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The roughness effect on the frequency of frictional sound

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Abstract

Dry sliding of two bodies in contact generates a wide range of effects like friction, wear, heat and sound among others. The main interest of this study is in the frequency characteristics of the generated sound.

In the past, frequency spectrum and sound pressure level with relation to surface topography (surface roughness in particular), have been studied mainly for concentrated contacts like stylus or hemispherical tip pin on a rough surface. Studies on flat–flat contacts were mainly focused on the topography of contacting surfaces and its relation to occurrence or non-occurrence of squeal (high pitch, high sound pressure level sound) in brake systems.

The present study aims to clarify the effect of surface roughness on the frequency of non-squealing frictional sound generated in dry flat–flat sliding contact.

Sound was generated by the dry contact in rubbing by hand of two rectangular cross-section stainless-steel plates having similar surface roughness. The roughness of the contacting surfaces varied in the range $R_z = 0.8$–$12.4\,\mu$m. The sound spectra had 5 peaks (P_1, P_2, P_3, P_4 and P_5) in order of increasing frequency and it was found that the peak frequency was shifted when the roughness of the rubbed surfaces changed. The first peak P_1 was most sensitive to change of surface roughness and it shifted from 3.0 to 4.5 kHz when the maximum surface roughness changed from $R_z = 10.9$ to $3.4\,\mu$m. When the surface was relatively rough, this peak was close to the first bending natural frequency of the plate at 2.377 kHz.

Keywords: Surface roughness; Frictional sound; Frequency shift; Frictional noise

1. Introduction

Dry sliding of two bodies in contact generates a wide range of effects like friction, wear, heat and sound among others. While sound generation in dry sliding has not received as much attention in the field of tribology research as friction and wear, the phenomenon has been used for sound reproduction through the 20th century following the invention of the phonograph by Thomas Edison.

In the phonograph surface roughening of a waxed drum was used to encode sound information and the effect of surface roughness in playback is quite evident: if the sharp stylus is always kept in contact with the rough surface then larger amplitude of roughness would produce larger amplitudes of sound, short wavelength of roughness or increased sliding speed would generate sound of higher frequency.

Similar considerations apply for small area concentrated contacts with size smaller or comparable to the surface wavelength. Such understanding confirmed in a stylus on random rough surface apparatus [1] led Othman et al. to the design of a new device for measuring surface roughness by measuring dry friction noise [2]. In a series of studies, Yokoi and Nakai [3–6] investigated the frictional sound generation mechanism using a hemispherical tip pin-on-rim apparatus. They have shown that the sound pressure level is linearly proportional to the random rim roughness [6].

In a more theoretical approach, Akay [7] considered the equations of vibration of a corrugated bar under frictional excitation and of a guitar string along which a reed is rubbed. Both bending and longitudal vibrations are excited and contact force characteristics involve primarily the spatial period of corrugation or string winding and the speed of sliding.

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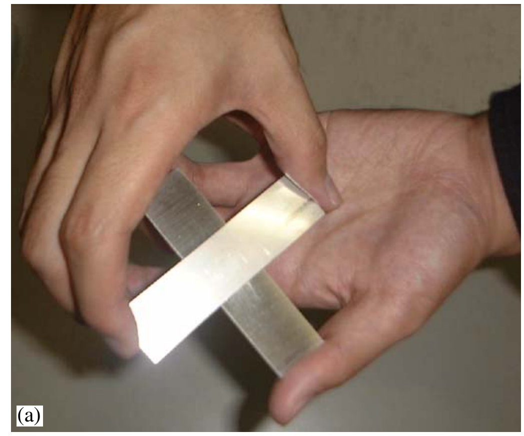
In concentrated contact of softer materials the surface profiles can change significantly even during a single sliding pass. Good correlation was found between lump formation and pressure spikes of frictional sound in single pass sliding of aluminium pin over aluminium flat [8].

When the apparent contact area is large compared to the spacing between corrugations or roughness wavelength, the contact interaction is qualitatively different. In such contacts multiple asperity tips interact during sliding. Journal bearings, sliding guides and brakes are all examples of such type of contacts and they are dominant in real machine applications. Much of the frictional sound research on such large area contacts is motivated by the problem of brake squeal [9–15]. Squeal is high pitch, almost sinusoidal, high sound pressure level sound, which may cause discomfort. Attempts to model it have been tried [9–10], but the critical aspect in the modeling of a complete brake system is the coupling between the components, particularly the rotor/pad interface [11]. The characteristics of the pads in a rotor/pad interface after running in silent and squealing conditions were investigated by Eriksson et al. [14]. They found correlation between the squeal characteristics of brake pads and the number and size of "contact plateus" formed during sliding. By introducing a "squeal index" they concluded that larger number of small plateus are more likely to generate squeal than smaller number of large plateus. To further clarify the effect of surface topography on the formation of squeal, Chen et al. [16] conducted a repeated reciprocating flat–flat and ball–flat tests with steel. They reported that in the tests in which squeal was generated it came through the following phases: initial run-in with low friction and no squeal; increase of friction coefficient accompanied by squeal; sometimes, if sliding continues, the squeal would disappear. The roughness of the contact surface was highest during squeal generation.

The interest of the above-mentioned studies on frictional sound generated in large area contacts was mainly in the effect of surface topography on the presence or absence of squeal. The present study aims to clarify the effect of surface roughness on the frequency characteristics of non-squealing frictional sound generated in dry flat–flat sliding contact.



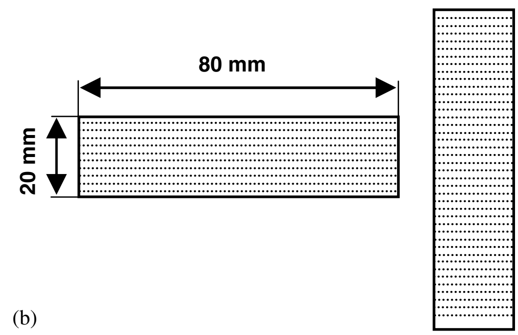


Fig. 1. Cross-rubbing by hand (a) of plate specimens (b).

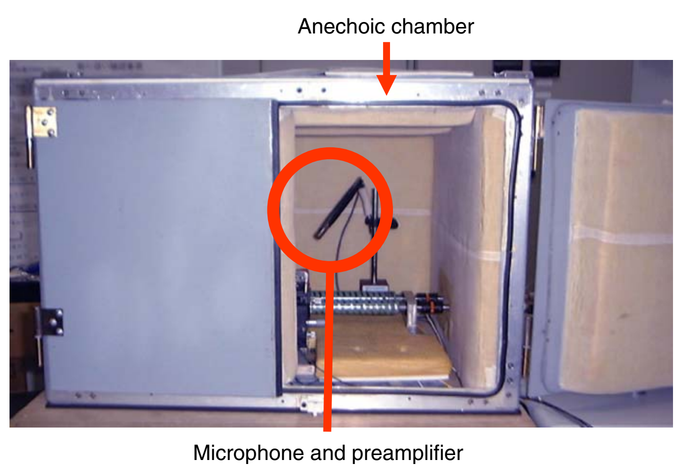


Fig. 2. Anechoic chamber and microphone.

2. Experimental setup

The specimens used in the experiment were $80 \times 20 \times 3$ mm plates made of stainless-steel SUS-304 (JIS analog to ANSI-304). The surfaces were roughened by sand paper having grit size 40, 100 and 400 to achieve average values of maximum surface roughness R_z of 10.9, 6.2 and 3.4 μm, respectively. The specimens were repeatedly rubbed against each other by hand in a crossed configuration (Fig. 1(a)). Fig. 1(b) shows the direction of the grooves on the surfaces—for one of the specimens, along, and for the other across. In this way, in crossed rubbing, the roughness marks on both specimens are aligned and asperities interlock during sliding. Well-controlled rubbing by hand avoids the undesired stick–slip motion and system resonance which could be introduced by the dynamic properties of a holding system. A complex holding system would also introduce difficulty in the analysis of modes of vibration and possibly mask the effect of surface roughness.

Sound pressure was measured by a microphone, placed at about 30 cm away from the rubbed specimens and data were acquired with a sampling frequency of 50 kHz on a personal computer. Testing was performed inside an

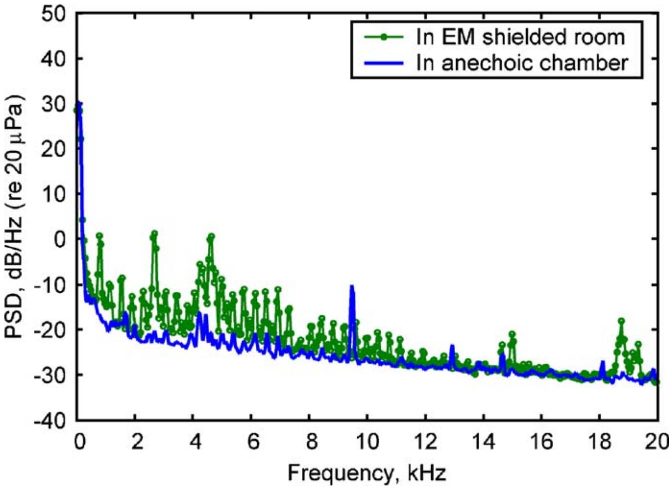


Fig. 3. Comparison of background noise in the chamber and in an electro-magnetically shielded room with no sound sources.

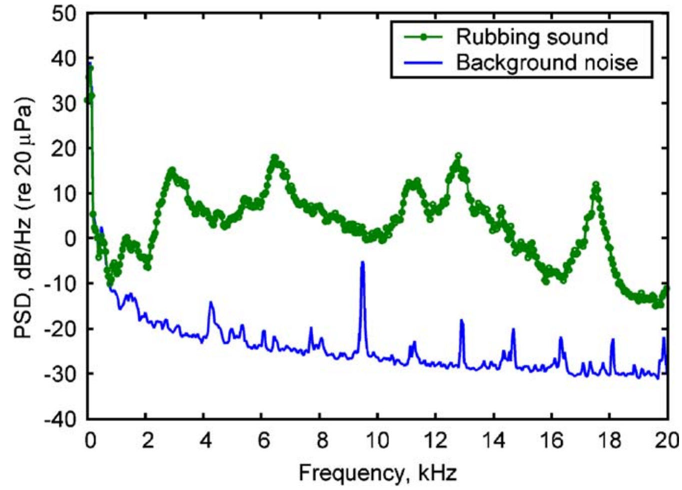


Fig. 4. Comparison of background noise and rubbing sound spectra.

anechoic chamber (Fig. 2). In Fig. 3 background noise inside the chamber is compared to the background noise in electro-magnetically shielded room with no sound sources. Obviously the chamber provides sufficient protection from background noises, generated by other equipment in the room despite the fact that the chamber's door was held open during testing. The chamber also prevents sound wave reflections from the walls.

By comparison of the spectra of background noise and rubbing sound (Fig. 4) we find that below 0.45 kHz, the background noise is dominant and this range is not further considered in our study. The upper end of the frequency range of interest in this study is 20 kHz.

First, the suitability of the test method was evaluated. Tests under subjectively ''high'' and ''low'' rubbing frequency were carried. At ''high'' frequency the average rubbing speed was measured to be 170 mm/s, while at ''low'' speed average rubbing speed was 80 mm/s. Power spectral density (PSD) of sound generated under the higher rubbing speed has higher level, but qualitatively the spectra are very similar with peaks occurring at the same frequencies (Fig. 5), except for a peak at 9.5 kHz which we confirmed to be due to electrical noise.

Similarly the load was also changed from ''low'' (0.6 N) to ''high'' (25 N) and although at high load the peaks are much broader, their location on the frequency scale seems not affected significantly (Fig. 6).

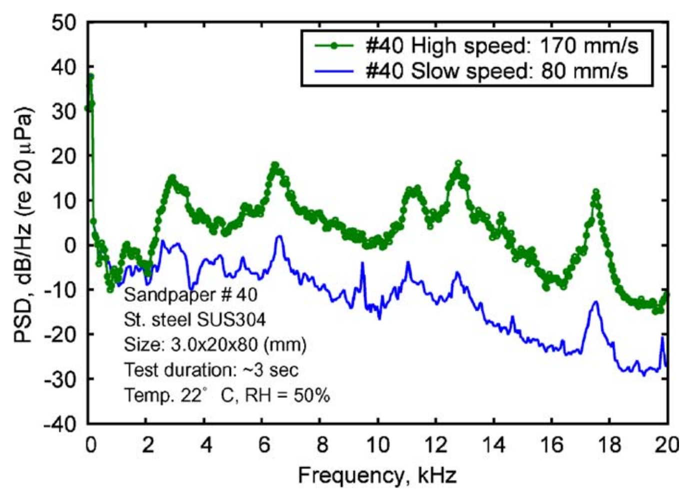


Fig. 5. Comparison of sound spectra at ''low'' and ''high'' rubbing speed.

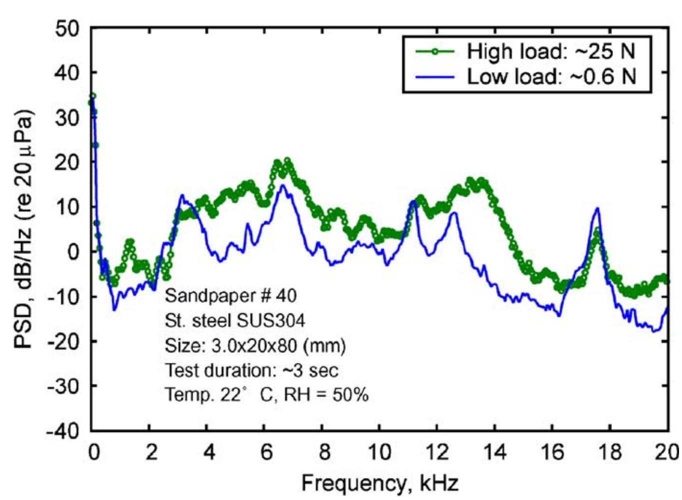


Fig. 6. Comparison of sound spectra under ''low'' and ''high'' load.

3. Results

Rubbing tests were carried for three pairs of plate specimens, the specimens in each pair were finished with the same grit size of sand paper and had approximately equal maximum surface roughness R_z. PSD of sound for the three pairs is shown in Fig. 7(a) together with the acoustic response of a single plate in a ball impact test in the configuration shown in Fig. 7(b). In the frequency range of interest from 0.4 to 20 kHz there are five clear peaks in the rubbing sound spectrum which are numbered as P_1, P_2, P_3, P_4 and P_5 in order of increasing frequency. They closely correspond to the experimentally determined

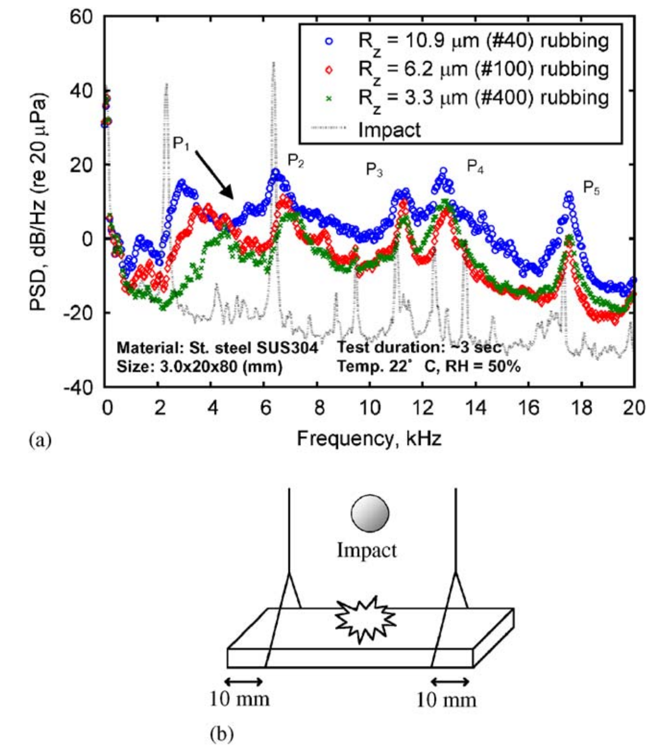


Fig. 7. (a) PSD of sound generated in rubbing of specimens finished to surface roughness $R_z = 10.9$, 6.2 and 3.4 µm and in impact test using the setup shown in (b).

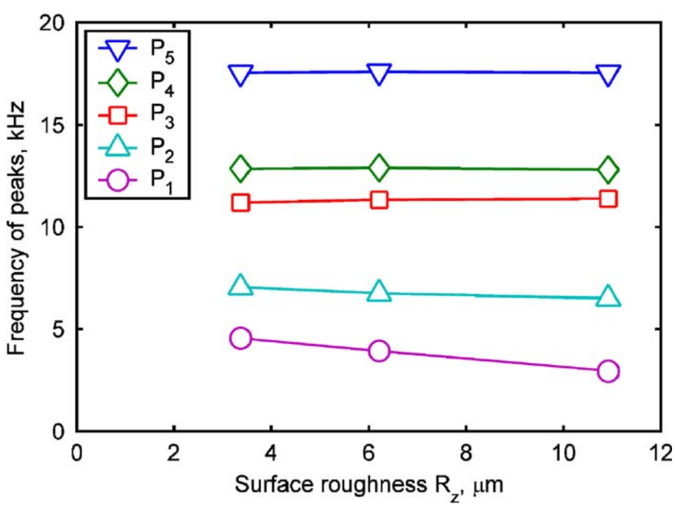


Fig. 8. Shift of peak frequencies for different surface roughness.

free vibration natural frequencies of the plate. The location of the peaks P_1, P_2 and P_4 shift to higher frequency as the surface roughness is reduced. The lowest frequency peak, P_1, is most sensitive to change in the surface roughness. It shifted from 3.0 to 4.5 kHz, when the maximum surface roughness changed from $R_z = 10.9$ to 3.4 µm (Fig. 8). When the surface was relatively rough, this peak was close to the fundamental bending natural frequency of free vibration of the plate at 2.377 kHz.

The tests were repeated after redoing the sand paper finish and similar results were obtained. Fig. 9 shows the

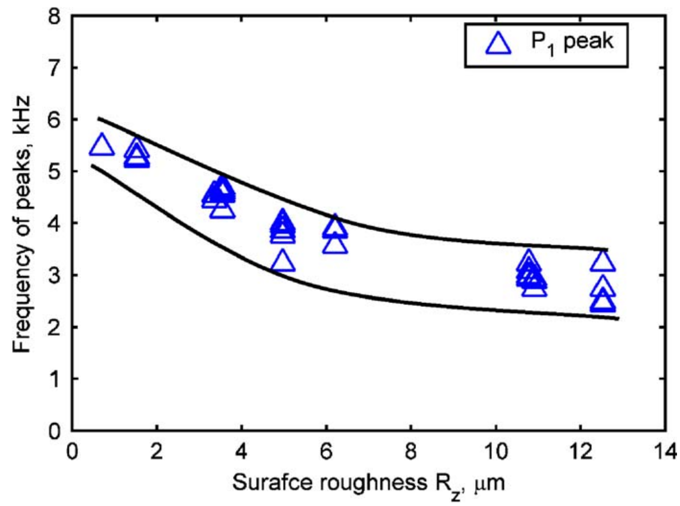


Fig. 9. Shift of the frequency of peak P_1 with the change of the maximum surface roughness R_z.

correlation between the frequency at which peak P_1 occurs and the maximum surface roughness R_z. In the whole tested roughness range the peak P_1 shifted from 2.4 kHz at $R_z = 12.4$ µm to 5.4 kHz at $R_z = 0.8$ µm.

4. Discussion

Previous works on sound generated in concentrated contacts show that sound pressure level increases with the increase of surface roughness. Different forms of the relationship were proposed. Othman et al. [1] suggest that the relationship has the form

$$\mathrm{SPL} = (R_a/\mathrm{b})^{\mathrm{c}},\ \mathrm{dB}, \quad (1)$$

where b and c are experimental constants, while Yokoi and Nakai [6] propose a relationship of the form

$$\Delta\mathrm{SPL} = 20\log_{10}\left(\frac{R_{z_2}}{R_{z_1}}\right)^m,\ \mathrm{dB}, \quad (2)$$

where the change of the sound pressure level in dB is related to the mth power of the surface roughness ratio. The relationship (2) was originally put forward by Takahashi [17] for line contact of a cylinder sliding against flat with $m = 1$. Yokoi and Nakai proposed that for concentrated contact of hemispherical pin on flat $m = 0.8$ should be used.

Although our data is not obtained under strictly constant load and sliding speed, the tendency of the sound pressure level to increase with surface roughness (Fig. 10) is in agreement with previous observations on concentrated contacts. It must be noted that in the present tests with plate on plate contact the sound pressure level in Fig. 10 was obtained after removing the frequencies below 450 Hz, which are dominated by background noise.

With respect to the frequency spectrum of frictional sound, Othman et al. [1] conclude that regardless of surface roughness and contact load, the sound spectra have a peak

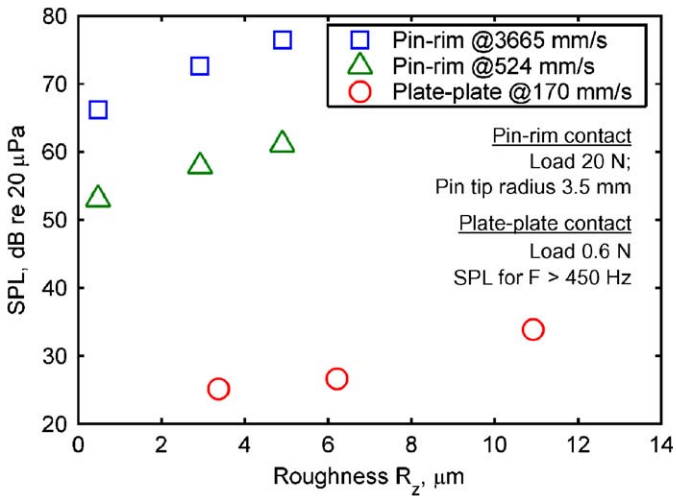


Fig. 10. Sound pressure level of frictional sound for varied roughness. Pin-on-rim data from Yokoi and Nakai [6].

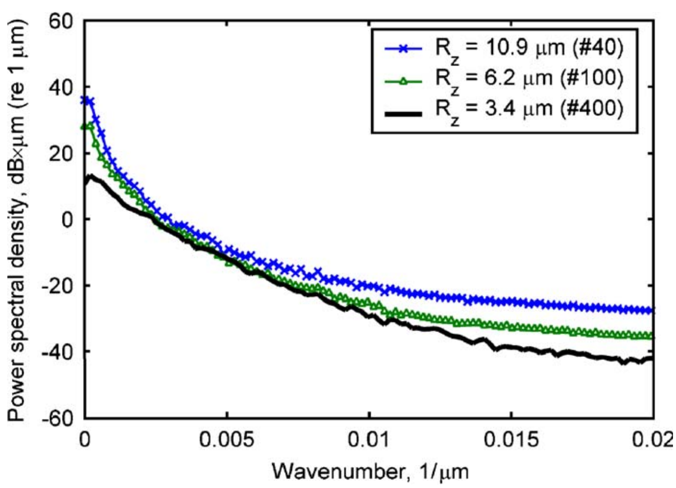


Fig. 11. PSD of the surface profiles of three plates finished with sand paper #40, #100 and #400.

(which they have named "dominating frequency"), which depends on the material of the specimen over which a sharp stylus traverses.

Yokoi and Nakai [6] observed that largest peaks in the spectrum of frictional sound occurred at the lateral (i.e. in the direction of friction) natural frequencies of vibration of pin. From their spectrum data it is evident that no significant shift of peak frequencies occurred with pin sliding against counterface with different roughness. In this regard the observation of peak frequency shift for flat–flat contacts is unique. The occurrence of such a peak shift in the sound spectrum cannot be related to a similar peak shift in the spectra of the surfaces, which look smooth over a wide range of spatial frequencies (wave numbers) (Fig. 11). Although the cause of such a shift is not clear yet, if it would be confirmed on a wider scale, e.g. for various holding systems, such phenomenon together with sound pressure level change would be useful for condition monitoring of sliding contacts from the viewpoint of change of surface roughness. A monitoring method based on audible sound would have many advantages over traditional methods some of which are: real-time monitoring, non-contact measurement, and portability. Another potential use of the present findings would be to control the frictional sound generated at particular frequency range by changing the roughness of the rubbing surfaces.

5. Conclusions

We have observed for the first time the peak frequency shift caused by the varied roughness of the surfaces rubbed in flat–flat contact.

Most sensitive to change of surface roughness was the sound spectrum peak closest to the fundamental natural bending frequency of the specimen at 2.377 kHz. In the whole tested roughness range it shifted from 2.4 kHz at $R_z = 12.4\,\mu m$ to 5.4 kHz at $R_z = 0.8\,\mu m$.

Acknowledgment

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References

[1] Othman MO, Elkholy AH, Seireg AH. Experimental investigation of frictional noise and surface-roughness characteristics. Exp Mech 1990;47:328–31.
[2] Othman MO, Elkholy AH. Surface roughness measurement using dry friction noise. Exp Mech 1990;47:309–12.
[3] Nakai M, Yokoi M. Generation mechanism of frictional noises in dry friction. Japanese Journal of Tribology 1990; 35(5).
[4] Yokoi M, Nakai M. A fundamental study on frictional noise (1st report—The generating mechanism of rubbing noise and squeal noise). Bull JSME 1979;22(173):1665–71.
[5] Yokoi M, Nakai M. A fundamental study on frictional noise (3rd report—The influence of periodic surface roughness on frictional noise). Bull JSME 1981;24(194):1470–6.
[6] Yokoi M, Nakai M. A fundamental study on frictional noise (5th report—The influence of random surface roughness on frictional noise). Bull JSME 1982;25(203):827–33.
[7] Akay A. Acoustics of friction. J Acoust Soc Am 2002;111(4):1525–48.
[8] Stoimenov BL, Kato K, Adachi K. The relationship between frictional sound and lumps build-up at the contact interface in single-pass dry sliding between aluminium pin and flat. In: 30th Leeds–Lyon symposium on tribology. Lyon, September 2003.
[9] Hendricx W, et al., Experimental and numerical modelling of friction induced noise in disc brakes. SAE Technical Paper Series 2002-01-1192, 2002.
[10] Milner N. Analysis of disk brake squeal. SAE Paper No. 780332, 1978.
[11] Papinniemi A, Lai JC, Zhao J, Loader L. Brake squeal: a literature review. Appl Acoust 2002;63:391–400.
[12] Nishiwaki M, Harada H, Okamura H, Ikeuchi T. Study on disk brake squeal. SAE paper No. 890864, 1989.
[13] Bergman F, Eriksson M, Jacobson S. Influence of disc topography on generation of brake squeal. Wear 1999;225–229:621–8.

[14] Eriksson M, Bergman F, Jacobson S. Surface characterisation of brake pads after running under silent and squealing conditions. Wear 1999;232:163–7.
[15] Eriksson M, Bergman F, Jacobson S. On the nature of tribological contact in automotive brakes. Wear 2002;252:26–36.
[16] Chen G, Zhou Z, Kapsa Ph, Vincent L. Effect of surface topography on formation of squeal under reciprocating sliding. Wear 2002;253:411–23.
[17] Takahashi K. The friction noise under heavy load. Bull Fac Sci Eng. Chuo Univ 1973;16:53–69 [in Japanese].