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Modelling of the gas induced fading of organic linings in dry clutches

Alexander Fidlin [a,*], Simon Bäuerle [b], Felix Boy [b]

[a] *Karlsruhe Institute of Technology, Institute of Engineering Mechanics, Dynamics/Mechatronics, Kaiserstraße 10, Karlsruhe, Germany*
[b] *University of Kassel, Institute for Mechanics, Engineering Dynamics Group, Mönchebergstraße 7, Kassel, Germany*

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ABSTRACT

In this contribution the influence of a phase transition from solid organic material to gas on the contact behaviour in dry clutches is investigated. This phase transition may lead to a decrease in transmissible torque commonly known as fading-effect. This process is modelled by describing the clutch friction surface as a porous medium and calculating the flow and inherent pressure field of a gas formed by a thermally induced decomposition of the organic clutch lining. The basic problem is badly conditioned and therefore reduced by asymptotic development of the governing equations. The simulation results show the capability of the proposed model to predict the influence of the phase transition on the fading-effect.

1. Introduction

Phase transitions caused by friction may change the contact behaviour considerably. The influence of solid–solid or solid–liquid transitions as they can be observed in the change of austenite to martensite in steel, or the liquefaction of ice under pressure, have been investigated e.g. in [1,2]. This contribution discusses the general question of how solid–gaseous phase transitions may change the frictional properties by investigating the example of gas induced fading in organic clutch pad linings.

Fading in dry clutches describes the rapid loss of transmissible torque under extreme thermal load [3]. It appears during the synchronisation, when excessive frictional power is converted into heat. To the best of the authors knowledge there is no satisfying explanation for the phenomenon. In [4–6], it is shown that the organic binder inside the clutch lining decomposes producing liquid and gaseous reaction products. Consequently, there are two possible explanations for the contribution of binder degradation to the problem of fading: Liquid reaction products could moisten the surface and thus reduce the friction coefficient as reported in [6,7]. On the other hand, an evolving gas could cause a pressure cushion reducing the friction as explained in [8]. Other approaches are based on the analysis of thermo-elastic instabilities [10], wear and dynamics of worn particles in the contact interface [11].

The aim of this work is to provide an essential physical model, which is able to describe and examine the contribution of the thermally induced outgassing on the fading-effect in dry clutches. It is assumed that a heavy thermal load due to friction decomposes the lining binder and leads to the formation of a gas cushion and thus a pressure field within the friction contact. The pressure field is regarded as the only influence on the transmissible torque and the fading effect. The effects of wear and transport of the worn particles are neglected in order to demonstrate the pure effect of outgassing.

This papers investigation comprises three model stages: a first simple axisymmetric model and two model extensions taking into account the wobbling of the clutch disk in the second stage and the thermo-elastic deformation of the pressure plate in the third stage. The derivation of the governing equations in Section 2 is shown for the first model stage, focussing on the essential model properties. The extended model equations of the other stages are explained in Section 2.4. In the following Section 3, the methods for the numerical solution of the problem are presented, followed by the results in Section 4. Both these sections are accompanied by the necessary parameter information in Appendix A. The discussion ends with a conclusion in Section 5.

2. Model formulation

The main objective, in order to be able to describe the fading effect, is to determine the arising pressure field. Therefore, a simplified axisymmetric model of a dry clutch, consisting of a fixed clutch disc and a rigid steel pressure plate rotating at a constant angular velocity ω (see Fig. 1), is used for the following investigation. Clutch disc and pressure plate are both simplified as annuli, where the first one is supposed to possess an effective

* Corresponding author. Tel.: +49 721 608 42396.
E-mail addresses: alexander.fidlin@kit.edu (A. Fidlin), baeuerle@uni-kassel.de (S. Bäuerle), boy@uni-kassel.de (F. Boy).

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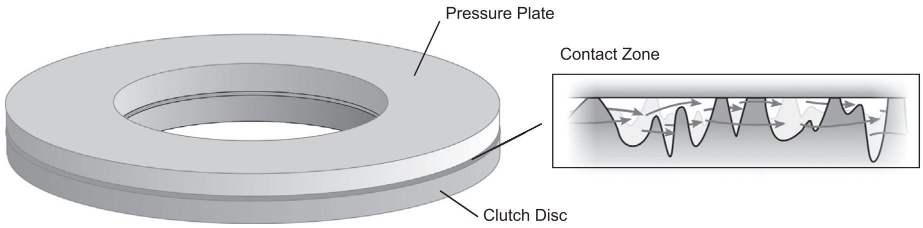

Fig. 1. Sketch of a reduced, axisymmetric dry clutch model consisting of two annuli (clutch disc and pressure plate on the left hand side). In the contact zone an arising gas flows through the surface asperities (right hand side).

surface roughness whereas the second one has an ideally flat surface.

Both parts are pressed onto each other by a constant force F_d, which leads to friction and an inherent heat generation. If the rising temperature exceeds a certain threshold, the gas production sets in and the evolving gas flows through the asperities. The developing pressure field influences the normal force, the friction force and, consequently, the heat generation which is back coupled with the pressure evolution itself.

2.1. Mathematical modelling of the pressure field

In assuming that the gas flow through the asperities resembles a Stokes flow of a compressible fluid through a porous medium, the velocity field $\vec{v}$ can be calculated from the pressure gradient ∇p by Darcy's Law (cf. [9])

$$\vec{v} = -\frac{k}{\mu_f}\nabla p, \tag{1}$$

where μ_f is the constant dynamic viscosity and k the permeability of the porous medium. Following [9] the mass balance for porous media is given by

$$\frac{\partial(m\rho)}{\partial t} + \nabla\cdot\left(\rho\vec{v}\right) = Q_0, \tag{2}$$

where the porosity m is the ratio of void and total volume and Q_0 a volume specific production term, modelling the evolution of gas due to decomposition. If the behaviour of a perfect gas is implied by stating

$$\rho = \frac{p}{RT_f} \tag{3}$$

the description of the pressure field

$$\frac{1}{R}\frac{\partial}{\partial t}\left(m\frac{p}{T_f}\right) - \frac{1}{\mu_f R}\nabla\cdot\left(k\frac{p}{T_f}\nabla p\right) = Q_0 \tag{4}$$

is obtained by combining formulas (1)–(3). Thus the pressure field p is dependent on the temperature field T_f in the porous medium. In view of the problems geometry it is convenient to use cylindrical coordinates with radius r, angle φ and height z. In addition, the conditions

$$p = p(r,z) \tag{5}$$

$$T_f = T_f(r,z) \tag{6}$$

$$\frac{\partial(.)}{\partial\varphi} = 0 \tag{7}$$

ensure the demanded axial symmetry.

Bearing in mind that the mean asperity height is around 30 μm (cf. Fig. 1) it seems sensible to make the two following assumptions: Firstly, the temperature of the fluid T_f shall be constant along the height of the surface asperities and secondly it shall be equal to the temperature $\hat{T}_p$ on the contacting surface of the pressure plate. Thus the temperature T_f in the porous medium is known by calculating the temperature field T_p in the pressure plate, which is done by evaluating the transient heat conduction Eq. (32).

Furthermore, constitutive laws for the porosity m, the permeability k and the mass production Q_0 in Eq. (4) are needed. Since the porosity and the permeability are geometrically motivated parameters, they will clearly change with a deformation of the porous medium, which is only relevant for the two extensions to the model. Approximating these dependencies, the linear relations

$$m = m_0(1 + k_{fm}\Delta s) = m_0 f_m, \tag{8}$$

$$k = k_0(1 + k_{fk}\Delta s) = k_0 f_k \tag{9}$$

are first order approximations, where m_0 and k_0 are the values of an undeformed medium, Δs is the relative deformation of the asperities, which is modelled as the compression of a Winkler foundation ([12]), and k_{fm} and k_{fk} are scaling parameters. In case of the rigid axisymmetric model the permeability and the porosity are assumed to remain constant.

The mass production results from thermal decomposition of the clutch lining, whereby only sublimation is considered. The local amount of produced gas arises from a chemical process with complex dependencies beyond the scope of the present work. As the focus lies on the influence of the outgassing on the dynamical behaviour and not the formation of the gas itself, the modelling of the production term is restricted to a heuristic temperature dependent law. It implies a linear relation

$$Q_0 = k_m\left(\hat{T}_p - T_T\right)\sigma(\hat{T}_p - T_T) \tag{10}$$

between mass production and temperature. The qualitative meaning of this formula is that the gas production sets in after a certain threshold temperature T_T is exceeded. Here, σ is the Heaviside-function and k_m is an empirical parameter. The law with the appropriately chosen parameters assures that at least the global amount of produced gas over time is correct and can be seen as a first approach to the problem. It is known from industrial experience that the usual mass loss of a clutch disc is about 10 mg during a 1 s synchronisation process. Assuming that a certain percentage of this amount will be forming gas, a rough estimated value for the parameter k_m can be found iteratively by simulation to guarantee a correct order of magnitude for the produced gas over time.

In addition to the field equation, the following boundary conditions for the control volume of the porous medium are stated: The conditions

$$p|_{r=R_i} = p_0 \tag{11}$$

$$p|_{r=R_a} = p_0 \tag{12}$$

determine the pressure on the inner and outer radius R_i and R_a to be equal to the ambient pressure p_0.On the lower and upper surface of the clutch disc, the equations

$$-\frac{k}{\mu_f}\frac{\partial p}{\partial z}\bigg|_{z_f=0} = 0 \tag{13}$$