

Statistical Analysis of Impacts of Surface Topography on Brake Squeal in Disc-Pad System

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ABSTRACT

A disc-pad system is established to study impacts of surface topography on brake squeal from the perspective of statistical analysis. Firstly, surface topographies of brake disc and pad are precisely measured on the scale of micron and are statistically analyzed with a three-dimensional evaluation system. Secondly, the finite element model of brake disc and pad without surface topographies is created and verified through component free modal tests. Thereby the valid brake squeal model for complex modal analysis is built with ABAQUS. An effective method is developed to apply interface topographies to the smooth contact model, which consequently establishes sixty brake squeal models with topographies. Thirdly, impacts of surface topography on brake squeal are studied through comparison and statistical analysis of prediction results with and without topographies.

The analysis manifest that topography amplitudes and evaluation index deviations of brake pad far exceed those of the disc, indicating the surface of brake pad is relatively much rougher. Moreover, squeal prediction results confirm that surface topographies can both cause contact pressure variation and affect the randomness of brake squeal characteristics, namely, numbers and values of squeal frequencies. Additionally, contact interface topographies can cause system modal coupling states to change, which further affects squeal tendency and uncertainty. Meanwhile, statistical characteristics and variations of surface topographies demonstrate close correlation with those of brake squeals. Hence the consideration of surface topographies can effectively improve squeal prediction precision, and stochastic characteristics of brake squeal during tests can be well justified by the time-varying surface topography.

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INTRODUCTION

Brake squeal has long been a confusing problem in automotive NVH field because of the prevalently adopted complex modal analysis fails to reach a satisfactory prediction precision [1, 2, 3, 4, 5, 6]. Brake squeals in previous tests have demonstrated definite randomness and uncertainty, while simulation results under same conditions remain consistent [7, 8]. One of the key reasons is that contact interface topographies [9, 10, 11, 12, 13, 14, 15] and their friction induced time-varying stochastic characteristics during tests have been ignored in simulations. The contact pressure, which directly affects brake squeal [7, 8, 16, 17, 18, 19, 20, 21], can be greatly influenced by surface topography due to its significant impacts on contact stiffness and frictional wearing characteristics [16, 17, 18, 19, 20, 21], which can cause variations of contact pressure. Therefore, it is essential to establish a brake squeal model with surface topographies.

Despite previous achievement [9, 10, 11, 12, 16, 21] in topography's impacts on brake squeal, limitations of research so far exist as follows: firstly, a brake squeal model with complete contact interface topographies [21] has never been built, and the effective dimension of topography modelling is still inconclusive; secondly, practical evaluation index of surface topography [9, 19] is currently insufficient and statistical analysis of stochastic characteristics of brake squeal is yet unavailable; thirdly, evolvement from statistics of surface topography to probability density of stochastic squeal hasn't been systematically studied.

Under such context, this paper establishes a disc-pad system, designs a highly precise topography measurement and creates a comprehensive three-dimensional evaluation system. Besides, complete interface topographies are firstly introduced to actualize the real contact states, which can effectively benefit squeal prediction precision. Moreover, squeal prediction results with and without surface topographies are compared and statistically analyzed. In addition, this study conducts

correlation analysis of statistical characteristics of surface topography with those of stochastic brake squeal. Thus illuminates the probability density evolvement from topography to squeal and further enlightens brake squeal mechanism.

SURFACE TOPOGRAPHY MEASURING TEST AND STATISTICAL ANALYSIS

Test Object, Equipment and Method

The disc-pad system (Figure 1) in this study is composed of ventilated disc and brake pad (consists of frictional lining and brake back-plate). The ventilated disc is made of grey cast iron and the frictional lining is made of semi-metal-based non-asbestos brake friction material.

The test equipment CV-2000 (Figure 2) possesses a vertical resolution of $0.5\ \mu\text{m}$ and a horizontal sampling step of $2\ \mu\text{m}$. When the probe slides along the surface in +X direction, variations of topography in direction Z can be recorded through contact with probe.

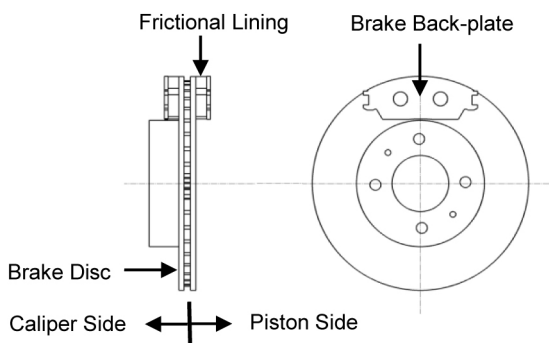
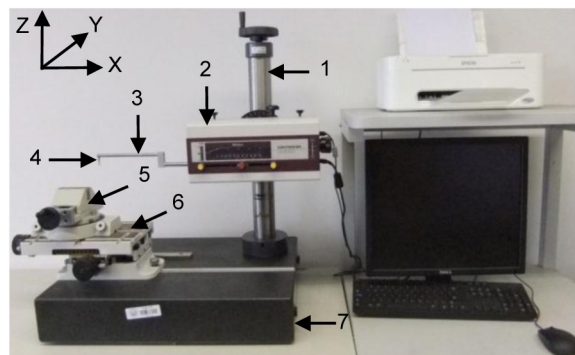


Figure 1. Disc-pad System Assembly Diagram



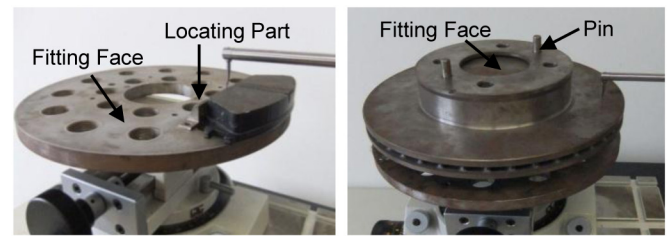
1-upright column 2-gauge 3-measuring arm 4-probe 5-caliper 6-cross table 7-foundation support

Figure 2. CV-2000

Two sets of fixtures (Figure 3) are designed for pad and disc respectively. A locating part is imported for fixing the pad and the disc is fastened to its fixture with two pins. The upper face

of foundation support is selected as horizontal base and fitting faces are parallel to the base with an error tolerance of $0.02\ \mu\text{m/mm}$.

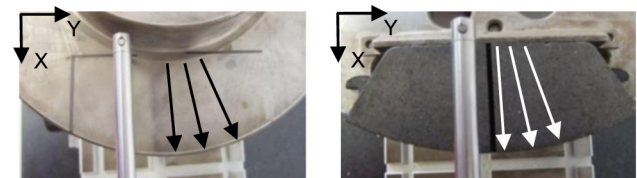
As shown in figure 4 (a): starting from outer edge of the tool withdrawal groove around disc hat, the probe slides outwards along +X direction till the outer edge of disc to obtain the topography of one radial generatrix. Each radial generatrix is measured twice for consistency check by indexes of roughness and straightness with 5% relative error tolerance. Complete topography of the entire annular contact area can be obtained by rotating the caliper clockwise 1° each time for 360 times. Same method applies to the brake pad with wrap angle of 60° .



(a) Pad-fixture Assembly

(b) Disc-fixture Assembly

Figure 3. Test Piece-fixture Assembly Diagram



(a) Disc Measuring Test

(b) Pad Measuring Test

Figure 4. Surface Topography Measuring Test

Surface Topography Evaluation System

This study establishes a three-dimensional topography evaluation system (Appendix 1) consisting of eight indexes from four categories of amplitude, spacing, shape and function. The 3D polar coordinate system (p, θ, z) is introduced and the plane ($p, \theta, 0$) is defined as datum plane. M and N represent numbers of point measured in the circular and radial directions.

Surface Topography Visualization and Statistical Analysis

Measured surface topographies are visualized by MATLAB. Sixty disc topography samples are created as shown in figure 5 (a): starting from the initial assembly position, the first sample is selected by a pad shaped window (in black) with wrap angle of 60° . Then the window rotates 6° clockwise for the second sample (in red). Thus creates sixty topography samples with serial number 1 to 60 when the window rotates sixty times and eventually covers the entire frictional contact area within 360° . Statistics of sixty disc topography samples on both sides is illustrated in figure 6 and appendix 2.



Joint analysis of figure 5, 6 and appendix 2 indicates: firstly, amplitudes of peaks and valleys of pad topography are approximately 4 to 7 times of those of disc topography. Average value of pad topographies are about 10 to 20 times larger compared with disc topography. Hence the pad surface is relatively much rougher.

Secondly, a relative lower average S_{sm} of disc topography means it changes more frequently in a “positive-negative-positive” pattern; namely, the disc topography has a more uniform distribution between two sides of the datum plane. A higher S_{ds} indicates more topography peaks per unit area on the disc than on the pad.

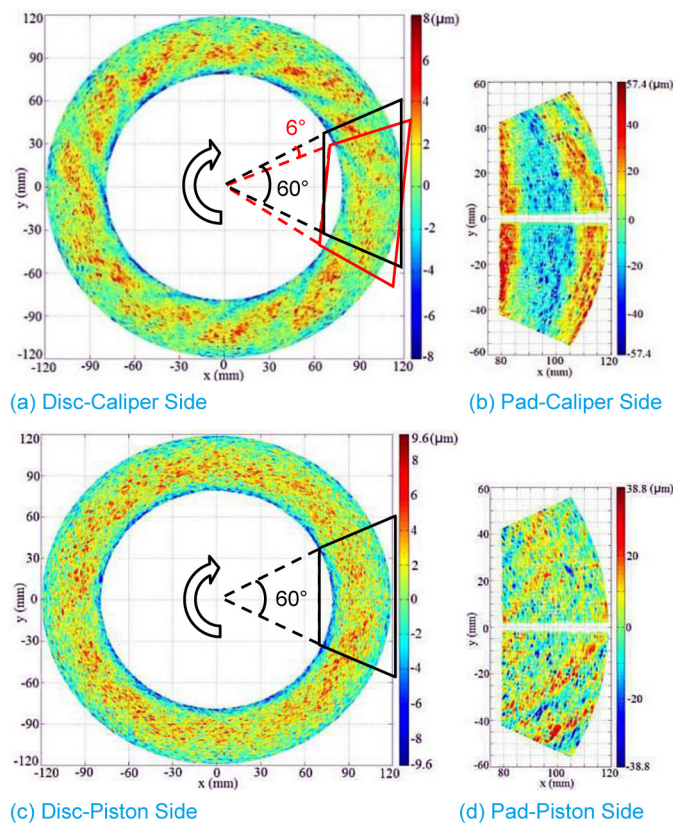


Figure 5. Surface Topography Visualization

Thirdly, $S_{\Delta q}$ of pad topography is about 4 to 8 times of that of disc topography. Thus the slop deviation of each measured point on pad surface towards its average slop exceeds that of disc topography. Pad topographies possess both positive and negative S_{sk} , while S_{sk} of disc topographies are all negative. Thereby the asymmetrical parts of disc topography tend to distribute below the datum plane.

Fourthly, a larger S_{bi} of pad topography means pad surface has a better supporting performance.

Each index of disc topography in figure 6 demonstrates complicated distribution and variation among sixty samples, despite only 10% topography difference between adjacent two

samples. Thus substantiates that these indexes are highly sensitive toward topography change and are effective for topography evaluation.

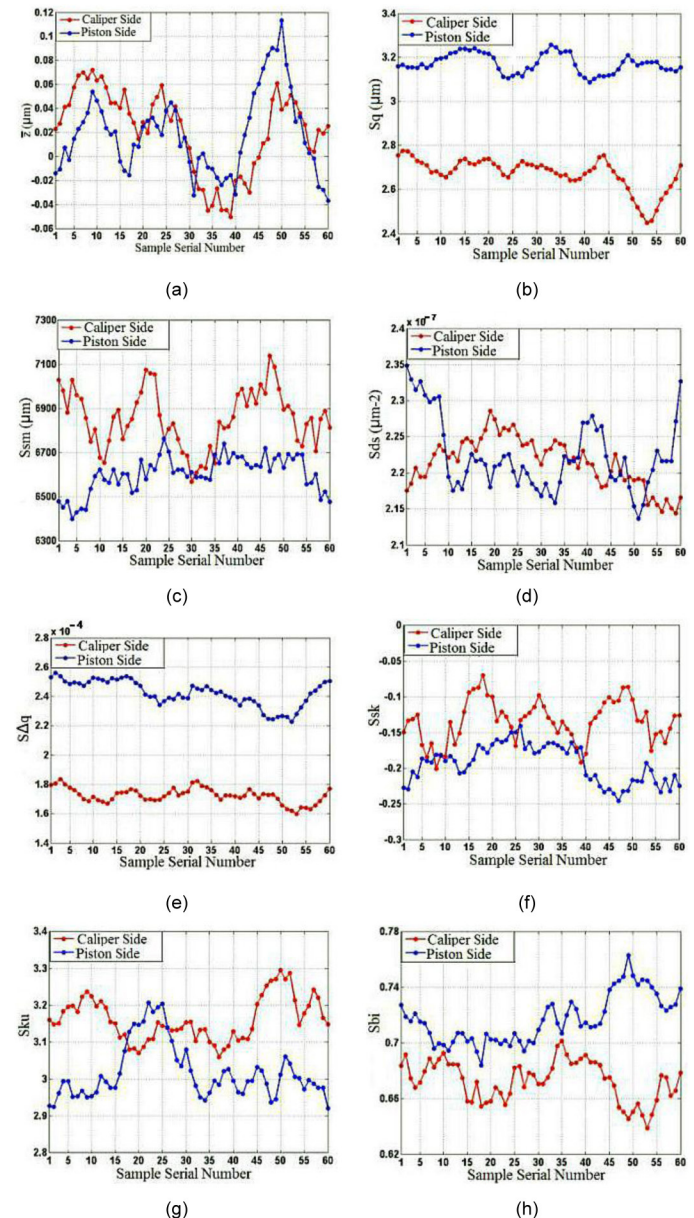


Figure 6. Statistical Comparison of Disc Topography Evaluation Index

BRAKE SQUEAL MODELLING AND VERIFICATION

Finite Element Modelling without Surface Topography

Major component geometric parameters are shown in table 1. CATIA 3D models of disc-pad system and components are illustrated in figure 7. To apply surface topographies to smooth contact model, frictional lining and brake back-plate are partly simplified as shown in figure 8. Mesh dimensions [14, 23] of components in appendix 3 are determined with HYPERMESH

Table 1. Geometric Parameters of Disc-pad System

Sign	Parameter	Unit	Value
D	Disc Diameter	mm	240
h_d	Disc Thickness	mm	19
d	Width of Disc-Pad Contact Area	mm	43
h	Radiating Rib Thickness	mm	6.9
l	Radiating Rib Length	mm	44.8
h_b	Brake Back-plate Thickness	mm	4.1
h_l	Frictional Lining Thickness	mm	12
S	Disc-Pad Contact Area	mm ²	4383
S_b	Brake Back-plate Loaded Area	mm ²	4891
S_p	Piston Circular Area	mm ²	1963.5

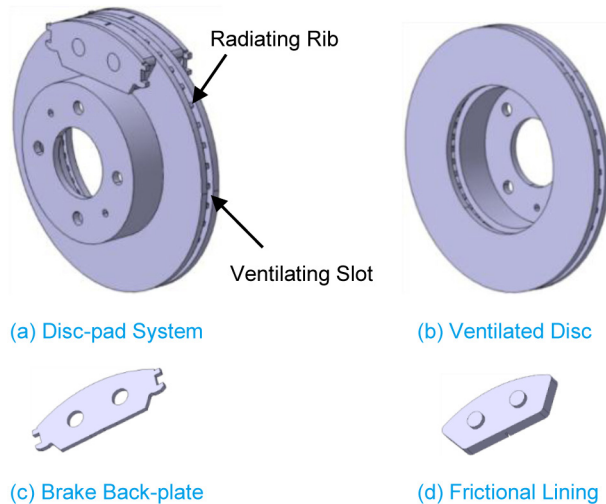


Figure 7. CATIA Models of Disc-pad System



Figure 8. Geometrical Simplification

Verification of Finite Element Analysis Model without Surface Topography

Finite element models established are verified by free modal tests (Figure 9). Free modal frequencies and vibration modes across the effective test frequency range (0~7000 Hz) are obtained. Meanwhile, free modal simulations of disc and pad without topography are conducted via ABAQUS with material properties in table 2.

Frequency comparisons (Appendix 4) between test and simulation for both disc and pad under given vibration modes all illustrate a relative error within 5%, thus verifies the effectiveness of smooth surface finite element models.

Table 2. Material Properties

Part	Young Modulus (Mpa)	Poisson's Ratio	Density (tonne/mm ³)
Disc	1.22×10^5	0.23	7.19×10^{-9}
Frictional Lining	8.6×10^3	0.30	2.615×10^{-9}
Brake Back-plate	1.82×10^5	0.30	7.80×10^{-9}

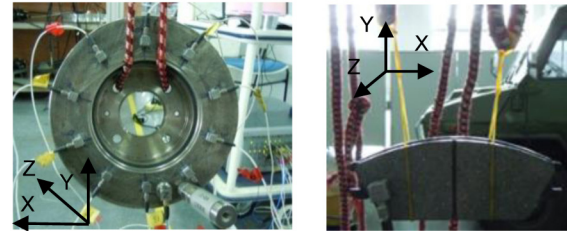


Figure 9. Free Modal Test Setting of Disc and Pad

ABAQUS Based Brake Squeal Modelling for Complex Modal Analysis

Brake Squeal Modelling without Surface Topography

Verified finite element model is imported into ABAQUS according to assembly relationship. Contact between disc and frictional lining is defined as "surface-to-surface contact", and connection between frictional lining and back-plate is defined as "Tie". The 3 translational DOF and 2 rotational DOF (X, Y) of disc hat end face are restrained. Both translational and rotational DOF (X, Y) of the pad are restrained.

Equivalent even-distributed pressures are applied on back-plates on both sides in direction Z. In equation $P_b \cdot S_b = F = P \cdot S_p$, F is brake force, P is brake hydraulic pressure, S_p and S_b represent areas of piston sub-face and back-plate, P_b (0.5Mpa) refers to pressure on back-plate. Simulation period is 5s, disc rotates at 100r/min and equivalent frictional coefficient is 0.4.

Application of Surface Topography

To apply surface topography equates changing coordinate values Z of each node on contact interface. Take the disc as an example: firstly, measured topography (2μm/step) is radially resampled to match the radial dimension (0.5mm/mesh) of the finite element model. As the annulus contact area of disc ranges 40mm radially and measured 1° circumferentially each time, topography matrixes (360×81) can be achieved for both sides of disc. Secondly, matrixes (360×81) of HYPERMESH serial node numbers as well as corresponding original coordinate values Z can also be obtained. Thirdly, MATLAB program is designed to replace original coordinate values Z with measured topographies. Thus applies topographies successfully.

Similar rules apply to the pad except the discontinuity at the circumferential bisector of contact area due to the chip space. Besides, the number of nodes with topography on each radial generatrix varies due to the straight side of pad.