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Analysis of Vibration Generated by the Rubbing of Flat Surfaces

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Abstract

Among the phenomena that occur as a result of contact between two surfaces is friction sound, in which surface roughness is of great importance. In this study, the parameter of contact stiffness is used to explain the frequency characteristic of vibration generated by the rubbing of flat surfaces under a small load. A 3-disk configuration rubbing method was used, which provides a unique characteristic of the system's frequency response function containing specific information about the rubbing vibrations. It is shown that the peak frequency of the rubbing vibration can be explained by using a two-degrees-of-freedom model incorporating the parameter of contact stiffness. A quantitative relationship between the surface roughness and the peak frequency of the rubbing vibrations was established.

Abstrak

Analisis Getaran yang Terjadi pada Usapan Permukaan Rata. Bunyi gesekan adalah salah satu fenomena yang terjadi akibat interaksi kontak antara dua permukaan yang dipengaruhi oleh faktor kekasaran permukaan. Dalam kajian ini, parameter kekakuan kontak dipakai untuk menjelaskan karakteristik getaran yang terjadi pada saat sebuah permukaan diusapkan pada sebuah permukaan yang lain dalam kondisi beban yang kecil. Metode usapan konfigurasi 3 (tiga) cakram digunakan dalam kajian ini, yang menghasilkan respon frekuensi yang unik yang mengandung informasi karakteristik dinamik sistem. Frekuensi puncak getaran yang diakibatkan oleh usapan dapat dijelaskan dengan menggunakan model dinamik dua derajat kebebasan yang mengandung parameter kekakuan kontak. Pada kajian ini, suatu hubungan kuantitatif antara kekasaran permukaan dan frekuensi puncak getaran usapan telah dihasilkan.

Keywords: friction induced vibration, contact stiffness, surface roughness

1. Introduction

Friction between objects is a phenomenon encountered in daily life. A common observation is that friction generates wear, heat, and sound. Besides wear, friction sound has drawn attention from researchers because of requirements in decreasing the noises from machineries in order to improve the quality of human life.

The majority of discussions concerning friction sound in literature were motivated by the problem of high sound pressure levels in automotive brake systems, such as brake squeal. Brake squeal is caused by self-excited vibrations of brake components [1-3]. It is a noisy, high-pitched sound that causes annoyance for both the vehicle’s passengers and for pedestrians. Various attempts have been conducted to eliminate the squealing sounds of brake systems, such as the use of a shim on the back plate of the brake pad [4]. Nevertheless, related problems continue to appear in daily life.

One of the most important aspects of friction sound is surface roughness. Some of the fundamental works on the relationship between friction sound and surface roughness were conducted by Othman et al. [5]. They used a stylus pin on rough surfaces to investigate the relationship between dry friction sound and surface roughness. This work later led to the development of a device for measuring surface roughness by measuring the sound produced by dry friction [6]. A series of reports have also been published by Nakai and Yokoi [7-9]. They used a pin sliding on a rim to investigate various aspects of friction sound, including the effects of rim roughness on the generated sound. Stoimenov et al. [10,11] revealed that the peak frequency of friction sound generated by rubbing two flat rough surfaces together is determined by the roughness at the contact interface. The peak frequency shifts to a higher frequency when the contact becomes smoother. Other researchers reported that the sound level of the friction sound increases with an increase of both roughness and sliding velocity [12], as well as the area of contact [13].

One of the parameters that incorporate surface roughness is contact stiffness. This parameter has been used in dynamics models to explain the occurrence of dynamic instabilities in friction systems, such as brake squeal, as described in Ref. [2].

In this study, the parameter of contact stiffness is used to explain the vibration characteristics generated by the rubbing of flat surfaces against each other under a light load. The analysis focuses on the peak frequency of the vibration acceleration resulting from the sliding. The objective is to establish a relationship between the surface roughness and the peak frequency of rubbing vibrations.

2. Methods

When two flat surfaces create friction, their asperities interact, whether individually or in a group, impacting each other. A simulation of this phenomenon is described in Ref. [14]. In this case, it can be assumed that the magnitude of these impacts affects the amplitude and the frequency of the vibrations they generate. Therefore, the magnitude is affected by the size of the asperity, i.e., roughness.

In order to analyze the effects of roughness on the characteristics of the vibration, a three-disk configuration was used, as described in Fig. 1. This method is an extension of the rubbing method used in Ref. [11]. Three disks, denoted as disk **a**, disk **b**, and disk **c**, are stacked on top of each other. Disk **a** is designated as the uppermost disk while disk **b** and disk **c** are designated as the middle and the lowermost disk, respectively. This configuration provides two contact interfaces in the system: the one between disk **a** and disk **b**, denoted as the upper contact interface, and the one between disk **b** and disk **c**, denoted as the lower contact interface. In the tests, the uppermost disk was rubbed against the middle disk while the lowermost disk stayed in static contact with the middle disk. This test configuration brings the upper contact interface into the friction stage and the lower contact interface into the static contact stage.

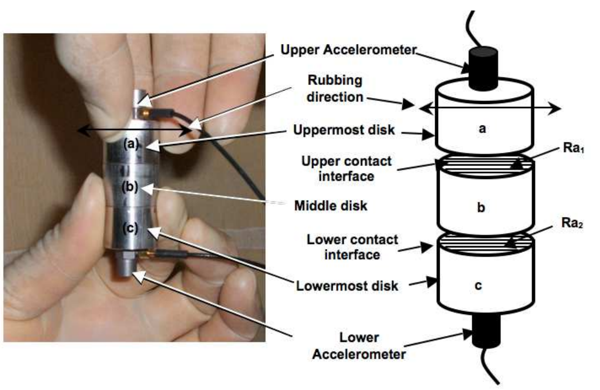


Figure 1. Three-disk Configuration Rubbing by Hand

Using this test configuration, a different contact role can be assigned to each of these contact interfaces. Rubbing the uppermost disk will cause asperity-related impacts on the upper contact interface, which will create excitation in the system. The middle disk, which is excited by the uppermost disk, will transfer the vibration to the lowermost disk through the asperities in the lower contact interface, acting as the static contact. Therefore, the magnitude of excitation is affected by the roughness of the upper contact interface and the magnitude of energy transferred to the lowermost disk is affected by the roughness of the lower contact interface.

The specimens used in this experiment are ϕ25x15 mm disks made of stainless steel. The weight of each disk is 0.036 kg. The lowest vibration mode of the disk is calculated to be 65 kHz, well above the audible range. The roughness, Ra, of the surfaces in contact was prepared by using sandpaper and evaluated by using a surface profile meter.

The rubbing of the disks is conducted by hand rubbing [11] in the direction of the surface grooves. This method provides no additional holding system whose resonances may cause additional noise in the recorded signal. The vibrations resulting from the rubbing test were acquired by using two accelerometers, a conditioning amplifier, and a PC with a data acquisition system. The sampling frequency was 50 kHz.

The accelerometers were positioned on the uppermost and the lowermost disks to record the acceleration in the normal direction (Figure 1). The analysis was conducted using the vibration data recorded in the normal direction (normal acceleration).

Figure 2 shows the Power Spectral Density (PSD) of a three-disk configuration rubbing tests acquired by accelerometers positioned on the uppermost and the lowermost disks together with the background Power

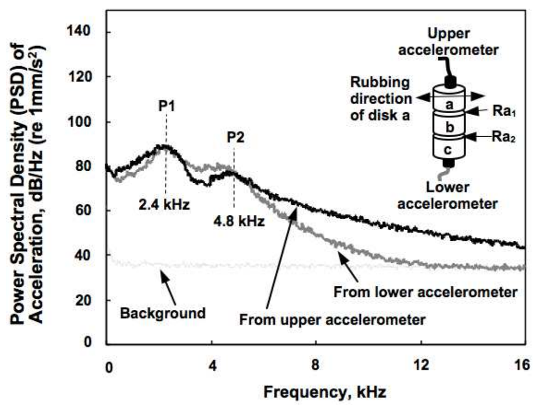


Figure 2. Comparison between Power Spectral Density (PSD) of Acceleration Obtained from Upper and Lower Accelerometers and that of Background Acceleration

Spectral Density. Observed in the figure are two major peaks at frequencies of 2.4 kHz and 4.8 kHz. These peaks were acquired by both accelerometers without any significant differences. Thus, the position of the accelerometer does not affect the resulting value of the peak frequency. Therefore, in further discussion, we have decided to present only the data recorded from the accelerometer placed on the lowermost disk.

3. Results and Discussion

Contact configuration with similar roughness Ra at both contact interfaces. Fig. 3(a) shows the PSD of normal acceleration of the three-disk configuration with all surfaces in contact having similar roughness values: $Ra_1=Ra_2=0.45$ µm. The similarity of the surface roughness was confirmed by separate tests. It is shown that the peak frequency that occurred from rubbing only disk **a** and disk **b** is similar to that which occurred from rubbing only disk **b** and disk **c** (i.e., 3.5 kHz). However, when disks **a**, **b**, and **c** were put into the three-disk configuration, two peaks emerged. The first peak occurred at a frequency of 2.4 kHz and the second one occurred at a frequency of 4.8 kHz. The first peak and the second peak are denoted as **P1** and **P2**, respectively.

Fig. 3(b) shows the effect of surface roughness, Ra, on the frequency of peak **P1** and peak **P2**. In the first case, the upper contact roughness Ra_1 and the lower contact roughness Ra_2 have a roughness of 0.45 µm. In the second case, Ra_1 and Ra_2 have a similar roughness of 0.15 µm. It can be observed that both peak **P1** and peak **P2** moved to higher frequencies as the surface roughness became smoother. The shift in peak frequency as the result of roughness changes confirms the findings reported previously in Ref. [10]. The shift in frequencies of **P1** and **P2** as the result of surface roughness is summarized in Fig. 3(c).

Contact configuration with different roughness Ra at contact interfaces. Fig. 4 shows the PSD of acceleration resulting from rubbing the three-disk configuration with different levels of roughness at the upper and the lower contact interfaces. As given in the figure, each disk of this contact pair produced a different peak when rubbed separately. The upper contact interface, between disk **a** and disk **b**, has a roughness Ra of 0.55 µm, and the rubbing of these disks together produced one peak at a frequency of 3.6 kHz. The lower contact interface, between disk **b** and disk **c**, has a roughness Ra of 0.23 µm. Rubbing disk **b** and disk **c** produced a peak at a frequency of 4.9 kHz. When disks **a**, **b**, and **c** were put into a three-disk configuration, peak **P1** occurred at a frequency of 2.5 kHz and peak **P2** occurred at a frequency of 6.4 kHz.

In order to investigate the effects of roughness on the frequencies of **P1** and **P2**, various levels of roughness for the upper and lower contact interfaces were prepared, as listed in Table 1. Two test conditions were designed, namely test condition A and test condition B.

In test condition A, the roughness of the upper contact interface was kept at a same roughness value, i.e., at Ra=0.55 µm, while the roughness of the lower contact interface varied from Ra=0.3 µm to Ra=0.02 µm. In test condition B, the roughness of the upper contact interface varied while that of the lower contact interface was kept at a roughness value of Ra=0.55 µm.

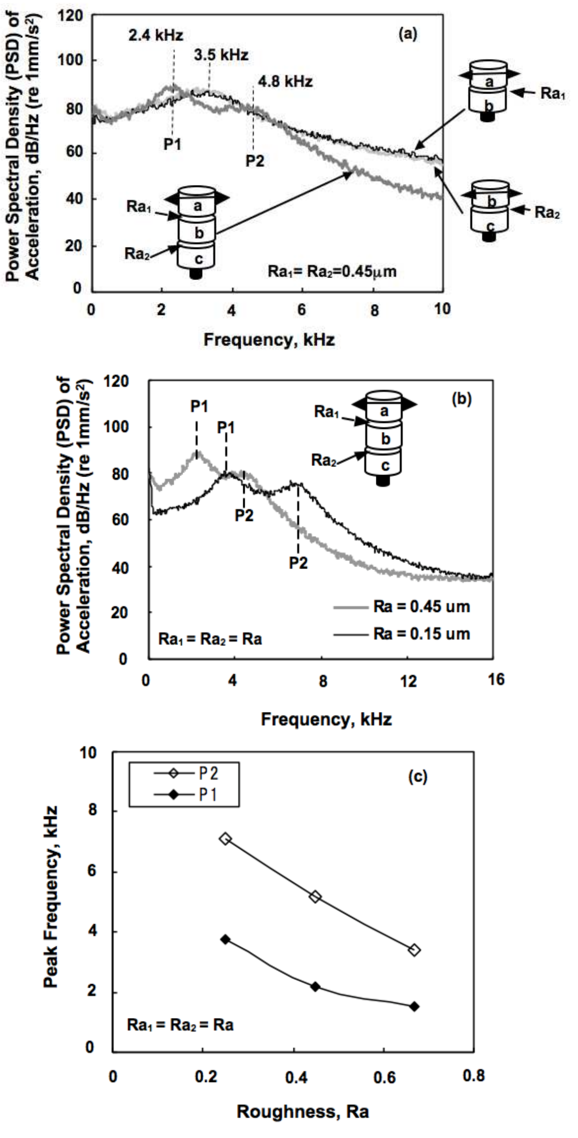


Figure 3. Rubbing of 3-disk Configurations with Similar Roughness at Both Upper and Lower Contact Interfaces; Comparison between Power Spectral Density (PSD) obtained from 2-disk Configuration and that from 3-disk Configuration (a), Effect of Roughness on PSD of 3-disk Configuration (b), and Effect of Roughness on Peak Frequency Shift of 3-disk Configuration (c)

The results are summarized in Fig. 5(a) and Fig. 5(b) for the respective test conditions. In test condition A (Fig. 5(a)), peak P1 occurred at a frequency of 2.68 kHz for the lower contact roughness of Ra=0.3 µm. P1 frequency did not seem very sensitive to the changes in roughness value in the lower contact interface. Its frequency stayed at around 2.5 kHz within the designated roughness range of the lower contact interface, i.e., from Ra=0.3 µm to Ra=0.02 µm. On the other hand, **P2** frequency increased as the lower contact interface became smoother. **P2** occurred at a frequency of 5.26 kHz with the lower contact roughness of Ra=0.3 µm. Its frequency **P2** increased to 8.32 kHz when the lower contact roughness reached a value of Ra=0.02 µm.

In test condition B, it can be seen that both the frequencies of **P1** and **P2** do not change significantly when the roughness of the upper contact interface is changed. Peak **P1** occurred at a frequency of around 3.4 kHz in all roughness conditions. However, Peak **P2** only increased slightly from 5.36 kHz with the upper contact roughness of Ra=0.3 µm to a frequency of 6.62 kHz with the upper contact roughness of Ra=0.02 µm.

Dynamic model for disks in contact configuration and peak frequency estimation. The occurrence of two peaks, P1 and P2, in the three-disk configuration can be explained using a simple dynamic vibration model. In this model, a contact interface is represented by a spring having stiffness ***k***, representing the normal stiffness of the contact. With this assumption, the two-disk configuration system can be represented as a single-degree-of-freedom model (Fig. 6(a)), and the three-disk configuration system can be represented as a two-degrees-of-freedom model (Fig. 6(b)). Thus, the frequency response of a system consisting of two disks will have a single peak, while systems consisting of three or four disks will have double or triple peaks, respectively, as demonstrated in Fig. 7.

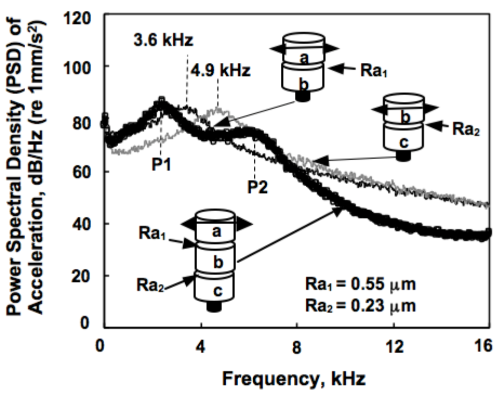


Figure 4. Rubbing of 3-disk Configurations with Different Levels of Roughness at the Upper and Lower Contact Interfaces; Comparison between Power Spectral Density (PSD) Obtained from 2-disk Configuration and from 3-disk Configuration

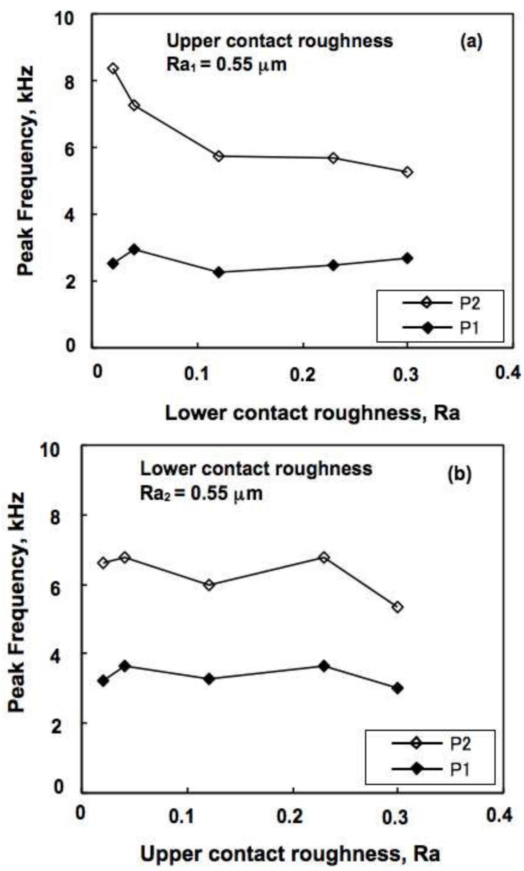
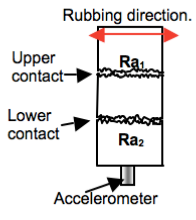


Figure 5. Effect of Roughness on Peak Frequency Shift in the 3-disk Configuration for Test Condition A (a), and Effect of Roughness on Peak Frequency Shift of 3-disk Configuration for Test Condition B (b)

Table 1. Contact conditions

	Test	Upper contact roughness (Ra_1, µm)	Upper contact roughness (Ra_2, µm)
	A	0.55	0.30
		0.55	0.23
		0.55	0.12
		0.55	0.04
		0.55	0.02
	B	0.30	0.55
		0.23	0.55
		0.12	0.55
		0.04	0.55
		0.02	0.55

Furthermore, the principle frequency of a one-DOF system, in this case denoted by f_p, is determined by the mass ***m*** and the spring's stiffness ***k***. The principle frequencies of a two-DOF system, denoted by f_{p1} and f_{p2}, are determined by the masses m_1 and m_2, and the stiffness of the spring k_1 and k_2. The frequencies of f_p, f_{p1}, and f_{p2} can be calculated by using Eq. (1) and Eq. (2).

$$k=(f_p 2\pi)^2 m \qquad ....(1)$$

$$f_{p1,2}=\frac{1}{2\pi}\sqrt{\frac{1}{2}\left(\frac{k_1+k_2}{m_1}+\frac{k_2}{m_2}\right)\pm\sqrt{\frac{1}{4}\left(\frac{k_1+k_2}{m_1}+\frac{k_2}{m_2}\right)^2-\frac{k_1k_2}{m_1m_2}}} \qquad (2)$$

Now consider a system consisting of three disks: disk **a**, disk **b**, and disk **c** (Fig. 8(b)). Rubbing two disks separately, e.g., disk **a** and disk **b** or disk **b** and disk **c**, will result in one peak, as shown in Fig. 8(a). This peak is denoted as f_p. The frequency of f_p for each case in Fig. 8(a) is decided by the roughness of the contact interfaces. Using Eq. 1, the stiffness k can be estimated; k_1 for the contact between disk **a** and disk **b**, and k_2 for the contact between disk **b** and disk **c**. Furthermore, the obtained values of k_1 and k_2 can be used to calculate the value of f_{p1} and f_{p2} in the three-disk configuration (Fig. 8(b)) using Eq. 2. The calculated values of f_{p1} and f_{p2} are compared to the experimental values of **P1** and **P2**.

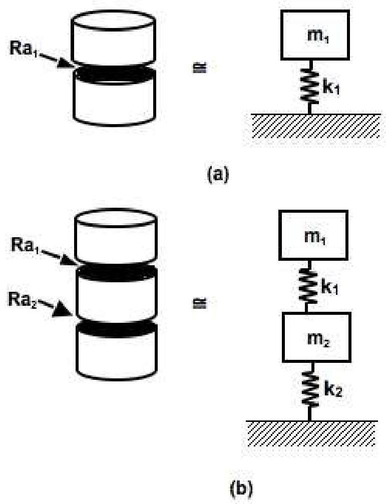


Figure 6. Dynamic Model of Disks in Contact

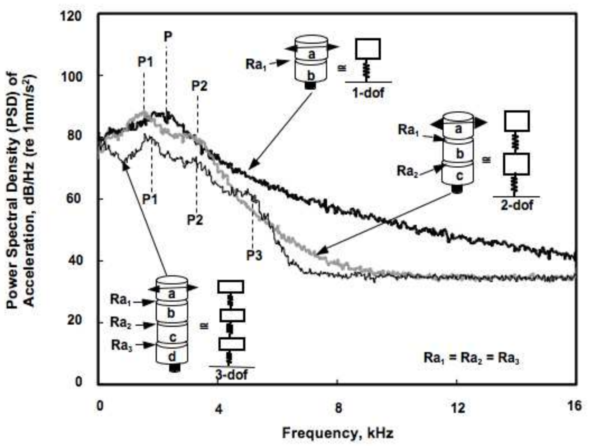


Figure 7. Dynamic Modeling of Disks in Configuration and Occurrence of Peaks at Frequency Response Functions; all Contact Interfaces have Similar Roughness

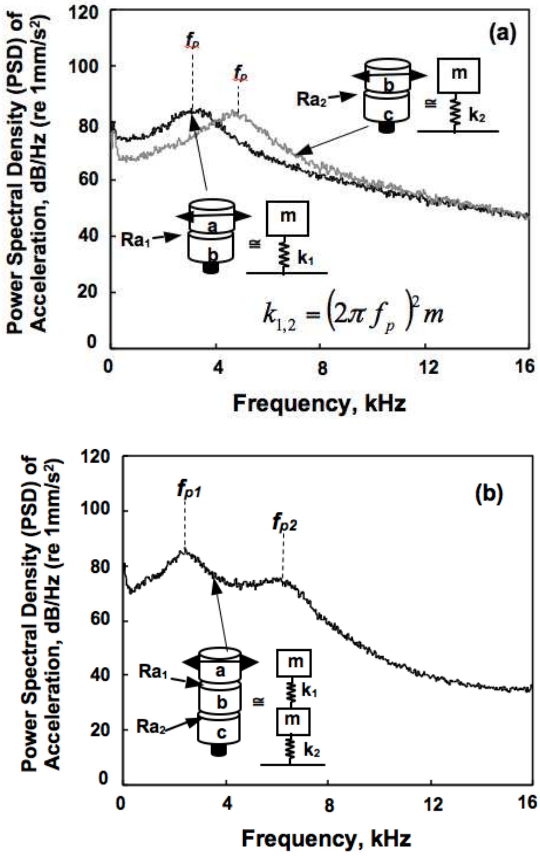


Figure 8. A Method for the Estimation of Peak Frequencies; Peak Frequencies Obtained from Rubbing the Two-disk Configuration are Used to Calculate the Contact Stiffness of the Respective Contact Combinations (a). The Values of Contact Stiffness are Used in the 3-disk Configuration Model (b) to Estimate the Peak Frequencies f_{p1} and f_{p2} using Equation 1

Effect of surface roughness on peak frequencies of rubbing vibration acceleration. The two principle frequencies of the three-disk configuration obtained from the experiment and the calculation are compared in Fig. 9. f_{p1} and f_{p2} were obtained using the method described in Fig. 8 and Eq. 1 and Eq. 2. **P1** and **P2** were obtained from the experiment. Fig. 9(a) shows the results from the condition in which both the upper and the lower contact roughness are similar, and Fig. 9(b) and Fig. 9(c) show the results from contact condition A and contact condition B as described in Table 1, respectively.

It can be seen in those figures that f_{p1} and f_{p2} are in good agreement with the experimental value of **P1** and **P2** regardless of contact condition A or contact condition B. These results show that the contact stiffness parameter is an effective parameter for representing the surface roughness in estimating the peak frequency of the vibrations resulting from the rubbing of flat surfaces under a light load. The change of peak frequency is explained as the result of the change in contact stiffness, as shown in Ref. [11] but with better agreement between the experimental data and the model using the method in this study. In different cases, the change in contact stiffness can also be affected by the change in normal force, contact area, and Young's modulus.

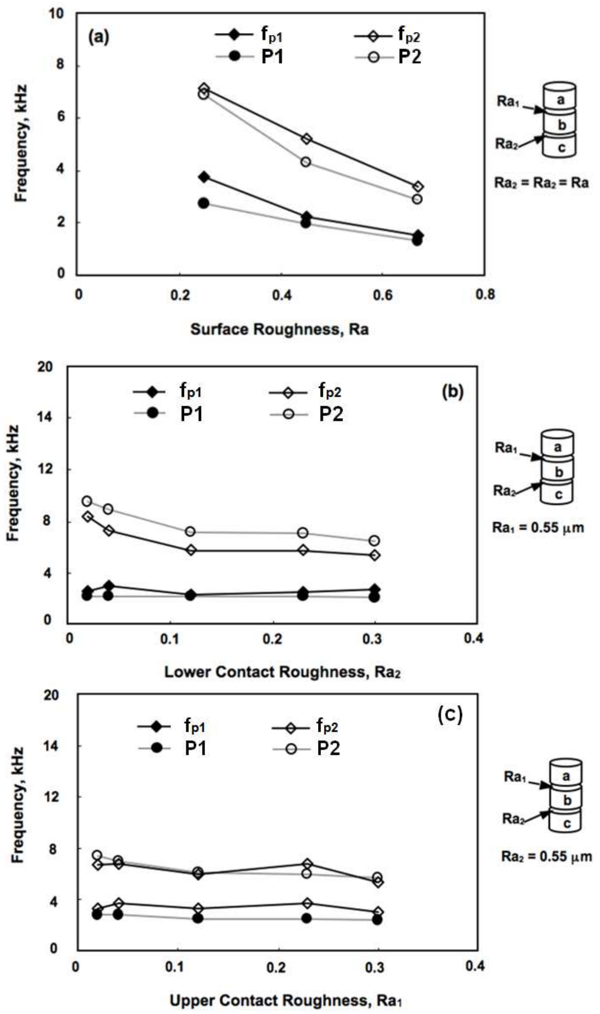


Figure 9. Effect of Contact Stiffness on Peak Frequencies; Similar Roughness for Upper and Lower Contact Interfaces (a), Different Roughness for Lower Contact Interface (b), and Different Roughness for Upper Contact Interface (c)

4. Conclusions

A three-disk configuration system was used to analyze the effects of surface roughness on the peak frequencies of rubbing vibrations. The results can be summarized as follows: (1) The frequency of peaks that occurred in the three-disk configuration system is shown to have a significant relationship with the roughness of the surface, which is effectively represented by the parameter of contact stiffness. A two-degrees-of-freedom model incorporating the contact stiffness parameter was proposed and used to estimate the quantitative value of the peak frequencies. (2) A quantitative relationship between the surface roughness and the peak frequency of rubbing vibrations has been established.

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