Reduction of squeal on laminated brake disc fastened with distributed contact pressure

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Abstract: - The purpose of this study is to evaluate frequency response function of laminated disc to prevent or reduce the squeal for motorcycles. Firstly, a laminated brake disc was prepared in which two thin discs were fastened by several bolts. Normal type of brake disc pressed from one thick plate was also tested to compare the data. The thickness of each plate of newly developed laminated disc was half of the normal disc to keep the constant condition of total thickness. To change natural frequency of each plate for the laminated disc, modified type of laminated disc was prepared in which they have individually different thickness. To also change the pressure distribution for contact between two thin discs, some types of curved discs were fastened to be flat to construct the laminated disc in which they had previously been machined with different height of the convex shape. The SPL(sound pressure level) of brake squeal was measured when the brake squeal was observed at conditions of low sliding speed. The difference of frequency responses of these discs was investigated to analyze the natural frequency of the brake discs. To explain the difference of the amplitude of the gain and damping ratio, contact pressure between two thin curved discs was analyzed by finite element code. Increase of the damping ratio of the discs was discussed by conventional impact test considering the difference of accelerances in the normal direction measured on the disc and phase difference in the response of normal acceleration measured on the right and left surface of laminated disc. The lamination of two thin discs was effective to reduce the SPL at the squeal. Clear resonance responses were canceled in the range of 5 to 20kHz on the modified laminated disc with two plates with individually different thickness, while they were shown on the simply laminated disc. When the disc was laminated with two thin previously curved discs with convex shape and then they were fastened, loss of friction was increased due to high contact pressure and relative displacement between two thin discs.

Key-Words: - brake squeal, brake disc, motorcycle, frequency response function, damping ratio, contact pressure

1 Introduction

Brake squeal is ongoing problem for the automotive industry. The brake squeal is perceived by users as annoying of a problem with the brake system. A lot of techniques have been utilized to prevent the brake squeal by users or dealers in front of future customers in market [1-4]. Addition of a damping material into a disc brake system is a good way to reduce the vibrations and the brake noise [5,6]. One of method has been known to put brake pad insulators consisting of a sandwich of some steel plates separated by a damping material into a disc brake system for reduction or prevention of the squeal [7]. When the pad vibrates in the bending modes, the insulator is subjected to mechanical deformations changing a part of energy of vibration into heat by shear damping. The damping material of insulators was deteriorated by thermal iterations when the brakes are applied. The others method is still not adequately explored as a substitute for brake pad insulator, though currently these customer needs can only be satisfied by use of brake pad insulators. To solve the problem some of currents, authors produced a new brake disc laminated with thin two plates to add damping elements into the brake system. However, detailed discussion on the effect has not been progressed when the new brake disc was applied.

The purpose of this study is to evaluate frequency response of laminated disc to prevent or reduce the squeal for motorcycles. Firstly, a laminated brake disc was prepared in which two thin discs were fastened by several bolts. Normal type of brake disc pressed from one thick plate was also tested to compare the data. The thickness of each plate of newly developed laminated disc was half of the normal disc to keep the constant condition of total thickness. To change natural frequency of each plate for the laminated disc, modified type of laminated disc was prepared in which they have individually different thickness. To also change the pressure distribution for contact between two thin discs, some types of curved discs were fastened to be flat to construct the laminated disc in which they had previously been machined with different height of the convex shape. The SPL of brake squeal was measured when the brake squeal was observed at conditions of low sliding speed.

The difference of frequency responses of their discs was investigated to analyze the natural frequency of the brake discs. To explain the difference of the amplitude of the gain and damping ratio, contact pressure between two thin curved discs was analyzed by finite element code. Increase of the damping ratio of the discs was discussed by conventional impact test considering the difference of accelerances in the normal direction measured on the disc and phase difference in the response of normal acceleration measured on the right and left surface of laminated disc.

2 Experimental

2.1 Configuration of test discs

Fig.1 shows five types of brake discs used in this study. Normal type of brake disc conventionally pressed from one thick plate was denoted as TYPE-S. Four types of modified laminated brake disc were prepared in which two thin discs were fastened by several bolts. For modified types laminated discs with two plates of 3mm/3mm, 3.75mm/2.25mm in thickness were denoted as TYPE-D3.00 and TYPE-D3.75, respectively. The total thickness of each disc was same of that of normal disc. To change the contact pressure distribution between two thin discs, some types of curved discs were subjected to constraint displacement to be flat in fastening in which they had previously different height of the convex shape. The laminated discs composed with previously curved two thin discs of 0.2mm and 0.4mm in height of convex was denoted as TYPE-C0.2 and TYPE-C0.4, respectively. The external diameter of the disc was 292mm and the brake disc was made of SUS410dB quenched by high frequency induction heater, respectively.

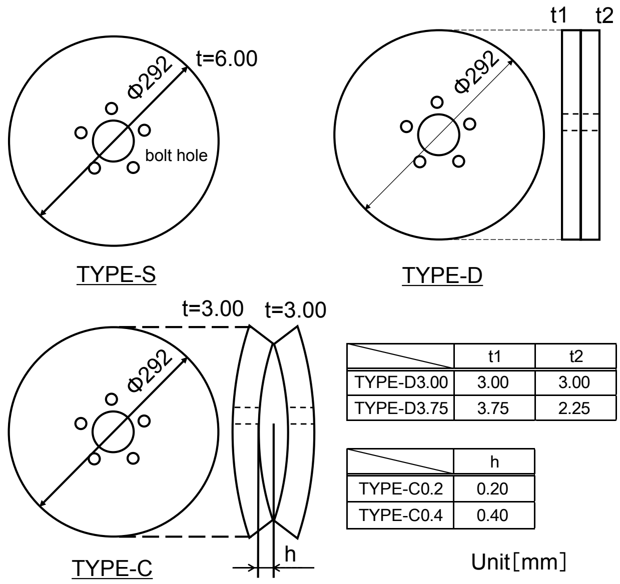


Fig.1 Configuration of brake discs.

2.2 Braking test

Fig.2 shows the experimental system used in the braking test. The disc was rotated by the AC motor and rotational speed of the disc was controlled by an inverter at 30 rpm. The caliper had four pistons and two pads oppositely set on the disc. The pads were pushed to the disc by the line pressure (0.5MPa) through four pistons to apply the normal force. The SPL of the brake squeal was measured to investigate the frequency distribution of the squeal. Before each braking test, the discs heated by the last tests were cooled below 50^{O}C to eliminate the influence of initial thermal deformation of the brake discs.

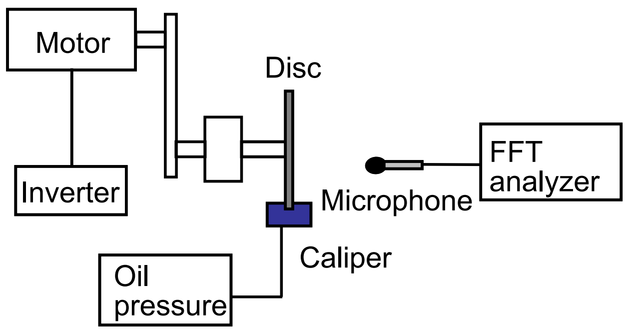


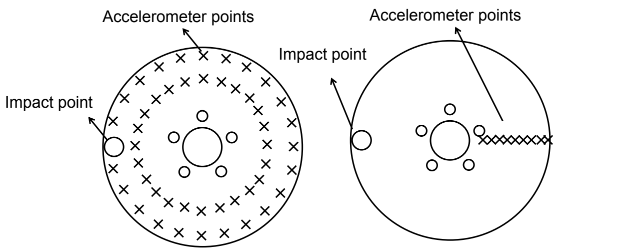
Fig.2 Brake squeal test apparatus.

2.3 Natural frequency test

The frequency response was investigated to analyze the natural frequency of the brake disc. The frequency response function was determined by exciting disc with an impact hammer and the acceleration response with an acceleration pick up. The impulse force was applied to the thickness direction of the disc. During the measurements, the disc was fixed by a shaft in order to simulate under braking. The impact point was kept at a fixed point and the accelerometer was put at the location divided 15^o apart in circumference direction or divided 10mm apart in radial direction of the disc as shown in Fig.3 (a) (b). The damping ratio for each natural frequency of disc was also measured using 3dB method. The damping ratio is defined by

$$\xi = \frac{\Delta f}{2f} \times 100 \qquad (1)$$

where Δf is the frequency band width at 3dB below the resonant peak and f is the resonant peal frequency. The properties for FFT analysis are described in Table 1.



(a)Accelerometer position divided 15° apart in circumference direction

(b) Accelerometer position divided 10mm apart in radial direction

Fig.3 Measurement point for frequency response analysis.

Table 1 Properties for FFT analysis.

symbol	Parameter	Description
fs	20000[Hz]	Sampling frequency
Ls	4096	Sampling length
Wf	Hanning	Window function

3 Result and discussion

3.1 Reduction of brake squeal on laminated brake disc

Significant peak of SPL was observed at about 14.4 kHz of frequency on both of TYPE-S and TYPE-D3.00 disc at squeal, while there was difference in averaged SPL where 77.1dB and 53.6dB were observed by each disc, respectively. Table 2 shows the modal damping ratio around the frequency of brake squeal. High damping ratio was observed on laminated disc (TYPE-D3.00).

Table 2 Modal damping ratio at squeal.

	Frequency[Hz]	modal damping ratio[%]
TYPE-D3.00	14588	0.23
TYPE-S	14400	0.077

3.2 Frequency responses on laminated brake disc with individually different thickness plates

Fig.4 shows the FRF (frequency response function) measured on normal type (TYPE-S) and laminated disc (TYPE-D3.00) by impact test. The number of resonance responses on TYPE-D3.00 (laminated disc) under 20kHz was increased compared with those of TYPE-S (normal disc), because the total stiffness of laminated disc was lower than that of normal disc and then basic resonance frequency was also lower than that of normal disc. Test result showed that applying the laminated disc unexpectedly increased the number of resonance responses, while it was effective to reduce the SPL at the squeal as shown in the last session. Concerning the commercial uses of laminated discs, the number of resonance responses should be reduced with another aspect, because disadvantage was there through many numbers of resonance responses to prevent the brake squeal at wide frequency ranges between 0 and 20kHz.

To change natural frequencies of each thin plate of laminated disc, modified type of laminated disc was prepared in which they had individually different thickness. The natural frequency test was also conducted in which the accelerometer was equally put at 15^o apart in circumference direction of disc as shown in Fig3(a). Fig.5 shows difference of the FRFs (frequency response function) of the modified laminated disc constructed with two plates with individually different thickness (TYPE-D3.75) and conventionally laminated disc with two same plates (TYPE-D3.00). Clear resonance responses were canceled in the range of 5 to 20kHz on the modified laminated disc (TYPE-D3.75), while they were shown on the TYPE-D3.00. Fig.6 shows the phase difference in the response of normal accelerations measured on the right and left surface of laminated disc (a) TYPE-D3.00 and (b) TYPE-D3.75 after impulse shock, respectively. The large phase difference was shown on TYPE-D3.75 in the range of 2.5 to 10kHz, while there was little difference on TYPE-D3.00. This result suggested that many times of collisions between two thin discs were occurred under the vibration due to the difference of natural frequencies of each disc itself of TYPE-D3.75. The discussion was confirmed by that difference of accelerations in the normal direction was observed on the right and left surface of the modified laminated disc (TYPE-D3.75), while there was little difference from that on TYPE-D3.00 as shown in Fig.7. Actually, remarkable

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squeal was not observed when TYPE-D3.75 was used.

However, the improvement in FRF (frequency response function) was shown only in the range at high frequency as shown in Fig.5 even when two discs with same thickness was simply laminated for the brake disc.

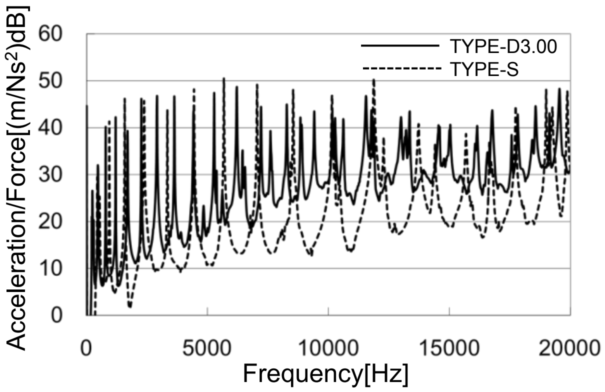


Fig.4 Comparison of FRFs on TYPE-S and TYPE-D3.00.

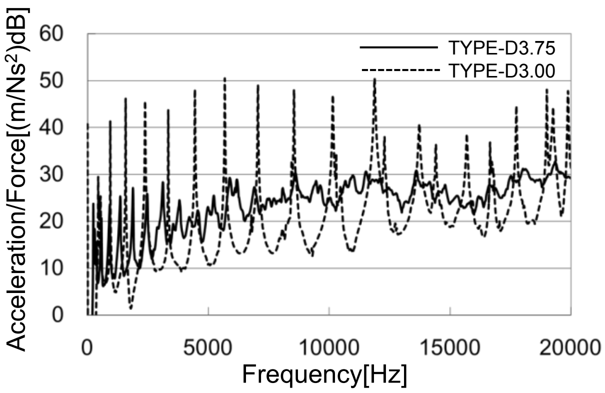
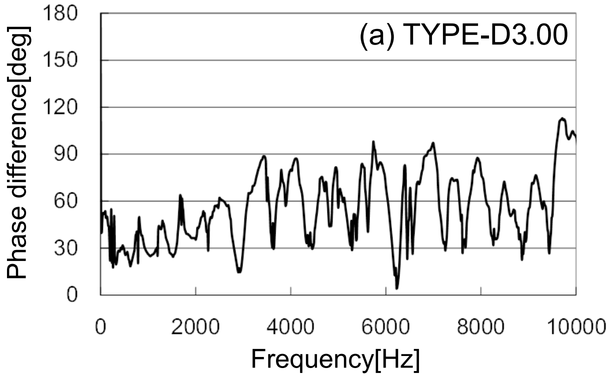


Fig.5 Difference of FRFs measured on TYPE-D3.75 and TYPE-D3.00.



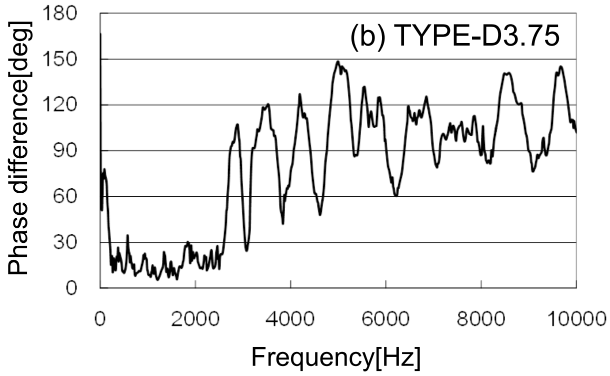


Fig.6 Phase difference in response of normal accelerations measured on right and left surface of laminated disc (a) TYPE-D3.00 and (b) TYPE-D3.75.

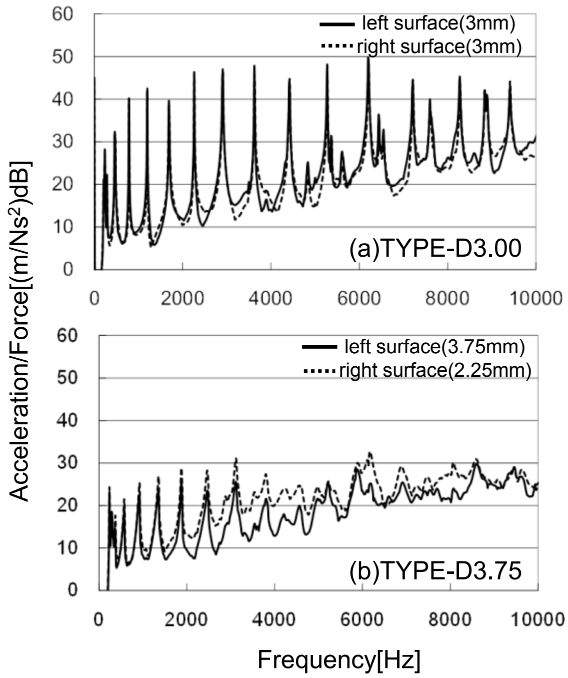


Fig.7 Difference of accelerations in normal direction measured on right and left surface of disc on (a) TYPE-D3.00 and (b) TYPE-D3.75 .

3.3 Increase of damping ratio of laminated brake disc fastened with distributed contact pressure

To expand the effect shown in last session, another modification of laminated disc was introduced in this study. In order to change the contact pressure distribution between two thin discs

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in the laminated disc, some types of curved discs were prepared in which they have previously different height of the convex.

Fig.8 shows difference of the FRFs of the laminated disc constructed with two curved plates with 0.2mm height of the convex shape (TYPE-C0.2), 1.0mm height of the convex shape (TYPE-C0.4) and conventionally laminated disc with two same plates (TYPE-D3.00). Among three types of specimen, the lowest amplitudes at the peaks were obtained at resonance frequencies when laminated disc had the highest convex shape before fastening. Fig.9 shows the damping ratio with respect to frequency on modified laminated disc with curved plate (TYPE-C0.2) (TYPE-C0.4) and conventionally laminated disc (TYPE-D3.00). High damping ratio was obtained on the TYPE-C1.0 which had 1.0mm height of the convex shape before fastening. These results indicated that contact pressure distribution greatly affected to the experimental result of damping ratio.

To explain the differences of the amplitudes of the gain and damping ratio, contact pressure between two thin discs was analyzed by finite element code (ABAQUS 6.11). The calculation was simply executed with 1/10 model of the fastened laminated disc as shown in Fig.10 with material constants listed in Table 3. The natural frequency test was also conducted to investigate the distribution of the compliance, where the accelerometer was put at the location divided in radial direction of the laminated disc as shown in Fig.3 (b). The compliance was calculated from the accelerance divided $4\pi^2 f^2$, where f is the frequency.

Fig.11 shows the comparison of compliances averaged in the range of 0 to 5kHz and the calculated contact pressure with respect to location of laminated disc in radial direction. Positive contact pressure was observed near the external periphery in the laminated disc (a) TYPE-C0.2 and (b)TYPE-C0.4 which had previously curved shape, while contact pressure was not hardly seen in the conventionally laminated TYPE-D3.00. The compliance in the normal direction of the laminated disc was also increased with an increase of radial coordinate. It was considered that the frictional displacement between two thin discs was increased in the location where the compliance in the normal direction was large under vibration. Therefore, when the disc was laminated with two thin previously curved discs with convex shape and then they were fastened, loss of friction was increased due to high contact pressure and relative displacement between two thin discs.

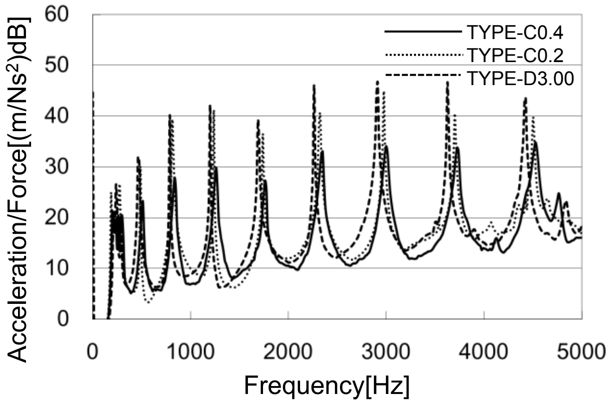

Fig.8 Difference of FRFs on TYPE-D3.00, TYPE-C0.2 and TYPE-C0.4.

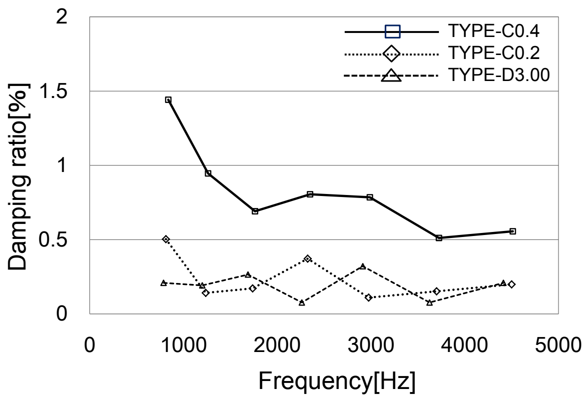

Fig.9 Damping ratio with respect to frequency on TYPE-C0.4, TYPE-C0.2 and TYPE-D3.00.

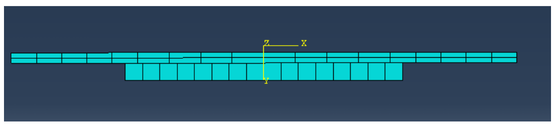

Fig.10 FE model of brake disc.

Table3 Material constants of brake disc.

Symbol	Parameter	Description
E	206[MPa]	Young's modulus
v	0.3	Poisson's ratio

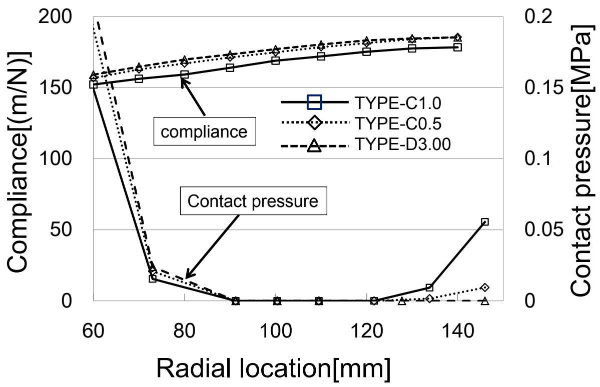

Fig.11 Comparison of compliances averaged in range of 0 to 5kHz and the calculated contact pressure with respect to location of laminated disc in radial direction.

4 Conclusion

(1) The lamination of two thin discs was effective to reduce the SPL at the squeal.

(2) The number of the resonance responses on laminated disc with two plates with same thickness under 20kHz was increased compared with those of normal disc, because the total stiffness of laminated disc was lower than that of normal disc and then basic resonance frequency was also lower than that of normal disc.

(3) Clear resonance responses were canceled in the range of 5 to 20kHz on the modified laminated disc with two plates with individually different thickness, while they were shown on the simply laminated disc.

(4) When the disc was laminated with two thin previously curved discs with convex shape and then they were fastened, loss of friction was increased due to high contact pressure and relative displacement between two thin discs.

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