Gamma_3,\, t > 0 & k\vec{\nabla}T\cdot\vec{n} = 0 \\ \forall M \in \Omega,\, t = 0 & T = T_0 = 0 \end{cases} \tag{1}$$

Table 1
Physical parameters of the brake pad.

Domain	Ω_1	Ω_2
Thermal conductivity $k\,[\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}]$	4	50
Volumetric specific heat capacity $c\,[\mathrm{J}\cdot\mathrm{m}^{-3}\cdot\mathrm{K}^{-1}]$	1.828×10^6	3.393×10^6

The direct problem therefore consists in searching the evolution of the temperature field at any point of the brake pad for a braking scenario characterized by a heat flux density dissipation $\varphi(M,t)$. The inverse problem here is to find $\varphi(M,t)$ from measurements given by one or more temperature sensors in the pad.

Given the complexity of the geometry, the resolution of the problem whether direct or inverse is done numerically from a spatial discretization. We use here the finite element method (fem) which is based on the variational formulation of the problem posed (Eq. (1)):

$$\int_\Omega cg\frac{\partial T}{\partial t}d\Omega = -\int_\Omega k\vec{\nabla}g.\vec{\nabla}Td\Omega - \int_{\Gamma_2} ghTd\Gamma + \int_{\Gamma_1}\varphi(M,t)g\,d\Gamma \tag{2}$$

where $g \in H^1(\Omega)$ is the test function.

The discretization is carried out using tetrahedrons for which we consider linear interpolation laws (P1 type elements). The variational problem (Eq. (2)) is then written compactly, respecting the order of the different terms:

$$\mathbf{C}\dot{\mathbf{T}} = \mathbf{A}\mathbf{T} + \mathbf{U}(t) \tag{3}$$

where $\mathbf{C}$ and $\mathbf{A}$ are respectively the capacitance and conductance matrices, of dimension $[N_{mesh}\times N_{mesh}]$ with N_{mesh} as the number of degrees of freedom of the discretized domain. $\mathbf{T}$ and $\dot{\mathbf{T}}$ are the vectors of temperature and derivative of the temperature as a function of time. The last term $\mathbf{U}$ $[N_{mesh}\times 1]$ corresponds to the spatial distribution of flux density on the boundary $\varphi(M,t)$. This relationship is the so-called complete thermal problem that we generally seek to solve, and whose spatial dimension can be very large in the case of a complex geometry. For the configuration studied, a sensitivity analysis leads to a mesh containing $N_{mesh} = 67\,353$ nodes (Fig. 2).

For the inverse problem, the identification of the flux density $\varphi(M,t)$ is carried out starting from $N_{meas} = 50$ measuring points distributed uniformly in the brake lining at a depth of 3 mm of the interface between the disk and the brake pad (Fig. 3). By choosing a measurement time step $\Delta t = 1$ s, N_t temperature values are obtained for each sensor.

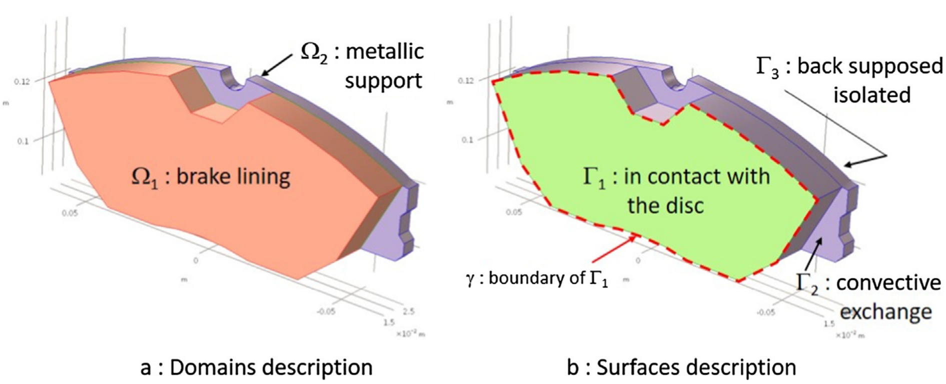

Fig. 1. Geometry of the studied system.