

Interactive Effects of Thermal Deformation and Wear on Lateral Runout and Thickness Variation of Brake Disc Rotors

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ABSTRACT

Brake judder is one of the most serious problems in automotive-brake systems. It is basically a forced vibration caused by the friction-surface geometry of a brake disc, and therefore, disc rotors play a significant role in judder. There are two types of judder: cold and hot. Hot judder is caused by the thermo-mechanical deformation of a brake disc due to high-speed braking. There are several shapes of deformation, e.g., coning and circumferential waviness. Circumferential waviness is caused by thermo-mechanical buckling and typically found as a butterfly shape in a 2nd rotational-order and hot-spotting. In a previous paper, two groups of disc castings with different material homogeneity were machined intentionally to have two kinds of dimensional variations. From repetitive high-speed braking tests of these discs, both the material and dimensional homogeneity were found to affect the wave-like deformation of discs in the 1st and 2nd rotational-orders with different significance between the two casting groups. There are many mechanisms affecting disc geometry during braking. Plastic deformation and wear cause permanent effects, while thermal expansion and elastic deformation are reversible. A disc's initial shape before braking affects its geometry both transiently and permanently. Considering these effects, the previous test results were reanalyzed in the present paper. Some discs exhibited large transient runout and DTV but small permanent DTV, while others behaved differently. The thermal deformation and differential wear were confirmed to interactively affect the transient and permanent geometry of operating brake discs.

CITATION: Okamura, T., "Interactive Effects of Thermal Deformation and Wear on Lateral Runout and Thickness Variation of Brake Disc Rotors," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(3):2016, doi:10.4271/2016-01-1939.

INTRODUCTION

Brake judder is one of the most serious problems in automotive-brake systems, and brake discs play a significant role in judder. It is caused by a large disc thickness variation (DTV) and has been generally classified into two groups: cold and hot. The mechanism of judder was classified in several manners [1, 2]. The author divided mechanical-induced judder into two mechanisms in view of brake-disc behavior [3, 4, 5] and then classified the causes of brake judder into four as indicated in Table 1 [6]. Among the four, thermally induced judder due to high-speed braking was focused on in this serial study.

Table 1. Classification and mechanism of brake judder in view of disc-rotor behavior

Judder classification		Cause/Mechanism
Cold	Mechanically induced	Off-brake DTV growth due to large lateral runout On-brake DTV growth due to inhomogeneous material
	Chemically induced	Corrosion Sticktion, adhesion, or transfer of friction material or wear debris
Hot	Thermally induced	Thermo-mechanical deformation due to high-speed braking

There are several shapes of disc thermo-mechanical deformation, e.g., coning and circumferential waviness. Eggleston [7] presented three modes of thermo-mechanical deformation: coning, butterfly, and corrugation. "Butterfly" and "corrugation" are circumferential wavelike deformation, which has been commonly studied through rotational-order analyses [8, 9, 10]. On the basis of these studies, the author classifies the modes of the friction-ring geometry of discs caused by thermo-mechanical deformation and differential wear as illustrated horizontally in Fig. 1. Figure 1 also vertically indicates assumed factors causing disc geometry changes during braking, and the causes and effects are related to each other in the matrix.

Coning is the most basic mode of thermo-mechanical deformation. It alone does not increase DTV or lateral runout (LRO) if it is coaxial with the rotational axis of a brake disc. Coning, however, is significant to thermally induced judder since it is usually generated along with circumferential waviness. Both coning and circumferential waviness are affected by the stiffness of the friction ring and that of the necking between the friction ring and hat of a brake disc.

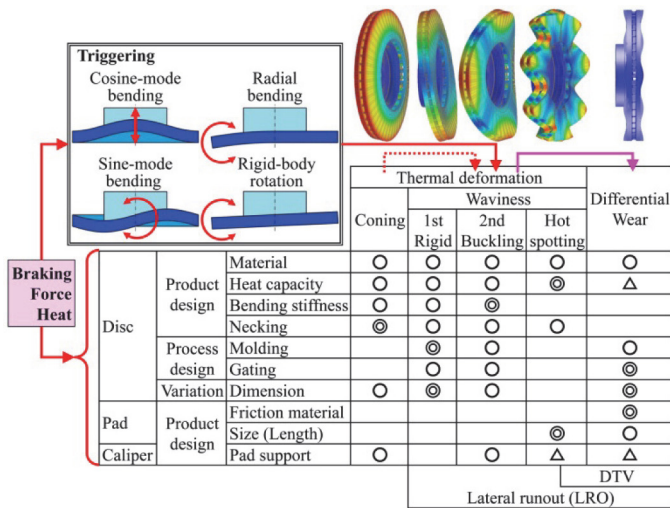


Figure 1. Factorial effect diagram of the friction-ring geometry of discs caused by thermo-mechanical deformation and differential wear in various modes

The circumferential wave-like thermal deformation of brake discs is typically found as a butterfly shape in a 2nd rotational-order and corrugation (or hot-spotting) around a 10th order, which are caused by thermo-mechanical buckling and are the significant cause of hot judder. Fieldhouse et al. intensively and extensively studied hot judder [2, 9, 11, 12, 13]. They evaluated the thermally induced internal load causing thermal buckling by using a simple beam model and also mentioned that repeated testing of the same brake disc caused hot-spotting to shift.

Some discs used in hot-judder-claimed vehicles had low-order circumferential waviness. Circumferential material homogeneity of disc castings was suspected to affect thermo-mechanical deformation since it affected the differential wear [4] and thermal strength of brake discs [14]. The author, therefore, focused on the effects of material and dimensional homogeneity on the wave-like deformation of ventilated discs in a previous paper [6], particularly in the low rotational-orders during repetitive high-speed braking. Disc castings of the same design including gray-cast-iron class were cast in two foundries by using horizontal- and vertical-molding machines, respectively. The two groups of disc castings with different material homogeneity were then intentionally given dimensional variations in four orientations by eccentric- and slant-machining. The discs were tested through repetitive braking on a motor dynamometer at a constant speed and torque with a braking energy equivalent to high-speed braking. As a result, both the material and dimensional homogeneity were found to affect wave-like deformation in 1st and 2nd rotational-orders. Horizontal-molded discs were affected more significantly by dimensional variations than were vertical-molded ones.

There are many mechanisms affecting disc geometry during braking including lateral runout and DTV. Thermo-mechanical plastic deformation and wear cause permanent effects, while thermal expansion and elastic deformation during braking cause reversible

effects. A disc's initial shape before braking affects not only its transient geometry during braking but also its permanent geometry after cooling. Considering these effects, the previous test results [6] were reanalyzed in the present paper. Some discs exhibited large transient runout and DTV but small permanent DTV, while others behaved differently. Thermo-mechanical deformation and differential wear were confirmed to interactively affect the transient and permanent geometry of operating brake discs.

The following sections are a description of the experimental setup, preliminary investigation results, and detailed investigations of typical cases with discussions on the interactive effects of thermal deformation and differential wear on the lateral runout and DTV of brake disc rotors.

EXPERIMENTAL SETUP

The test data reanalyzed in this study were obtained from the experiments conducted in the previous paper [6], from which the following descriptions on the experimental setup are extracted.

Disc Samples

Front ventilated discs of the same design (320-mm diameter and 28-mm thickness with radial ventilation-vanes) including gray-cast-iron class (G3000) for a certain vehicle were cast in two foundries by horizontal- and vertical-molding machines, respectively. To avoid the effects of other factors except for the intentional material and dimensional variations, the two groups of castings were respectively cast in the same melting batch and picked out from one cavity among multiple ones. The coordinate system for each disc-casting group was fixed on the basis of the gating locations for the respective moldings. To parametrically vary the distribution of the coolability, the stiffness of the friction ring, and that of the necking between the hat and friction ring in relation to the casting-fixed coordinate system of each brake disc, dimensional variations were given intentionally by two machining methods, i.e., eccentricity and slant of its ventilation paths. The test results of the horizontal-molded slant-machined discs were reanalyzed in this paper since those discs exhibited the most significant effects of dimensional variations among the four combinations of the material and dimensional homogeneity.

Figure 2 illustrates the casting-fixed coordinate system based on the left-right symmetry gating locations for the horizontal molding and the slant machining of the ventilation-path plane of each friction ring. The disc castings were clamped to maintain the outer circumference of the ventilation vanes concentric to the pilot hole of the fixing plate, but they were machined to slant their ventilation-path plane against their friction surface. The minimum thickness positions of their outboard cheek were located in the four rectangular orientations in the casting-fixed coordinate system as illustrated in Fig. 2. Hereafter, discs will be defined as HSLxx, of which the last two digits indicate the slant direction using the analogy of a 12-hour clock as designated in Fig. 2.

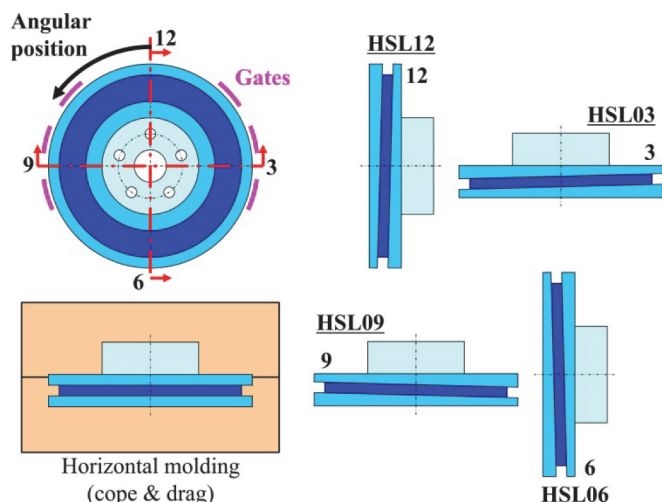


Figure 2. Casting-fixed coordinate system and dimensional variations by slant machining of ventilation-path plane

Measuring System

The measuring system illustrated in Fig. 3 was applied to obtain the linear profiles of the temperature and geometry of a rotating disc and then synthesize the results into 3D images. This system is composed of high-speed laser profilometers and infrared line-cameras. The profiles of the temperature and geometry of the outboard (OB) and inboard (IB) friction surfaces on the same disc radius were recorded at a sampling rate of 360 per revolution for every 10 revolutions, synchronized to the casting-fixed coordinate system during braking.

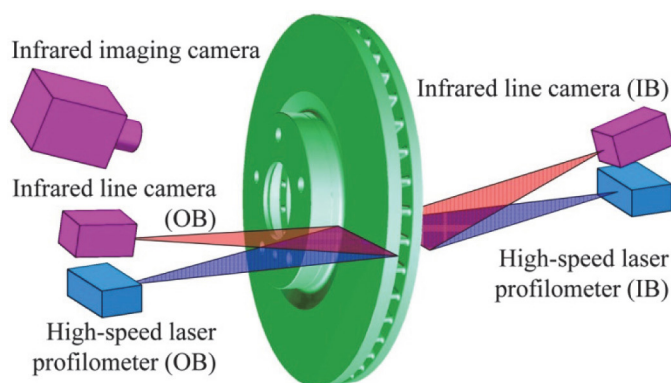


Figure 3. Measurement system for linear profile of temperature and geometry of outboard (OB) and inboard (IB) friction surfaces of rotating disc

Braking Condition

Table 2 lists braking conditions. To easily conduct rotational-order analyses of a disc's wave-like deformation during braking, a motor dynamometer was used in place of an inertia dynamometer. A constant speed and torque were selected to give the same braking energy within the same period to a disc as loaded in high-speed braking from maximum speed to stop for a vehicle. A two-piston floating caliper and non-asbestos organic (NAO) pads (from the same manufacturing batch) were used for the braking tests.

Table 2. Braking conditions

	Motor dynamometer	Factor	Inertia dynamometer
Speed	838 rpm	0.5	220 km/h to stop
Deceleration	Constant speed	0	0.2 G
Braking torque	572 Nm	0.9	
Braking time	31.2 sec	1.0	
Braking cycle	20	NA	
Braking interval	100°C IBT Control	NA	

PRELIMINARY INVESTIGATION OF LATERAL RUNOUT DURING REPETITIVE HIGH-SPEED BRAKING

3D Visualization of Deformation Shape

Figure 4 exhibits synthesized 3D images of the friction-ring deformation of a 9-o'clock-slant-machined disc at the end of the 1st, 3rd, and 20th braking in 20 cycles. The upper images indicate outboard friction surfaces, and the lower ones are inboard. At the first braking, only coning was prominent, as indicated on the left, then wave-like deformation causing hot-spotting around the 10th rotational-order developed after several braking cycles as exhibited on the middle, and finally, 2nd-order waviness became apparent at the end of 20th braking as exhibited on the right.

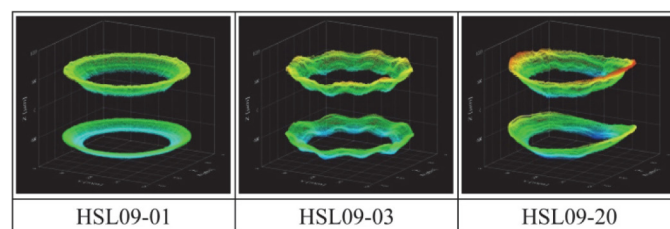


Figure 4. Friction-ring deformation-shape of 9-o'clock-slant-machined disc at end of 1st, 3rd, and 20th braking cycle

Major Rotational-Order Components of Wave-Like Deformation

Rotational-order analyses were conducted on the lateral runout at 5 mm from the outermost outboard friction-surface of the four discs at the end of each braking cycle through fast Fourier (FFT) analyses. The 1st and 2nd components in the low rotational-orders and the 7th and 9th ones in the medium orders (which represents hot-spotting) were prominent. Figure 5 plots the amplitude and phase angle of the 1st-, 2nd-, and 9th-order components of outboard lateral runout for 3-and 9-o'clock-slant-machined discs at the end of each braking. The amplitude of the 9th-order component of two discs was highest around the 3rd braking, and after that, decreased as plotted on the top. The 1st-order amplitude of the 3-o'clock-slant-machined disc plotted on the top left was the largest from the 1st braking and continuously increased to the end of 20 braking cycles. The 2nd-order amplitude of the 9-o'clock-slant-machined disc plotted on the top right increased after the 9th braking and became the largest among the three components after the 16th braking cycle. These trends of the amplitude varied between the four slant-machined discs as plotted in Fig. A1 in Appendix.

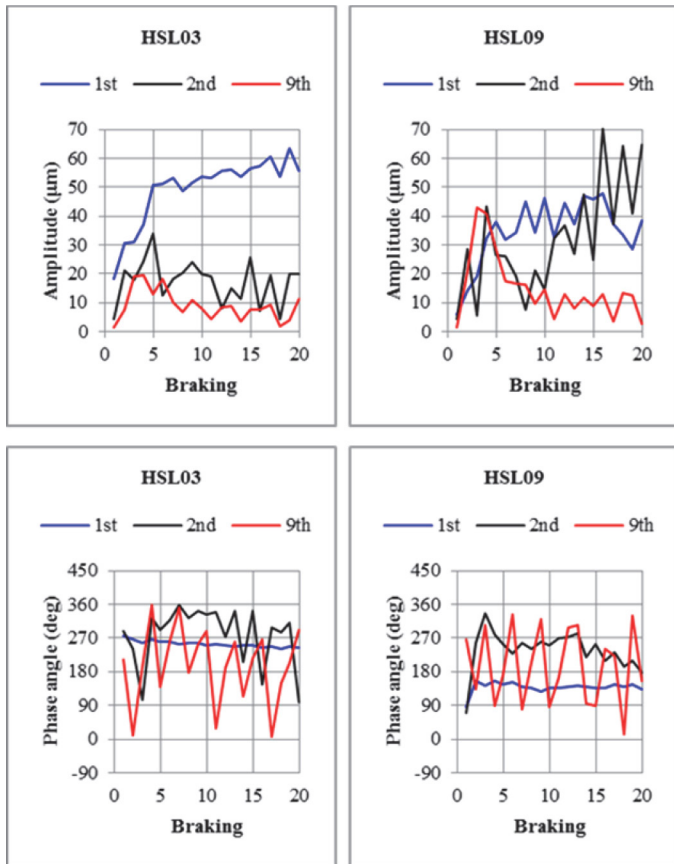


Figure 5. Amplitude and phase angle of 1st, 2nd, and 9th rotational-order components of outboard lateral runout of 3- and 9-o'clock-slant-machined discs on outermost circumference at end of each braking

The phase angle of the 1st-order component on the bottom in Fig. 5 was mostly constant at around 270 degrees for the 3-o'clock-slant-machined disc and 150 degrees for the 9-o'clock-slant-machined disc during all braking cycles. The phase angle of the 9th order, however, varied widely during 20 braking cycles. This means that the locations of hot-spotting shifted circumferentially during repetitive braking the same as Bryant et al. mentioned [9]. The phase angle of the 2nd-order component was somewhat shifted during braking cycles. As plotted in Fig. A1 in Appendix, the phase angle of the 1st-order component of the four discs depended on the direction of slant-machining, but the above-mentioned trends of the phase angles of three rotational-order components were consistent among the four discs. Detailed analyses on the effects of the material and dimensional homogeneity on the thermo-mechanical deformation of brake discs during high-speed braking were described in the previous paper [6].

LATERAL RUNOUT AND DTV CHANGES DURING REPETITIVE HIGH-SPEED BRAKING

Disc geometry during repetitive high-speed braking has various modes as illustrated in Fig. 1 due to the combined effects of linear thermal expansion, thermo-mechanical elastic deformation, plastic deformation, and differential wear. To investigate these effects, lateral runout and DTV of the four discs (illustrated in Fig. 2) at the sampling times designated in Fig. 6 were picked out and analyzed in

detail. "0" in Fig. 6 indicates "before braking," "3" indicates "at the end of braking," and "1" and "2" indicate "at one third of braking" and "at two thirds of that," respectively. The geometry of a disc before the (N+1)th braking is its permanent geometry after cooling following the Nth braking.

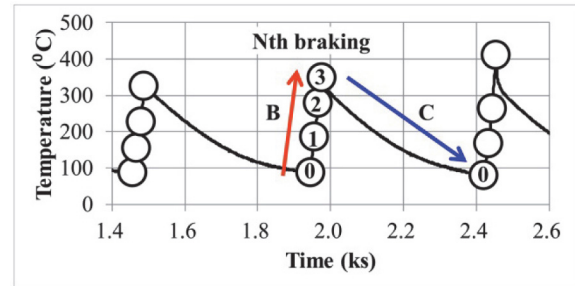


Figure 6. Focused timing during repetitive braking for investigating interaction of thermal deformation and differential wear on disc geometry

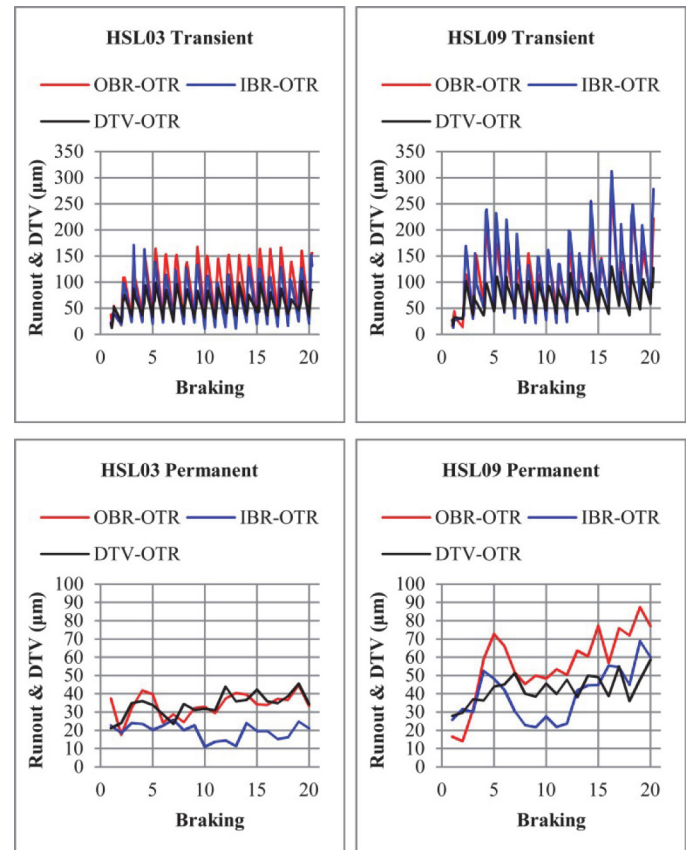


Figure 7. Transient and permanent lateral-runout and DTV for 3- and 9-o'clock-slant-machined discs on outermost circumference during repetitive high-speed braking

The inboard and outboard lateral-runout and DTV of the 3- and 9-o'clock-slant-machined discs at all of the sampling times during the 20 braking cycles are plotted on the top in Fig. 7, while those before braking are plotted on the bottom. The transient runout and DTV on the top in Fig. 7 and those permanent on the bottom perfectly differ between the two discs. The amplitudes of the three rotational-order components of the two discs also behaved quite differently as plotted in Fig. 5. The direction of slant-machining for these discs is left-right symmetry as illustrated in Fig. 2. The gaging design of the horizontal