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ANALYSIS OF JUDDER VIBRATION ORIGIN IN AUTOMOTIVE DISK BRAKE

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Abstract

Frequent braking may generate severe low frequency vibration due to non-uniform frictional contact between disk and pads. Under critical conditions, this non-uniform contact leads to locally concentrated heating, growing to hot spots in disk brake. Finally hot spot roughness induces the judder which makes the vehicle control difficult and even dangerous. Judder phenomenon for high quality of automotive brake design cannot help understanding the relationship of number of hot spots and judder vibration frequencies. This paper is to analyze the role of hot spots in judder vibration of automotive disk brake. Vibration and hot spot was measured in accordance with rotation of disk and pressure of master cylinder for finding the factors that causes hot spot phenomena. The vibration modes of disk brake are experimentally measured and analytically examined by the finite element method. Judder vibration measurements were conducted by using chassis-dynamometer. Hot spot measurements were photographed by using infrared camera. As results, the relationship between hot spot phenomena, and mode shape, pressure of master cylinder and rotation speed of disk respectively, was achieved by hot spot measurement and frequency analysis.

INTRODUCTION

During the braking of any motion body, its kinetic energy is converted into heat energy by means of frictional heating. This friction force also generates a frictional vibration and many other related phenomena. Automotive braking system plays a critical in the safety of the vehicle and its occupants. Nowadays hot judder phenomena have emerged as a severe problem to long term driving vehicles that face frequently braking.

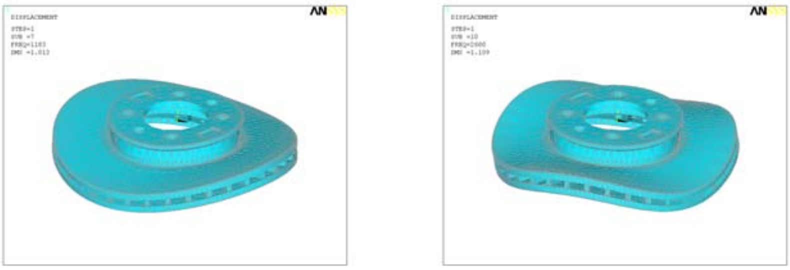
Judder vibration defines that low frequency (10~30Hz) [1] vibration of high magnitude occurs in steering system when braking is operated. It usually occurs between 80 to 140km/h of vehicle speed, and this speed is the same as excitation band of low frequency between 10 to 20Hz. And disk vibration by frequent braking generates locally non-uniform contact between brake disk and pad. This non-uniform friction makes brake disk have locally heat concentration and hot spots are grown. [2]~[5] Growth of hot spots increases magnitude of fictional vibration that influences excitation force of judder vibration.[6]

It is important to find the main factors that are responsible for origin of hot spots. In this experimental study, the vibration and hot spot was measured in accordance with disk rotation speed, and pressure of master cylinder for finding the main factors that causes hot spots. Hot spots were measured by using infrared camera. For comparing hot spot aspects with mode shapes of disk, mode shapes were measured by performing modal test, and analyzed by using finite element analysis. Relation between hot spot phenomenon, and rotation speed of disk was achieved by hot spot measurement and frequency analysis.

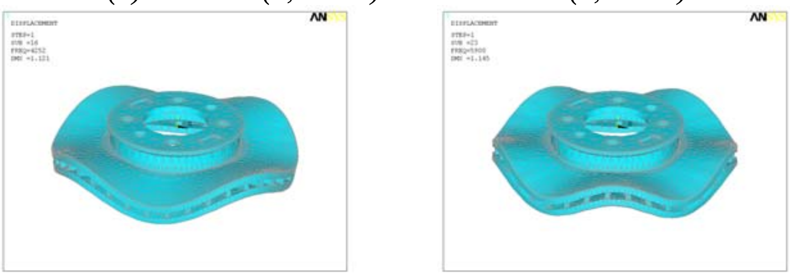
FINITE ELEMENT ANALYSIS

For achieving natural frequencies and mode shapes of brake disk, finite element analysis was performed by using ANSYS 8.0, a commercial finite element analysis software. The element type was used by Solid 187 (3-D 10-node Tetrahedral Structural Solid). The number of elements and nodes are 28,914 and 54,601, respectively. Table 1 shows material properties of brake disk.

Figure 1 shows main modes of brake disk that are related to the measured hot spots in this experiment. Mode frequencies of 1,183Hz, 2660Hz, 4252Hz and 5900Hz could generate 4, 6, 8 and 10 hot spots, respectively.



(a) 7th mode (1,183Hz) and 10th mode (2,660Hz)



(b) 16th mode (4,252Hz) and 25th mode (5,900Hz)

Figure 1 – FE Analysis Results: Mode Shape of Brake Disk

Table 1.Material Properties of Brake Disk

Materials		Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)
Brake Disk	Cast Iron	120	0.25	7200

MEASUREMENT METHOD

Modal testing of brake disk

The number of nodal points of brake disk was 90. Vibration of each nodal point was measured by random excitation with free-free boundary condition. LMS Test.Lab was used as the analysis equipment. After the measurement of FRF (Frequency Response Function), equipment setting of the frequency band and range was adjusted to 1Hz and 1~4096Hz.

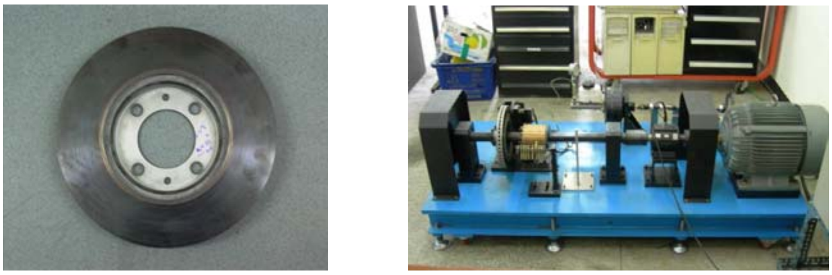


Photo 1 – Brake disk and chassis dynamo

Measurement of brake disk hot spot and vibration

Table 2 shows measurement conditions of vibration and hot spots. In this table, pressure values mean pressure of master cylinder of chassis dynamo. Chassis dynamo and infrared camera was used to measure judder vibration and hot spots.

Table 2. Measurement Conditions of hot spot and vibration

Pressure/rpm	1200	1320	1500	1800
Idling	√	√	√	√
1.5 bar	x	√	√	√
2 bar	√	√	√	√

Vibrations of disk brake were measured from initial to judder status. And auto-power spectrum and cepstrum was achieved by FFT analyzer. The frequency band and range were 1Hz and 1~6000Hz, respectively. And hot spots were measured by the infrared camera when hot spots occurred.

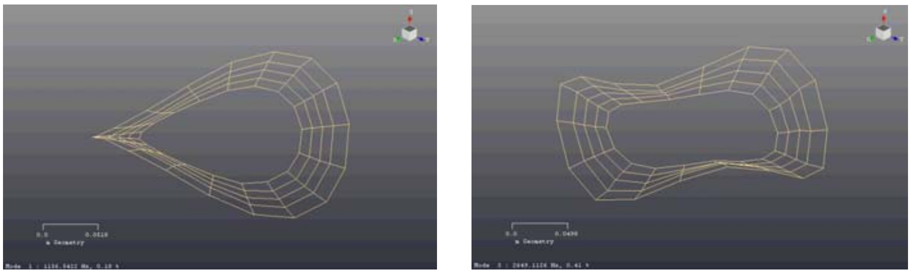
MEASUREMENT RESULTS AND ANALYSIS

Results of brake disk modal test

It was found that the mode frequencies related to hot spots are 1156Hz and 2650Hz. Mode shapes are illustrated in figure 2. The mode shapes of brake disk give a relationship between hot spots and Judder phenomenon. Table 3 shows results of FEA and measuring of mode frequency and shape of brake disk. But In this experimental results, mode shapes related to hot spots were 4252Hz and 5900Hz for the number of 8 and 10 hot spots, respectively. [7]

Table 3. Results of FEA and measuring of mode frequency and shape of brake disk

Mode	FE Analysis (Hz)	Experiment (Hz)	Error(%)
7th	1,183	1,156	2.3
10th	2,660	2,650	1.2
16th	4,252	x	-
25th	5,900	x	-

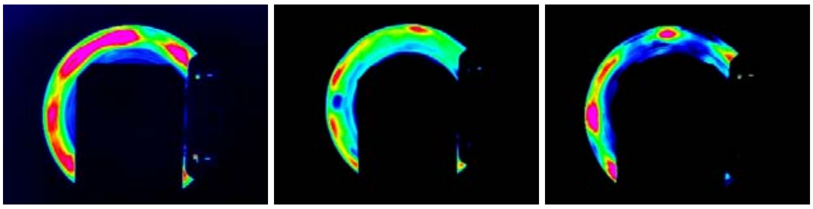


(a) 1110Hz *(b) 2460Hz*

Figure 2 – Mode shape of brake disk

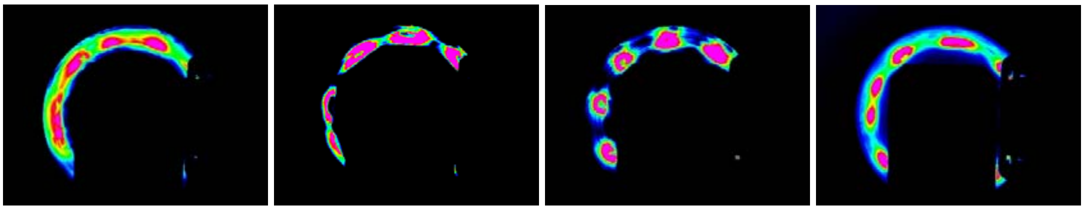
Results of hot spot measurement

Photo 2~3 shows that hot spots photographed by using infrared camera in accordance with rotation speed and pressure. The more pressure applied, the more visible and concentrated hot spots were observed. There were 8 hot spots at 1320rpm and 1500rpm (1.5bar), and 10 at 1500rpm (2bar), 1800rpm. When high rotation speed and low pressure was applied, the number of hot spot was nearly same as that in case of low rotation speed and high pressure. High pressure means increasing amplitude of random excitation. The higher rotation speed and pressure was applied, the greater number of hot spot was generated. Friction force or pressure between disk and pad is one of the most significant factors in the Judder vibration.



(a) 1200 rpm, 2bar (b) 1320rpm, 1.5bar (c) 1320rpm, 2bar

Photo 2 –photographed Hot spots (1200, 1320rpm)

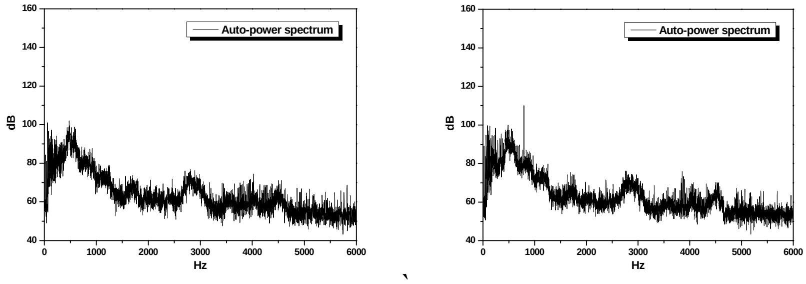


(a) 1500 rpm, 1.5bar (b) 1500rpm, 2bar (c) 1800rpm, 1.5bar (d) 1800rpm, 2bar

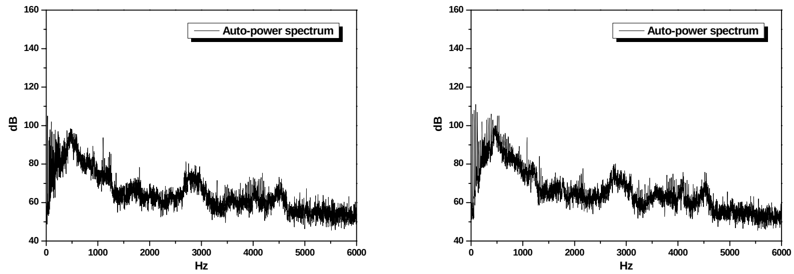
Photo 3 –photographed Hot spots (1500, 1800rpm)

Results of vibration measurement

Figure 3 shows auto-power spectrum in accordance with rotation speed in idle status. Frequency fluctuation aspect clearly presents natural frequencies of brake disk. Figure 4~6 shows auto-power spectrum and cepstrum in accordance with rotation speed and pressure of master cylinder. Frequency fluctuation of 1320rpm and 1500rpm (1.5bar) presented high amplitude of 2400Hz band of natural frequency respectively, except for low frequency band. And frequency fluctuation of 1500rpm (2bar) and 1800 rpm presented high amplitude of 2400Hz band and 3400Hz band of natural frequency. But as results of hot spot measurement, excitation of 3400 band was more significant than 2400Hz band. Frequency fluctuation was slowly changing when boundary condition was changed by idle to braking condition. And it gradually moved base or idle status to low frequency direction. According to experiment results, 2400Hz band that could generate 8 hot spots could be nearly same as 4252Hz of disk mode frequency. And 3400Hz band that could generate 10 hot spots could be nearly same as 5900Hz of disk mode frequency. The reason of these results could be estimated by transition of material properties in according to high temperature of hot spots and by non-linearity of frictional contact vibration boundary condition change. Rotation order component and $1/2f_0$ sub-harmonic vibration component is component that generates the judder vibration in cepstrum. Before hot spot occurred, these components were low value and increased by high peak value after hot spot occurred.

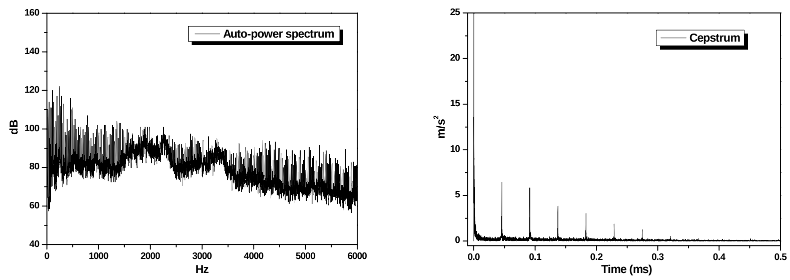


(a) 1200rpm *(b) 1320rpm*

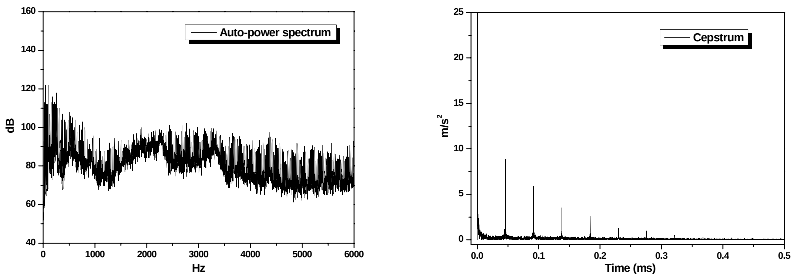


(a) 1500rpm *(b) 1800rpm*

Figure 3 – Auto-power spectrum at idle condition

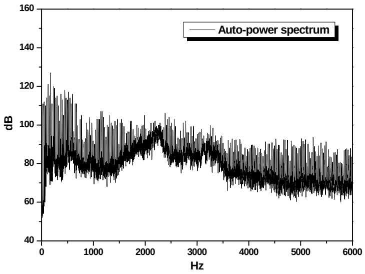


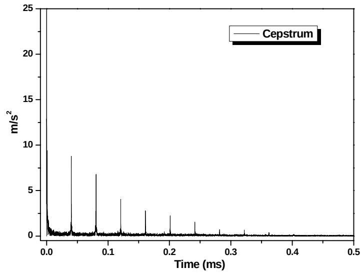
(a) Auto-power spectrum (1.5bar) *(b) Cepstrum (1.5bar)*



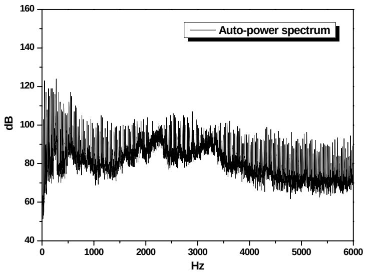
(c) Auto-power spectrum (2bar) *(d) Cepstrum (2bar)*

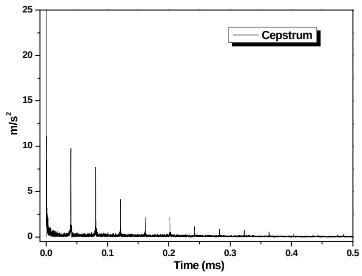
Figure 4 – Auto-power spectrum and cepstrum at 1320rpm





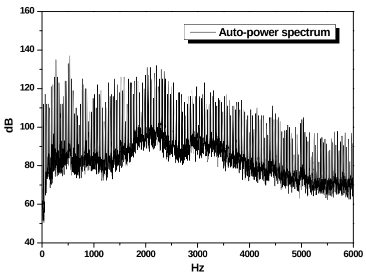
(a) Auto-power spectrum (1.5bar) *(b) Cepstrum (1.5bar)*

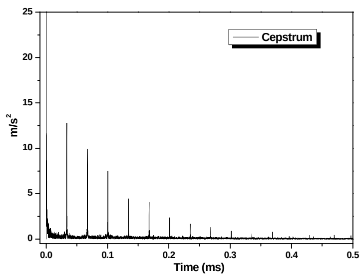




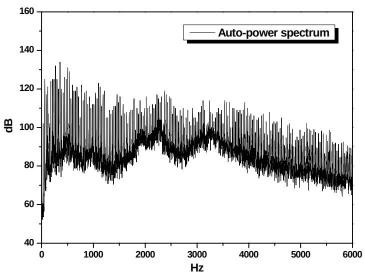
(c) Auto-power spectrum (2bar) *(d) Cepstrum (2bar)*

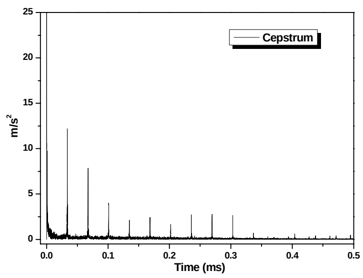
Figure 5 – Auto-power spectrum and cepstrum at 1500rpm





(a) Auto-power spectrum (1.5bar) *(b) Cepstrum (1.5bar)*





(c) Auto-power spectrum (2bar) *(d) Cepstrum (2bar)*

Figure 6 – Auto-power spectrum and cepstrum at 1800rpm

Analysis of hot spot and vibration measurement

Judder vibration is occurred by rotational order component and $1/2f_0$ sub-harmonic vibration component but when hot spots sufficiently occurs and rotational order component and $1/2\ f_0$ sub-harmonic vibration component is highly increased, severe judder vibration will occur. As results, hot spots generate excitation force of friction vibration to make judder vibration phenomenon. When amplitude of excitation force comes up to generate high frequency modes of brake disk or magnitude of excitation force comes up to generate low frequency modes, disk mode shape occurs and then non-uniform contact area occurs. As well as non-linearity of frictional contact boundary condition change is occurred, material properties transition of disk are occurred by hot spots that have high temperature. These characteristics make natural frequency of disk move to low frequency direction.

SUMMARY

(1) Main mode frequencies related to hot spots are 1156Hz, 2650Hz, 4252Hz and 5900Hz that can generate the number of 4, 6, 8 and 10 hot spots.
(2) The number of hot spots is related to vibration modes of disk. When amplitude of pressure between disk and pad is sufficiently high, it could excite high frequency band and the number of hot spot is increased.
(3) As well as non-linearity of frictional contact boundary condition is changed, material properties transition of disk are occurred by hot spots that have high temperature. These characteristics make natural frequency of disk move to low frequency direction.
(4) When rotation order component and $1/2\ f_0$ sub-harmonic vibration component is in resonance of steering system, hot spots growth increases amplitude of these components. This can make severe judder vibration in vehicle.

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