

Effect of Material and Dimensional Homogeneity on Thermo-mechanical Deformation of Brake Discs during High-speed Braking

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ABSTRACT

Brake judder is one of the most serious problems in automotive-brake systems, and brake discs play a significant role in judder. There are two types of brake judder: cold and hot. Hot judder is caused by the thermo-mechanical deformation of a disc rotor due to high-speed braking. There are several causes and shapes of the deformation, e.g., coning and circumferential waviness. Circumferential waviness 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. The author focused on the effects of material and dimensional homogeneity on the transient and permanent wave-like deformation of ventilated discs in low rotational-orders during repetitive high-speed braking. The tested discs were in two groups that had the same design and gray-cast-iron class but were cast in two foundries by using horizontal- and vertical-molding machines, respectively. Consequently the two groups of disc castings differed in the circumferential homogeneity of material. These discs were machined intentionally to have two kinds of dimensional variations in four rectangular orientations on the basis of the gating locations of each casting group. The temperature and deformation of disc rotors on the same radius were measured simultaneously during braking at a constant speed and torque. Measured deformation shapes were analyzed through fast Fourier analyses. As a result, both material and dimensional homogeneity were found to affect a disc's wave-like deformation in the 1st and 2nd rotational-orders with different significance between the two casting groups.

CITATION: Okamura, T., "Effect of Material and Dimensional Homogeneity on Thermo-mechanical Deformation of Brake Discs during High-speed Braking," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2673.

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. Leslie [1] broke down the sources of brake torque vibrations causing brake judder into three major areas: mechanical, thermal, and chemical. Fieldhouse et al. [2] broke down cold judder mechanisms into off-brake wear, corrosion, and uneven surface-film transfer. The author divides mechanical-induced judder into two mechanisms in view of brake-disc behavior [3, 4, 5] and then classifies the causes of brake judder into four as indicated in Table 1. Among the four, thermally induced judder due to high-speed braking was focused on in this study.

For studying the mechanism causing high-speed brake judder, researchers measured dynamic brake-disc geometry and temperature during braking [6, 7]. There are several shapes of disc thermo-mechanical deformation, e.g., coning and circumferential waviness. Eggleston [8] presented three modes of thermo-mechanical deformation: corrugation, butterfly, and coning. Circumferential wave-like deformation has been commonly studied through

rotational-order analyses [7, 9, 10]. On the basis of these studies, the author classifies the modes of thermo-mechanical deformation as illustrated in Fig. 1. Hot-spotting was classified as medium-order waviness in Fig. 1 since there is high order wave-like deformation corresponding to the number of ventilation vanes of a disc, which is called "rippling."

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 (LRO)
		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

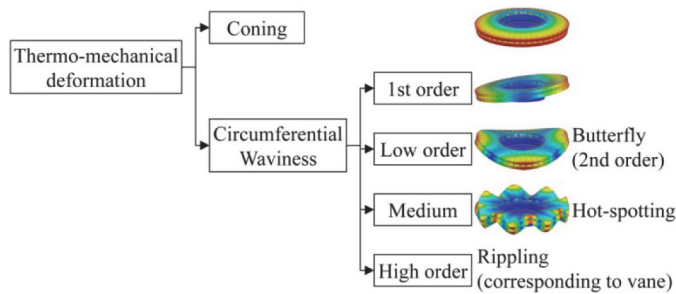


Figure 1. Shapes of disc thermo-mechanical deformation

Coning is the most common mode of thermo-mechanical deformation. Coning alone does not increase DTV or lateral runout (LRO), which both cause brake torque vibration and resultant judder, 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 and the potential of coning is mostly proportional to that of circumferential wave-like deformation. Both coning and circumferential waviness are affected by the stiffness of the friction ring and necking between the friction ring and hat. Disc design for coning reduction, therefore, is effective to reduce thermally induced brake judder [6, 11]. Okamura et al. [12] clarified the most important disc parameters affecting the thermal coning and stress of conventional front-vented brake discs on the basis of a CAE parametric study.

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, 13, 14, 15]. They evaluated the thermally induced internal load causing thermal buckling by using a simple beam model and also discussed the effect of residual stress caused by the casting process on the disc thermal deformation. Brunel et al. [16] proposed a numerical approach to obtaining the evolution of the temperature and out-of-plane displacement, i.e., circumferential wave-like deformation, during a braking test.

Thermal rippling in high rotational-orders was caused by the pillars or vanes of a disc's ventilation path. Fieldhouse et al. [2] found by using a finite element analysis that a disc's surface temperature profiles caused a rippling effect. Nagayoshi et al. [17] measured the temperature distribution of the disc friction surface during braking, which had the same pattern as the disc's ventilation vanes and caused a groan noise.

The literature described so far focused mostly on hot-spotting with medium rotational-order waviness, which was the major cause of hot judder in Europe. However, some discs used in hot-judder-claimed vehicles with a mileage of more than 10,000 km had low-order circumferential waviness. Since material homogeneity affected the differential wear [4] and thermal strength of brake discs [18], it was also suspected to affect thermo-mechanical deformation.

The author, therefore, focused on the effects of material and dimensional homogeneity on the transient and permanent wave-like deformation of ventilated discs, particularly in the low rotational-orders during repetitive high-speed braking. The tested discs consisted of two groups that had the same design and material but were cast in two foundries by horizontal- and vertical-molding machines, respectively. Consequently, the two groups of disc castings differed in the circumferential homogeneity of the material. Those discs were machined intentionally to have two kinds of dimensional variations, i.e., eccentric and slant, in four rectangular orientations on the basis of the gating locations of each casting group. The surface temperature and deformation profile of disc rotors on the same radius were measured simultaneously during braking at a constant speed and torque. The measured deformation shapes were analyzed through fast Fourier analyses. As a result, both 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.

The following sections are a description of the experimental scope and setup, test results, and findings on the effects of the material and dimensional homogeneity of brake discs on wave-like thermo-mechanical deformation.

SCOPE AND SETUP OF EXPERIMENT

Scope of Experiment

Figure 2 indicates a cause and effect diagram of thermo-mechanical deformation in various rotational-orders. High-speed or repetitive severe braking heats up disc rotors and causes thermal deformation in them. A brake disc with an insufficient thermal capacity for thermal energy loaded by braking leads to wave-like deformation through thermal buckling mechanism [2]. Increased contact pressures at the peaks of the wave-like deformation produce more friction and heat and consequently increase thermal expansion and deformation of the disc. This thermal deformation, therefore, is a self-excited phenomenon.

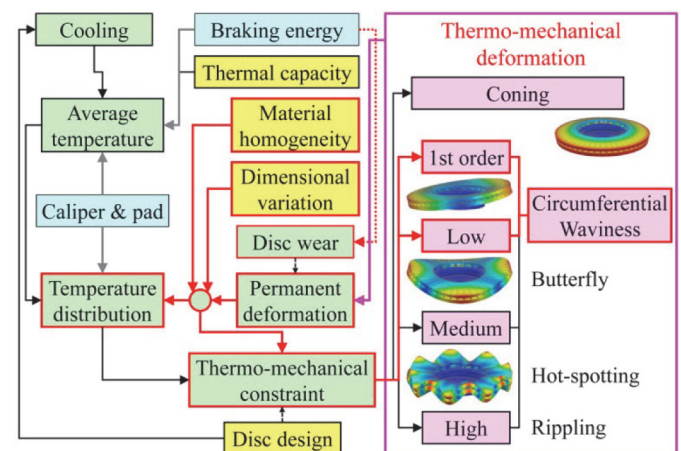


Figure 2. Cause and effect diagram of thermo-mechanical deformation in various rotational-orders

Bryant et al. [9] mentioned that repeated testing of the same brake disc caused hot-spotting to shift. The positions of peaks or valleys of low-order circumferential waviness, however, may correspond to the profiles of a disc's inhomogeneity in either or both material and dimension if the inhomogeneity causes thermal deformation. This study, therefore, was conducted to study the relationship between the material and dimensional homogeneity of ventilated brake discs and the amplitude and phase angle of a disc's transient and permanent wave-like deformation profiles, particularly in low rotational-orders during repetitive high-speed braking.

Disc Samples

The circumferential homogeneity of disc rotors mainly depends on the molding orientations and gating designs in their casting process. 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. Horizontal molding machines (illustrated on the left in Fig. 3) usually produce circumferentially more homogeneous castings than do vertical ones (on the right in Fig. 3) due to the effects of gravity. The circumferential homogeneity of a horizontal-molded disc tested in this study, which was measured with a graphite structure index [4], was better than that of a vertical-molded one. To avoid the effect 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.

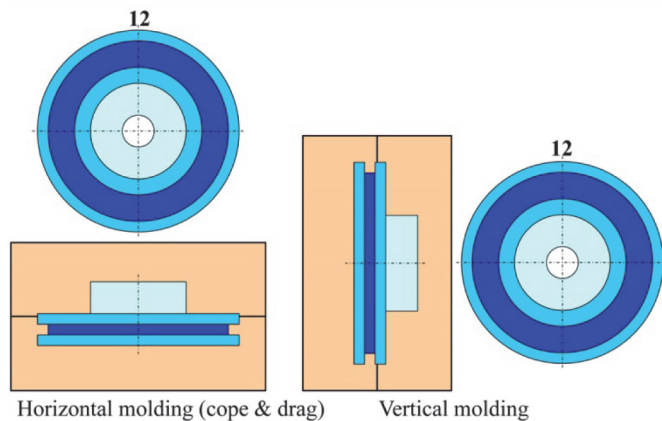


Figure 3. Horizontal and vertical moldings

The coordinate system for each disc-casting group was respectively fixed on the basis of the gating locations. To parametrically vary the distribution of the coolability and stiffness of the friction ring and the stiffness 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., eccentric and slant, as follows.

Figure 4 illustrates the eccentric machining of the outer circumference of the ventilation vanes from the pilot hole of the fixing plate of a disc rotor. Disc castings were clamped eccentrically during their machining process to have dimensional variations in four rectangular orientations, i.e., at 3, 6, 9, and 12 o'clock, in the

casting-fixed coordinate system. To avoid the effect of fixing bolt locations on a disc's thermal deformation, one of the bolt holes was drilled in the same orientation as that of the eccentricity of the ventilation vanes.

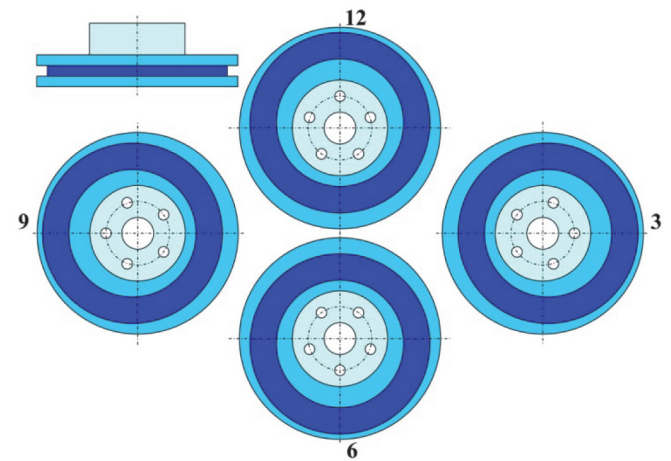


Figure 4. Dimensional variations by eccentric machining of ventilation-vane outer-circumference from fixing-plate pilot-hole

Figure 5 illustrates 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.

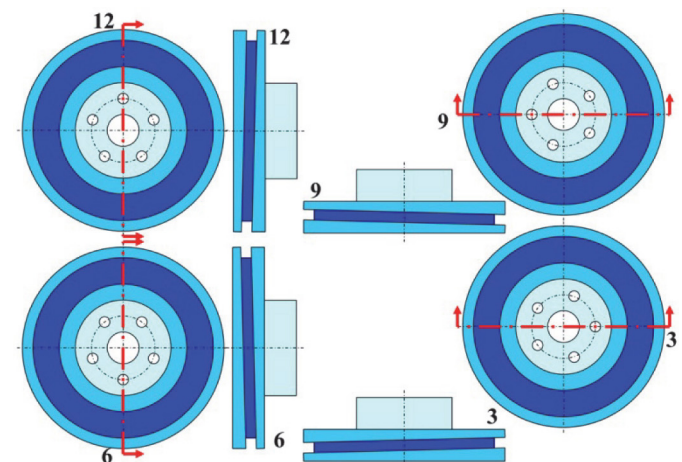


Figure 5. Dimensional variations by slant machining of ventilation-path plane

Experimental Setup

To study the thermal deformation of brake discs during braking, it is necessary to simultaneously measure the temperature and displacement of both friction surfaces of the rotating discs. This measurement also needs to synchronize to the disc's coordinate system rotating at a high speed. Non-contacting measurement of a disc's surface displacement and temperature was started as early as 30 years ago, e.g., by Inoue [6]. Today, capacitive displacement sensors, pyrometers, and thermography have been used commonly [1, 11], is, however, difficult to measure the temperature and deformation