

Differential Effects of Dimensions on Various Vibration Modes of Brake Disc Rotors

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ABSTRACT

The propensity of brake squeal depends significantly on the vibrational characteristics of disc rotors. In this study, we focused on the differential effects of disc dimensions on the natural frequencies of various vibration modes. We analyzed the results of the CAE factorial experiments presented in our previous paper, which were conducted on four disc rotors with different designs such as front-and back-vented and solid discs. As a result, the effects of disc dimensions on natural frequencies were confirmed to depend on vibration modes, their orders (or the number of nodal diameters), and the basic design of disc rotors. The dimensions that change the stiffness of the friction ring such as ventilation-path width and fin thickness had larger effects on the out-of-plane circumferential modes of high orders than those of low orders. The dimensions around the necking, on the other hand, had a large effect on the low-order modes. The significance of these effects depends on the basic design of disc rotors as well. The effects of some typical dimensions on natural frequencies obtained from CAE experiments were further verified by comparing them with physical test results.

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INTRODUCTION

Among the noise, vibration, and harshness (NVH) problems in automobiles, brake squeal still annoys consumers, OEMs, and brake component suppliers. Its propensity depends significantly on the vibrational characteristics of brake disc rotors, particularly their natural frequencies. Therefore, the SAE Brake NVH Standards Committee developed detailed recommendations (J2933) [1] for brake rotor modal frequencies measurement, data reporting, and use in quality control. Before this standard was published, Abdelhamid et al. presented a paper [2] in the 2010 SAE Brake Colloquium, which addressed the need for formalizing measurement techniques of rotor modal frequencies and documenting the proper set up and measurement parameters and proposed a rotor mode classification system so that important rotor modes may be tracked.

There are two approaches from the viewpoint of natural frequencies to maintain stable vibrational characteristics of disc rotors for reducing brake squeal. The first approach is optimizing the eigen-mode alignment of disc rotors and the second is reducing their variations. For optimizing the eigen-mode alignment of a disc rotor, Nelagadde et al. [3] presented a methodology applying a shape optimization technique to the design of an automotive ventilated disc-brake rotor. The

authors [4] constructed an original design system for brake disc rotors with excellent accuracy of calculated frequencies, which helps us to design new disc rotors with optimized eigen-mode alignment very quickly and accumulate knowledge for controlling eigen-mode alignment.

The variation in natural frequencies of disc rotors is caused by various factors in their manufacturing process from foundry through machining. To reduce the frequency variation, we analyzed the factorial effects of material and dimensional properties on natural frequencies of disc rotors with various designs and determined the critical factors affecting them [5]. Lee et al. [6] required that brake disc rotors should maintain $\pm 1.5\%$ of frequency variation for robustness (assuming that all other components should be decoupled sufficiently) and studied the effects of chemical components and casting process of gray-iron disc rotors on their natural frequency variations. Kuehl [7] studied the aging effect on the natural frequencies of gray-cast-iron disc rotors and concluded that the observed aging effect could be explained as a result of the relaxation of stresses put into the iron by the casting process itself, shot blasting, and/or machining.

In our previous paper [5], we analyzed the effect of the material and dimensions of disc rotors on their natural frequencies in out-of-plane (OP) and in-plane circumferential

(IPC) modes as a whole respectively. We then applied the analyzed results to the product and process design of disc rotors and achieved a $\pm 3.0\%$ variation in disc natural frequencies. In this study, we focused on the differential effects of disc dimensions on natural frequencies of various vibration modes in order to control modal alignment more freely and maintain frequency variation less than $\pm 3.0\%$. We analyzed again the finite-element-analysis (FEA) results obtained from the computer-aided-engineering (CAE) factorial experiments presented in our previous paper [5], which were conducted on four disc rotors with different designs as front- and back-vented and solid discs. As a result, the effects of disc dimensions on natural frequencies were confirmed to depend on vibration modes, their orders (or the number of nodal diameters), and the basic design of disc rotors. The dimensions that change the stiffness of the friction ring such as ventilation-path width and fin thickness had larger effects on the out-of-plane circumferential (OPC) modes of high orders than on those of low orders. The dimensions around the necking, on the other hand, had a large effect on the low-order circumferential modes. The significance of these effects depends on the basic design of disc rotors as well.

The effects of some typical dimensions on natural frequencies were further verified by comparing the analyzed results obtained from CAE experiments with physical test results. Assumed reasons for the differential effects of disc dimensions will be discussed additionally.

The differential effects of disc dimensions described in this study is significant to reduce variations in natural frequencies of products within a factory less than $\pm 3.0\%$ and can be applied to maintain consistency between the products from different factories in global sites. The knowledge obtained from this study is also effective for designing the optimal alignment of various vibration modes of new brake disc rotors and controlling the coupling potentials between out-of-plane and in-plane modes.

CAE EXPERIMENT IN OUR PREVIOUS STUDY

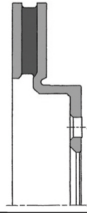
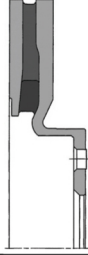
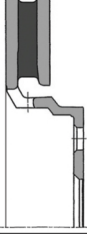
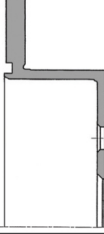
Design of CAE Experiment

The design of experiment (DOE) (namely, L36 orthogonal arrays for four disc rotors with various designs) and the FEA results were carried over from our previous study [5], which was conducted in order to determine the critical factors for reducing variations in the natural frequencies.

Various designs of brake disc rotors, such as solid and ventilated with conventional front-vented and back-vented cooling paths, are used today. Effects of disc dimensions on natural frequencies were assumed to depend on these designs. Therefore, we selected three typical ventilated and one solid discs, which are described in Table 1. Disc A is small and conventional front-vented, Disc B is large front-vented with

deep goose necking, Disc C is mid-sized back-vented with holes in necking, and Disc D is a solid drum-in-hat disc.

Table 1. Discs for CAE experiment [5].

Disc	A	B	C	D
Type	Front-vented		Back-vented	Solid with drum-in-hat
	Shallow necking	Deep necking		
Configuration (in same scale)				
Outer diameter	260 mm	320 mm	296 mm	298 mm
Disc thickness	22 mm	28 mm	28 mm	10 mm

We used L36 ($2^{11} \times 3^{12}$) orthogonal arrays after taking into account the number of assignable factors and the time needed for CAE analyses. Factors assumed to be critical were selected on the basis of our knowledge of the general effects of the basic design, dimensions, and material properties of brake disc rotors on natural frequencies. The levels of the selected factors were determined by taking into account requirements of various customers and our production capabilities. Basically, the levels for the dimensions finished in machining process were selected following the international standard tolerance grades IT12 to IT14 [8], while those made in the casting process were selected following the casting tolerance grade CT7 [9].

Table 2 lists the major factors, their variation ranges, and levels. The number of fins in ventilated discs is believed to largely affect the bending stiffness of the friction ring and resultant out-of-plane mode frequencies. This, however, was not taken into consideration in our experiments since in the original study we focused on determining the critical factors for reducing variation in natural frequencies caused during the manufacturing process.

Table 2. Major factors and levels for CAE experiment [5].

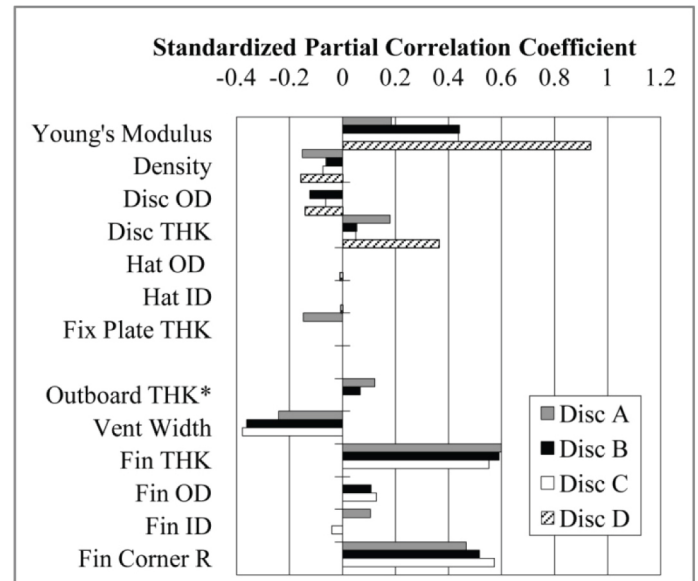
Factor	Range	Level
Young's modulus (GPa)	20	3
Density (kg/m ³)	200	3
Disc outer diameter (mm)	1.2	2
Disc thickness (mm)	0.4	3
Hat outer diameter (mm)	0.8	2
Hat inner diameter (mm)	0.8	2
Fixing plate thickness (mm)	0.6	2
Followings are only for ventilated discs		
Outboard plate thickness (Inboard for Disc C) (mm)	1.4	3
Inboard inner diameter (Outboard for Disc C) (mm)	1.2	2
Ventilation-path width (mm)	1.4	3
Fin thickness (mm)	1.4	3
Fin outer diameter (mm)	3.2	3
Fin inner diameter (mm)	2.8	3
Fin-corner radius (mm)	1.8	3

Eigenvalue Analysis

We used a real eigenvalue analysis to determine the factors affecting natural frequency variation for brake disc rotors. In the real eigenvalue analysis, all of the degrees of freedom, which are computationally available, were allotted only on a brake-disc model consisting of about 50,000 hexahedron elements. Therefore, we could precisely estimate the effects of such small dimensional variation, which are described in [Table 2](#), on the natural frequencies. We conducted CAE experiments with the help of our original brake disc design system [4]. This system automatically picked out eigen-frequencies less than 20 kHz for OPC nodal-diameter (ND) modes of up to 12 ND and IPC modes of up to the third order from 36 FEA runs for each of the four disc rotors in [Table 1](#).

Macroscopic Factorial-Effect Analysis of CAE Experimental Results

The material and dimensional properties in [Table 2](#) were assigned as independent variables, and their effects on the natural frequencies were studied using multiple regression analysis (MRA). The frequencies of OPC ND and IPC modes respectively for each model for FEA in the CAE experiments were standardized on the basis of those for the FEA model with the nominal values of the material and dimensional properties. These standardized frequency indexes were used as dependent variables in MRA. As a result, the significant factors affecting the natural frequencies and their contribution were determined. The standardized partial correlation coefficients for OPC ND modes obtained from MRA are illustrated in [Fig. 1](#). Note that the correlation coefficients shown in [Fig. 1](#) depend on the disc designs, ranges of assigned factors in [Table 2](#), and the combination of the two.

**Figure 1. Influential factors and their contribution on OPC ND mode frequency (*: Inboard THK for Disc C) [5].**

DIFFERENTIAL EFFECT OF DIMENSIONS ON VARIOUS VIBRATION MODES

Necessity of Microscopic Factorial-Effect Analysis

In our previous study [5], we assumed the effects of dimensions to be constant in OPC and IPC modes respectively. We therefore standardized the natural frequencies in OPC and IPC modes and analyzed their factorial effects. This effectively achieved a $\pm 3.0\%$ variation in disc natural frequencies by applying the knowledge obtained from our previous study to the product and process design of disc rotors. It, however, was not sufficient to reduce variations in natural frequencies further. We, therefore, examined the details of the CAE experimental results in our previous study in order to control modal alignment more freely and maintain less frequency variation than $\pm 3.0\%$.

[Figures 2 and 3](#) illustrate the frequency changes over OPC ND and IPC modes obtained from 36 runs in DOEs for Discs B and D. Frequency changes in OPC ND modes of Disc B in particular are far larger than those in IPC modes. Discs B and D have similar variance in IPC modes, whose frequency changes are mostly caused by Young's modulus. Disc B, on the other hand, exhibited larger changes in frequencies and more differential effects of disc dimensions on natural frequencies of OPC ND modes than the solid disc D. These were caused by the variations in dimensions around