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Thermoelastic instability in friction clutches and brakes – Transient modal analysis revealing mechanisms of excitation of unstable modes

Przemyslaw Zagrodzki *

Friction Holdings LLC, Technical Center, 731 Tech Drive, Crawfordsville, IN 47933, USA

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ABSTRACT

Sliding systems with frictional heating exhibit thermoelastic instability (TEI) when the sliding speed exceeds the critical value. TEI can lead to hot spots on contact surfaces and is generally of great practical importance in friction brakes and clutches. The phenomenon is well defined in terms of the theory of stability with a classic perturbation approach being commonly used. While the perturbation analysis determines the stability limit, recent interest extends further towards exploration of the unstable behavior. This is motivated by practical reasons, namely by the fact that many common friction brakes and clutches operate instantaneously at speeds exceeding the critical speed for TEI, i.e. in the unstable regime. In order to determine a transient solution, possible mechanisms of excitation of unstable modes of different nature need to be accurately defined and quantified. These mechanisms are normally not considered in stability analysis of the steady-state where an initial perturbation of the thermoelastic field is assumed. In many realistic situations, however, there is no indication of the existence of meaningful initial temperature variation. Lack of full understanding of these mechanisms has perhaps limited broader industrial applications of recent theoretical advances in TEI. In this paper a method of solving the transient thermoelastic process in frictional systems using finite element spatial discretization and modal superposition is presented. Then mechanisms that excite the unstable thermoelastic modes other than the initial perturbation of temperature are studied. The role of the background process (corresponding to nominal applied loads) in the excitation is shown in a clear form and illustrated by practical examples for automotive friction clutches. It is demonstrated, in particular, that while for some geometries and configurations of the sliding system the imperfections determine the excitation of unstable modes, with other configurations strong excitation occurs even in the absence of imperfections.

1. Introduction

The frictional heat flux generated at the contact interface of a sliding system is proportional to the contact pressure. Therefore, if some non-uniformity in pressure distribution across the surface occurs, the areas where the pressure is higher experience a higher temperature increase. This in turn causes greater local thermal expansion and thereby leads to further local pressure increase. Thus, the sliding system with frictional heating inherits a mechanism that tends to magnify contact pressure non-uniformity. This phenomenon, identified by Barber (1969), is known as frictionally excited thermoelastic instability (TEI). TEI can lead to local contact concentrations that manifest themselves by hot spots on the friction surfaces (Barber, 1969; Anderson and Knapp, 1990; Zagrodzki and Truncone, 2003; Kao et al., 2000; Lee and Brooks, 2003) and it has profound practical consequences in clutches and brakes as well as other sliding systems with frictional heating.

The phenomenon is well defined in terms of the theory of stability, with the perturbation approach being commonly used (e.g. Dow and Burton, 1972; Lee and Barber, 1993a; Du et al., 1997; Yi et al., 2000; Decuzzi et al., 2001; Krempaszky and Lippmann, 2005). While the classic perturbation analysis determines stability limits for the system, recent interest is directed towards exploration of the unstable behavior (Zagrodzki, 1990; Kao et al., 2000; Zagrodzki et al., 2001; Al-Shabibi and Barber, 2002; Afferrante et al., 2003; Choi and Lee, 2004). This is motivated by practical considerations, namely by the fact that many common friction brakes and clutches operate instantaneously at speeds exceeding the critical speed for TEI, i.e. in the unstable regime (Yi et al., 2000; Zagrodzki and Truncone, 2003). Exploration of the transient thermoelastic process to determine instantaneous temperatures, thermal deformations and stresses occurring in these conditions is therefore of great interest.

A linear model of the thermoelastic process in a brake or a clutch can usually be adopted for the stage of operation with full contact. On the other hand, it is known that hot spots produced even during short-term slip can be accompanied by local separation of the surfaces (Zagrodzki and Truncone, 2003). This is certainly an

* Tel.: +1 765 359 2567; fax: +1 765 359 2566.
E-mail address: pzagrodzki@frictionholdings.com

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undesirable situation that should be prevented and control of thermoelastic behavior is aimed at preservation of full contact. Thus, a linear model, without separation, in spite of its limitations, is useful in this type of practical application. We can distinguish two components of the thermoelastic process: the background process, which corresponds to contact pressure resulting from the applied external loads (not necessarily uniform or constant), and the perturbed process, resulting from the initial condition, superposed on the background process. Stability of a linear system does not depend on the background process and therefore this process is typically not included in the stability analysis (Dow and Burton, 1972; Lee and Barber, 1993a; Du et al., 1997; Yi et al., 2000; Decuzzi et al., 2001; Krempaszky and Lippmann, 2005). Also, in many known studies of transient behavior, e.g. Al-Shabibi and Barber (2002), Afferrante et al. (2003) and Voldrich (2007), an initial perturbation of temperature is assumed and the background process is not considered. Initial temperature variation seems to be unquestionable in some practical situations, for instance as a remnant of the preceding clutch or brake application. In many other important practical instances, however, hot spots were observed without any indication of a meaningful initial temperature variation. For example, severe hot spots were detected after a single application of a brake or a clutch by Anderson and Knapp (1990) and Zagrodzki and Truncone (2003). These observations indicate that factors other than the initial perturbation of temperature can excite the unstable process. The background process seems to play major role by producing temperature variation which contains components consistent with the unstable modes.

Understanding of these processes is crucial to the solution of important industrial problems. An example is the resolution of a hot spotting problem in an automotive transmission clutch by means of re-arrangement of clutch components, conceived as a result of identification of the mechanism exciting the unstable modes (Zagrodzki and Zhao, 2008).

In the paper, modal analysis is used in the solution of the thermoelastic problem in the sliding frictional system. More specifically, spatial discretization of the elastic and thermal problems is performed using the finite element method. In the thermal model the relative motion of system components is accounted for (in-plane sliding). Then the two problems are coupled by interfacial boundary conditions with frictional heating and a semi-discrete, time-dependent problem is obtained. The general solution of this problem is presented in analytical form. The semi-discrete problem is then reduced to an eigenvalue problem with eigenvalues representing the stability parameter, an approach similar to that used in Yi et al. (2000) and Al-Shabibi and Barber (2002). Next, by transforming the problem to modal variables, the transient solution is expressed by modal superposition; this solution was presented by Zagrodzki (2003), and used by Li and Barber (2004) and Li and Barber (2008). This comprehensive formulation clearly exhibits contributions from the initial conditions and from the nonhomogeneous part representing the background process and helps to elucidate the relations between them. In the background process, geometric imperfections are considered but also important practical cases are identified where the unstable process is excited in the absence of such imperfections.

The background process was included in recent study by Li and Barber (2008), who presented the solution for an axisymmetric problem, similar to one of the cases discussed in this paper. Note that the background process is also typically included in finite element simulations in time domain (Zagrodzki, 1990; Kao et al., 2000; Zagrodzki et al., 2001; Zagrodzki and Truncone, 2003; Choi and Lee, 2004; Zagrodzki and Zhao, 2008). This method, robust in tackling non-linear problems, does not offer the clarity of modal superposition and therefore provides only limited insight into the contributing mechanisms.

This paper concentrates on the method of transient modal analysis and the elucidation of the mechanisms exciting unstable modes. For convenience, the analysis is performed for constant sliding speed. Substantial contributions to the solution of problems with variable speed using modal analysis have been made by Al-Shabibi and Barber (2002) and then further enhanced by Li and Barber (2004) and Li and Barber (2008); the latter approach was proven to be particularly robust and it can be applied to the models used in this study.

2. Model and discretization of thermoelastic problem in the sliding system

The overall formulation of the problem and the method of solution used in this study were presented by Zagrodzki (2003). The general case of a sliding system composed of two or more solids with frictional heat generation at contact interfaces is considered. For illustration purposes, without loss of generality, a two-dimensional system comprising three components with two sliding interfaces shown in Fig. 1 is used throughout the most of this paper. This model represents a multidisk clutch or a brake with the central layer corresponding to the metal disk and the two external layers representing the friction material (Lee and Barber, 1993a; Zagrodzki and Truncone, 2003). The mechanical part of the problem is treated as a quasistatic elastic stress problem subjected to external loads and thermal strains. At the sliding interfaces, continuity of normal displacements is assumed and relative tangential displacements are allowed. The thermal part is described by a transient heat transfer problem. At the sliding interfaces temperature continuity is assumed and a frictional heat input is applied as a function of local contact pressure and speed. As a result, a fully coupled, time-dependent thermoelastic problem is obtained.

The stage of operation of the sliding system during which full contact occurs is considered. This assumption along with an assumption of linear material properties leads to a linear problem, which is treatable by modal analysis. Shear tractions, that have been shown to play only a minor role in most practical thermoelastic contact problems (Lee and Barber, 1993b), are neglected. This last assumption simplifies the problem without loss of generality.

The finite element method is used for spatial discretization of both the elastic and the thermal parts of the problem.

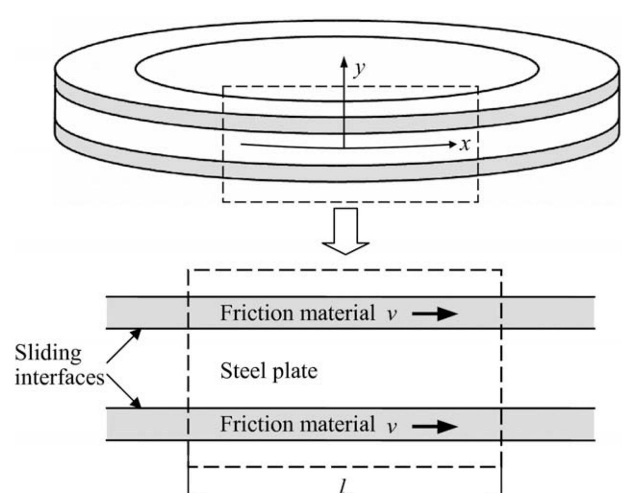

Fig. 1. Model geometry, in-plane sliding.