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An Experimental Investigation of Frictionally-Excited Thermoelastic Instability in Automotive Disk Brakes Under a Drag Brake Application

Thermoelastic instability in an automotive disk brake system is investigated experimentally under drag braking conditions. The onset of instability is clearly identifiable through the observation of nonuniformities in temperature measured using embedded thermocouples. A stability boundary is established in temperature/speed space, the critical temperature being attributable to temperature-dependence of the brake pad material properties. It is also found that the form of the resulting unstable perturbations or eigenfunctions changes depending upon the sliding speed and temperature.

1 Introduction

The heat generated in mechanical brakes and clutches causes thermoelastic distortion and affects the distribution of contact pressure. This interaction is unstable if the sliding speed is sufficiently high, in which case perturbations develop in the nominal pressure distribution, leading eventually to localized contact and the development of *hot spots*. The phenomenon is now generally referred to as *frictionally-excited thermoelastic instability* or *TEI*.

Experimental observations of TEI have been reported in many practical applications, particularly in railway (Wentenkamp and Kipp, 1976; van Swaaij, 1979; Dow, 1980; Fec and Sehitoglu, 1985) and aircraft brakes (Santini and Kennedy, 1975). However, interest in the phenomenon in the automotive industry is more recent, being prompted by changes in braking materials and other design improvements. The high local temperatures associated with TEI can cause material degradation, thermal cracking (Anderson and Knapp, 1989) and unacceptable braking performance such as brake fade. A particular area of concern is the relation between thermoelastically-induced hot spots in the brake disk and vibration in the brake system.

Theoretical investigations of the phenomenon have generally involved very idealized decriptions of the system geometry. For example, Burton et al.'s analysis (1973) of the critical sliding speed required to initiate instability represents the two sliding bodies as half-planes and the predictions for material properties typical of automotive practice are substantially higher than the speeds at which hot spots are observed experimentally (Kreitlow et al., 1985; Abendroth, 1985; Anderson and Knapp, 1989). A recent analysis by Lee and Barber (1993) represents the disk/pad system by a layer of finite thickness sliding between two half-planes and even gives significantly better predictions of critical speed. It also shows that the resulting unstable perturbation is antisymmetric, leading to a circumferentially-buckled deformation mode and hot spots at alternating locations on the two sides of the disk, which agrees with observations in automotive practice (Thoms, 1988).

A transient numerical simulation of a realistic automotive brake contact is possible in principle, but the mesh refinement in both time and space required to describe the unstable perturbation with sufficient accuracy to give good predictions for critical speed would involve very extensive computations. Considerable simplifications could be made, however, if the form and motion of the resulting perturbation were known. For example, an immediate reduction in complexity is achieved if we can restrict attention to perturbations that are antisymmetric with respect to the disk mid surface. Further simplifications would be possible if, for example, the perturbed temperature field (and hence the resulting hot spots) could be assumed to be stationary with respect either to the disk or to the pad.

The present paper therefore describes an experimental investigation of the form and behavior of the temperature perturbations associated with TEI in an automotive disk brake assembly. All the experiments were performed under "drag braking" conditions, i.e., at constant sliding speed, since theoretical predictions are generally based on this assumption and the relatively few analyses of thermoelastic effects during deceleration show that the results can be correlated with those for constant speed tests (Barber et al., 1985).

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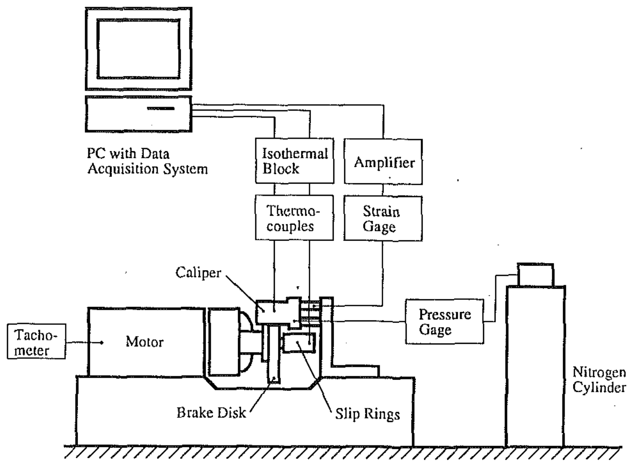

Fig. 1 Experimental apparatus and data acquisition system

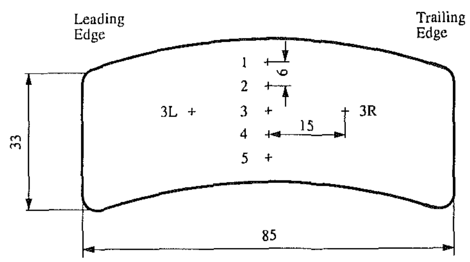

Fig. 2 Thermocouple locations in the brake pad (all dimensions in mm.)

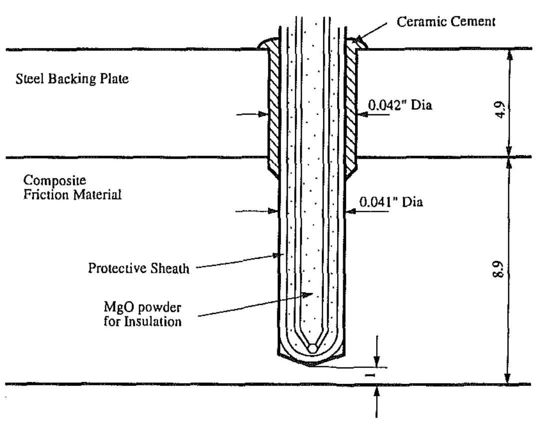

Fig. 3 Typical thermocouple installation in the brake pad (all dimensions in *mm* unless notified)

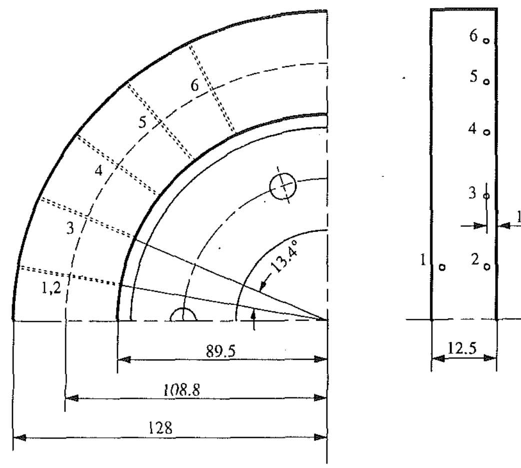

Fig. 4 Thermocouple locations in the brake disk (all dimensions in mm unless notified)

2 Experimental Apparatus

The experimental apparatus and data acquisition system are shown in Fig. 1. An automotive disk brake system with a solid disk and floating type caliper was assembled on a lathe bed which provides power to the brake disk by an electric motor. A compressed gas supply was used to actuate the brakes and dry Nitrogen gas was chosen to prevent oxidation in the piston and cylinder inside the caliper.

The rotational speed of the disk was monitored by a tachometer and the brake line pressure by a pressure gage. Four strain gages were mounted in a spacer forming a full bridge to measure the frictional force resulting from braking. Temperatures were measured by chromel-constantan thermocouples, all the connections being maintained at the same temperature by an isothermal block for more accurate measurement. Readings for the disk temperatures were extracted via slip rings.

Seven thermocouples were installed in the outboard brake pad with positions shown in Fig. 2 to investigate radial and circumferential movement of temperature perturbations relatively stationary with respect to the brake pad. These optimum positions were determined after many preliminary test runs. A typical thermocouple installation in the friction pad is shown in Fig. 3.

Thermocouple locations in the disk are shown in Fig. 4. Six thermocouples were press fitted through holes drilled 1.5mm below the disk surface. The outer halves of the holes were filled with cast iron rods. Five of these thermocouples were used to investigate the circumferential movement of temperature perturbations relatively stationary with respect to the inboard surface of the disk and one thermocouple was located near the outboard surface of the disk to check the symmetry of the perturbation.

All measuring devices were carefully calibrated before the tests and the calibrations were checked occasionally during the test series described in Section 3.

3 Test Procedure

All tests were performed at constant rotational speeds of 200, 300, ..., 1000rpm with brake line pressure not exceeding 50 psi. This corresponds to a light brake drag application which has been reported to cause drum brake fractures at highway speeds (Anderson and Knapp, 1989). Also, with this light braking condition, the power capacity of the electric motor was not exceeded and the rotational speed of the motor and disk could remain relatively constant up to 1000rpm. Only two variables i.e., rotational speed and brake pressure were varied to investigate their effects on thermoelastic instability. Other variables such as brake pad configuration were not changed and environmental conditions such as room temperature and humidity were kept constant as far as possible.

The brake pads used were of semi-metallic friction material and were provided by GM-Delco Moraine (manufacturer's specification DM 8034). Each test series consisted of about 50 test runs. A new disk brake rotor and a pair of new friction pads obtained from the brake manufacturer were used for each test series. Before each test series, new friction pads were run in at 400 rpm and 20 psi for an hour.

The general test procedure was to bring the brake rotor to the desired speed and apply the desired brake pressure. The rotor speed often dropped initially when the brake was applied and it was readjusted to the desired speed when this happened. The disk brake system was dragged for a maximum of 30 minutes until temperature fluctuations due to thermoelastic instability were fully observed. After a long period of dragging, brake pressure was released and rotational speed was reduced

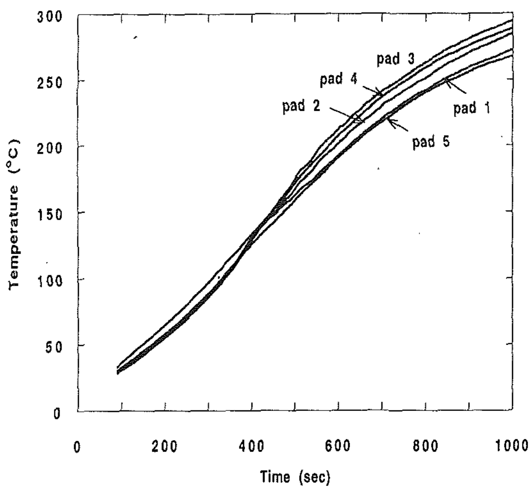

Fig. 5 Measured temperatures for the thermoelastically stable case (p = 50 psi, V = 400 rpm)

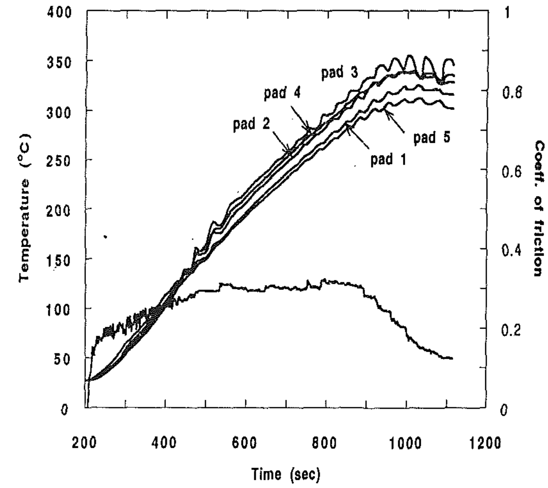

Fig. 6 Measured temperatures for the thermoelastically unstable case (p = 50 psi, V = 600 rpm)

to zero and the disk brake system was then allowed to cool down to room temperature before the next run. Data from all the thermocouples and strain gages were monitored and recorded continuously during the test.

Since even slight tilting of the friction pad with respect to the brake disk resulted in initially nonuniform pressure distribution at the sliding surface, the angles of the friction pad were carefully adjusted and checked before each test run.

4 Experimental Observations

4.1 Thermoelastically Stable Behavior. Some thermoelastically-influenced evolution of the temperature field occurs, even when sliding below the critical speed. A typical example is shown in Fig. 5. The temperature initially rises faster at the outer radius (pad 1 position) due to the higher sliding speed at the outside radius of the friction pad. The friction pad used in Fig. 5 is relatively new and hence has virtually no history of wear. As the temperature rises, the friction pad expands thermally and becomes convex outwards due to the effect of Dundurs' Theorem (Barber, 1992). Thus contact becomes more severe at the center of the friction pad as the temperature rises. This transfer of the high temperature contact region from the outside to the center of the friction pad occurs at about 150°C in Fig. 5. The resulting higher temperature and pressure at the center of the friction pad cause more rapid wear in this region. Upon cooling, the friction pad becomes depressed at the center and elevated at the edges. As a result of this wear pattern, the initial contact pressure in subsequent braking cycles becomes higher at inner and outer radius region. Consequently, the temperature was observed initially to rise faster at the inner and outer radii (pad position 1 and 5) after many repeated test runs.

4.2 Thermoelastic Instability. Typical cases of thermoelastically unstable states are shown in Fig. 6. Temperature perturbations appear as relatively long wavelength oscillations superposed on the nonuniform bulk temperature distribution described in Section 4.1. Note that all the conditions in Fig. 6 were the same as in Fig. 5 except that the rotational speed was increased to 600 rpm which is sufficient to cause temperature fluctuations at the comparable range of bulk temperature. This confirms that there is a critical speed for instability in sliding contact (Dow and Burton, 1972; Burton et al., 1973). We shall discuss the critical speed of the present system in more detail in Section 4.4.

4.3 Modes 1 and 2. When the system is thermoelastically unstable, temperature fluctuations are generally first observed

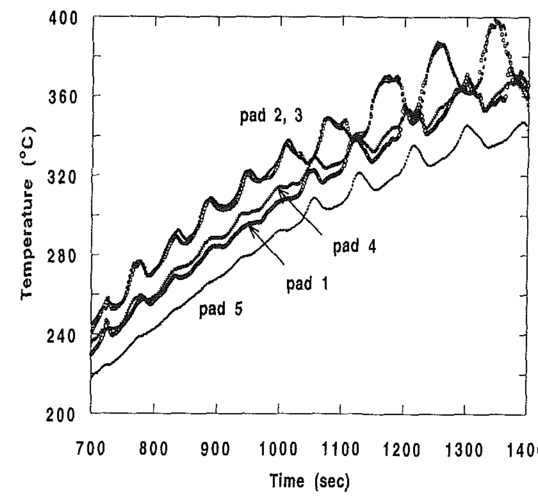

Fig. 7 Temperature fluctuations for thermocouple positions 1, 2, 3, 4, 5 in the brake pad (p = 30 psi, V = 600 rpm)

after bulk thermal expansion of the pad has caused concentration of contact pressure near the mean radius. The movement of the temperature perturbations has two distinct patterns, which we refer to as Mode 1 and Mode 2, respectively. In Mode 1, the temperature perturbation moves slowly in the circumferential direction with respect to the friction pad, whilst preserving an approximately constant profile in the radial direction. In Mode 2, the perturbation in the radial temperature profile oscillates in time, but is stationary with respect to the friction pad. During tests at constant sliding speed, Mode 1 is always observed first and a transition to Mode 2 occurs when the bulk temperature has reached some critical value. Mode 2 is important in that it is believed to be the precursor of the phenomenon known in the brake industry as *banding*.

Figures 7 and 8 show, respectively, typical radial and circumferential temperature perturbations during the transition from Mode 1 and Mode 2, which can be seen at approximately 1050 s. Figure 7 shows that the temperatures measured at various radial positions in the pad fluctuate synchronously in Mode 1, whereas the center temperature fluctuates with 180° phase difference from the outer and inner temperatures after the transition to Mode 2. By contrast, the temperatures at various circumferential positions shown in Fig. 8 fluctuate synchronously *after* the transition to Mode 2, but during the preceding Mode 1 phase, their peaks follow in the cyclic order 3L, 3, 3R, indicating a gradual motion of the perturbation in the direction of sliding. The speed of this motion was calculated

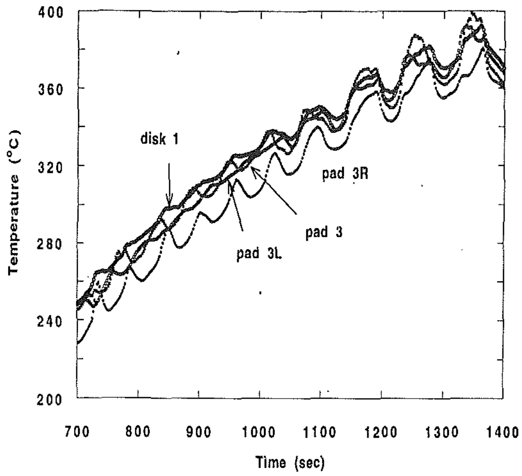

Fig. 8 Temperature fluctuations for thermocouple positions 3L, 3, 3R of the brake pad and position 1 of the brake disk (p = 30 psi, V = 600 rpm)

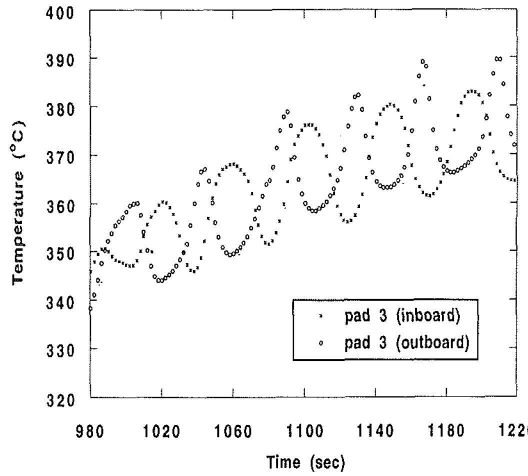

Fig. 10 Anti-symmetric oscillation of the temperature perturbations in Mode 2

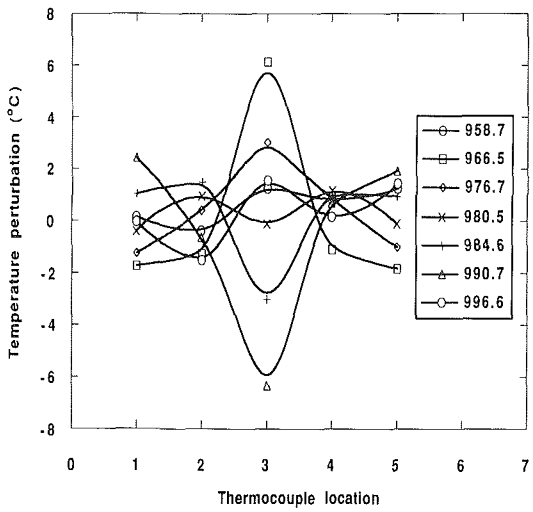

Fig. 9 Typical temperature perturbation components in Mode 2

as about 1 mm/s for the case illustrated in Figs. 7, 8. This is of course much less than the sliding speed (6840 mm/s). Qualitatively similar results were obtained throughout the test series, leading to the above characterizations of Modes 1 and 2.

Figure 8 also shows the temperature recorded by a thermocouple located in the disk at the mean contact radius. In Mode 1, no fluctuations in this temperature are observed, since those associated with the intermittent contact occur at rotational speed frequency and the thermal system cannot respond at that rate. However, in Mode 2, the relatively slow fluctuations in contact pressure in the radial direction cause a corresponding fluctuation in disk temperature, as can be seen in Fig. 8.

Temperatures measured at several circumferential locations in the center of the disk (i.e., disk positions 2, 3, 4, 5, 6) fluctuate at the same time for an extended period of time in Mode 2, which indicates that there is no circumferential temperature perturbation in the disk. However, at higher speeds, beyond our operating limit, a different mode has been observed in the automotive brake industry (Kreitlow et al., 1985; Abendroth, 1985; Thoms, 1988), involving significant circumferential variations in the disk temperature. This mode, which we may refer to as Mode 3, was modelled and analyzed theoretically by Lee and Barber (1993).

A typical temperature perturbation component in Mode 2, obtained by subtracting a bulk temperature component from the pad temperature, is shown in Fig. 9. Notice that these results correspond to the test recorded in Figure 6, for which the transition to Mode 2 occurred at about t = 800s. A complete period of fluctuation is shown in sequential time steps. The period is about 38 s in this case. The temperature perturbation in the radial direction is of approximately sinusoidal form and oscillates sinusoidally in time as shown in Figure 9. Note that the oscillation in temperature is greatest at the center of the pad, where the greatest mean temperature occurs.

It is tempting to interpret the temperature perturbations in both modes in terms of the interaction of sets of travelling plane waves. For example, a pair of identical sinusoidal plane waves, moving in directions inclined at $\pm\theta$, respectively, to the circumferential direction, would interfere to produce a two-dimensional pattern of peaks and troughs moving in the circumferential direction. The aspect ratio of this pattern depends on θ, the approximately circular hot and cold spots of Mode 1 being obtained for θ = 45 deg. Alternatively, the stationary oscillatory pattern of Mode 2 could be obtained by taking θ = 90 deg, i.e., by superposing waves moving radially outwards and inwards.

We must note, however, that the temperature perturbations obtained were consistently greater near the center of the pad than at the outer and inner radii, whereas a pattern of waves reflected from the inner and outer radial surfaces would predict equal amplitudes at these locations. This is probably associated with the fact that the mean temperature is greatest near the pad center, because of bulk heat transfer effects.

To investigate the symmetry of the temperature perturbation with respect to the central plane of the disk, a thermocouple was installed at the center of the opposing (inboard) friction pad. Figure 10 shows the variation of this temperature and that at the corresponding location in the outboard pad during a typical Mode 2 perturbation. The perturbations always exhibit some phase difference, but not necessarily exactly at 180° as would be required if the mode were to be strictly antisymmetric with respect to the disk center plane. In some cases, it was observed that the period of the perturbations on the two sides were slightly different, leading to changes in the relative phase during the process. In interpreting these results, it is important to realize that above the critical speed, a range of eigenfunctions of comparable spatial and temporal frequency may be unstable with slighlty differing growth rates and the resulting superposition would be expected to exhibit "beating" or amplitude modulated waviness. Effects of this kind are observable in the numerical simulation of related processes by Azarkhin and Barber (1985) and Zhang and Barber (1993). Also, some deviation from pure eigenfunction form might be anticipated as a result of variability in the wear process and other tribological effects at the interfaces.

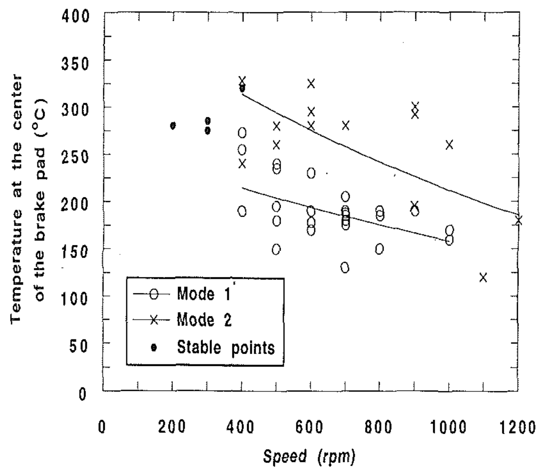

Fig. 11 Stability boundaries in temperature/speed space

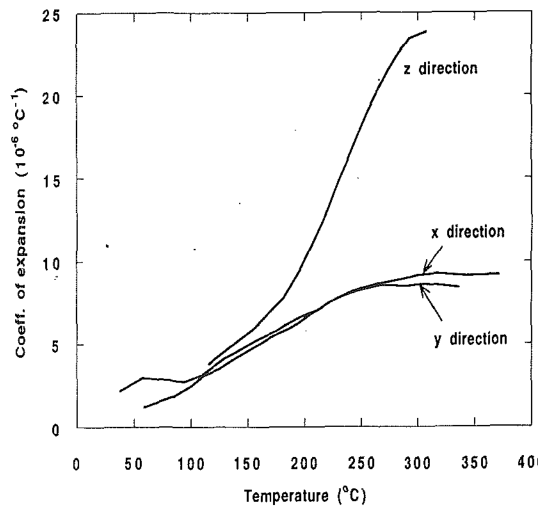

Fig. 12 Coefficient of expansion for pad material as a function of temperature

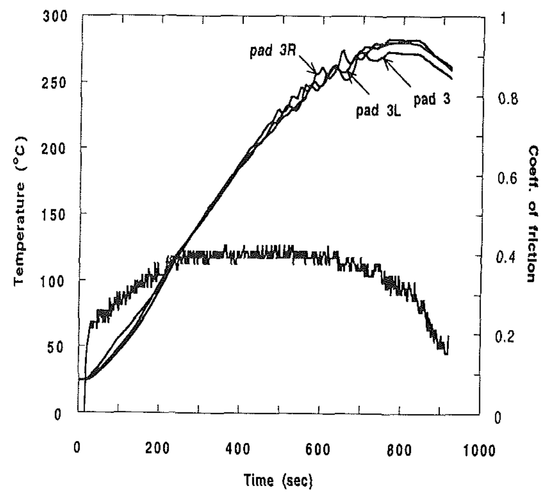

Fig. 13 Effect of brake fade on TEI (p = 30 psi, V = 600 rpm)

4.4 Critical Speed and Critical Temperature. The perturbation technique (Dow and Burton, 1972; Burton et al., 1973; Lee and Barber, 1993) predicts that the system should become unstable above a certain critical speed, which is independent of the applied load. However, the experimental results show that the unstable perturbation takes a significant time to develop (of the order of 5–10 min), during which the mean temperature of the system is increasing, as shown for example in Fig. 6. Once the perturbation develops, it rapidly reaches an approximately steady oscillatory state, suggesting a relatively high growth rate. It therefore seems probable that the initial delay in unstable growth rate is associated with the change in mean temperature and hence that the critical condition is a function of both sliding speed and mean temperature. This hypothesis was confirmed by tests at other combinations of temperature and speed, achieved by raising the mean temperature of the system during a preceding period of sliding in the stable domain.

The critical condition for instability of the system can therefore be plotted as a locus in speed-temperature space, as shown in Fig. 11. Two loci are given, one corresponding to the onset of Mode 1 and the other for the transition to Mode 2. The critical temperature plotted is that recorded at the center of the pad (pad location 3).

At low speeds, below 400 rpm, the system is generally stable even after it reaches thermal equilibrium. In this case, the steady value of temperature at the center of the pad is denoted as ● in Fig. 11.

The effect of temperature on the stability behaviour is probably attributable to the temperature-dependence of the brake pad material properties. Among other thermal properties, the dependence of the coefficient of thermal expansion on the bulk temperature is the most prominent. The coefficient of expansion for the friction pad measured by the manufacturer is shown in Fig. 12. It is anisotropic and the highest value is measured in the direction normal to the frictional surface, which corresponds to the direction of the applied pressure during the pad production. This anisotropy is common for many fiber-reinforced composites. Since the pressure perturbations develop as a result of thermal expansion normal to the friction surface, the coefficient of thermal expansion in this direction should determine the stability of the system. Other thermal properties such as thermal conductivity and specific heat are relatively insensitive to temperature changes.

In Fig. 11, the critical temperatúre for both Mode 1 and 2 tends to decrease as the corresponding critical speed increases though there is considerable scatter in the results. This tendency agrees well with the theoretical prediction that the system becomes more unstable with increasing coefficient of thermal expansion of a body when the perturbation is stationary with respect to that body. In other words, at lower speed, a higher coefficient of thermal expansion of the friction pad is needed for the system to be unstable.

The results presented in Fig. 11 were obtained from tests at various brake pressures in the range 30–50 psi, but no effect of brake pressure on the critical temperature was detected for either mode. This is also in agreement with theoretical predictions for TEI. Notice however that an increase in brake pressure increases the bulk temperature of the system and hences conduces to instability through the above effect of temperature on thermal expansion coefficient.

4.5 Coefficient of Friction and Brake Fade. The ideal automotive brake system should have constant brake torque output during any braking schedule. Thus, it is important to know the frictional behavior of the brake system under various braking conditions. In particular, the coefficient of friction in the sliding interface between the friction pad and disk often decreases at high temperature, resulting in the phenomenon know as *brake fade*. The cause of brake fade is thought to be thermal decomposition of the composite material at high temperature (Rhee, 1974; Henderson et al., 1982). However, it is also plausible that the localized high temperature contact regions resulting from TEI may initiate and/or accelerate brake fade.

To investigate this hypothesis, the average[1] coefficient of friction between the pad and the disk was measured assuming that the frictional resistance between the piston and wheel cylinder wall is negligible. Figure 6 shows typical friction behavior during drag braking. As the temperature of the friction pad increases, the coefficient of friction stabilizes and remains relatively constant in the range 0.3–0.4. With further increase in pad temperature, the brake often starts to fade when the temperature measured at the pad location 3 exceeds 250°C. The resulting decrease in frictional heating eventually causes the bulk temperature to drop. The coefficient of friction can fall to values as low as 0.01 when the brake is severely faded. The coefficient of friction in Fig. 6 shows an example of brake fade at temperatures above 300°C while the brake system is thermoelastically unstable. However, the thermoelastic instability in Fig. 6 is not probably the major cause of the fade since brake fade also occurs at low speeds when the system is thermoelastically stable.

On the other hand, the effect of brake fade on TEI was clearly observed. The temperature perturbations disappear soon after the coefficient of friction decreases as shown in Fig. 13. Thus, the reduction in the coefficient of friction helps the brake system become thermoelastically stabilized.

5 Conclusions

The onset of thermoelastic instability is clearly identifiable through the observation of significant non-uniformities in temperature measured in the automotive disk brake system. These instabilities generally take some time to develop even though the sliding speed is maintained constant. This is attributable to the temperature-dependence of the brake pad material properties, since the mean pad temperature increases as sliding progresses. Thus, for a given braking material, a stability boundary can be established in temperature/speed space.

The results also exhibit significant changes in the form of the dominant perturbation as temperature is increased. Just above the stability boundary, the prevailing temperature field involves a circumferential perturbation slowly moving with respect to the pad, which we refer to as Mode 1. As temperature increases during a test, this evolves into a radial perturbation, stationary with respect to the pad and oscillating in time, which we refer to as Mode 2. These observations of the process in actual disk brakes will give guidance to the choice of appropriate theoretical models.

Brake fade is often observed at temperature above 250°C. It stabilizes the thermoelastically unstable system and decreases the bulk temperature of the brake system.

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[1]This implies an average over two friction surfaces.