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Investigation on damping properties of contact surfaces with different asperity heights

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Abstract
The stiffness and damping of machines have a significant impact on machine's dynamic characteristic. Machines consist of a large number of parts and have a large number of joints between various machine elements, including bolted joints. The stiffness (contact stiffness) and damping (contact damping) at the joints have a significant effect on the vibration characteristics of the entire machine. Therefore, high contact stiffness and high contact damping are required to design high-precision machine tools. However, it is known that there is generally a trade-off relationship between contact stiffness and contact damping. Since contact stiffness and damping are determined by elasto-plastic deformation and sliding of asperities in the real contact area, the optimal design of surface geometry to control these phenomena should be discussed. In this study, contact surfaces with asperities of two different heights are designed to improve contact damping while maintaining contact stiffness. In a contact surface with two different asperity heights, a weak contact zone is created on a low asperity and a severe contact zone is created on a high asperity. High contact stiffness and high contact damping can be expected by allowing only the weak contact area to slip, thereby increasing the amount of damping. The effectiveness of the proposed method was verified by finite element simulation and experiments.
Keyword: contact damping, contact stiffness, contact surface, local slip, Finite element method

1. Introduction

The stiffness and damping of machine tools have a significant influence on machining accuracy. Machine tools consist of a large number of parts and have a large number of joints between various machine elements, including bolted joints. The contact stiffness and contact damping of these joints have a significant influence on the vibration characteristics of the entire machine. [1,2]

Although both contact stiffness and damping should be high, there is generally a trade-off relationship between them. [3,4] Some methods have been proposed to overcome this trade-off in previous reserches, they are not often used in actual machine design due to their low flexibility. [5]

In this paper, we propose a method to improve damping without decreasing the overall contact stiffness by facilitating localized slip on the contact surface. Specifically, by providing cusps height difference on the contact surface, a weak contact zone is created on a low cusp and a strong contact zone is created on a high cusp. The localized slippage only on the low cusps increases the contact damping while maintaining the contact stiffness. We conducted finite element simulations and experiments for verification.

2. Outline of Proposed Method

2.1. Outline of Proposed Method

Figure 1 shows a schematic of the contact between two surfaces and its load-displacement relationship in macro and micro scales. The metal surface has microscopic cusps and that they transfer force between the contacting surfaces when these cusps make real contact (Fig. 1(a)). The macroscopic damping and stiffness of the entire contact surface are observed as a hysteresis loops in a load-displacement relationship. The stiffness and damping of the entire contact surface is a convolution of hysteresis loops at each microscopic cusp. Height of microscopic cusp is a dominant factor of microscopic hysteresis loops.

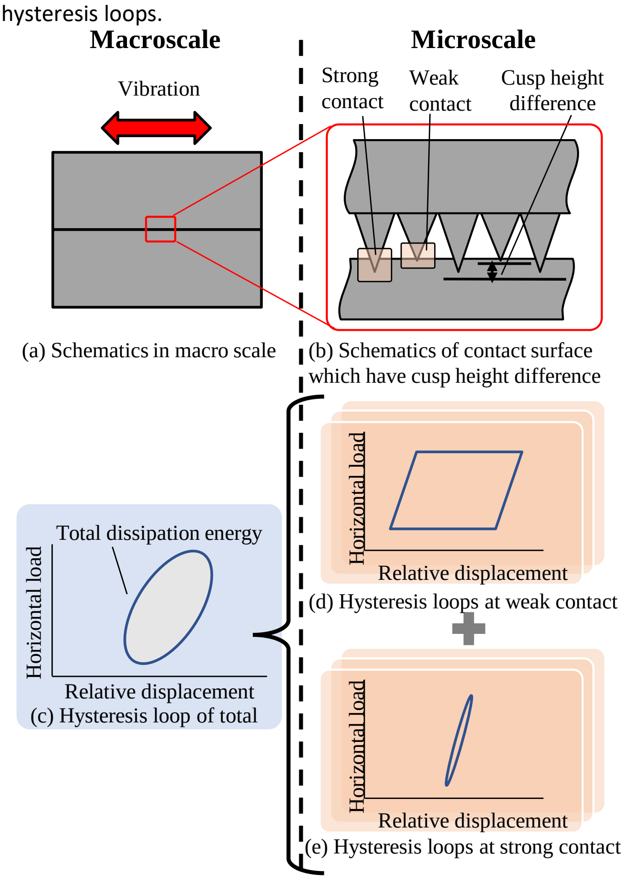

Fig.1 Schematic of the contact between two surface and its load-displacement relationship in macro and micro scale

Thus, we propose a method in which the distribution of the cusp height is controlled to maintain the stiffness and improve the damping.

In the proposed method, as shown in Figure 1(b), a weak contact zone and a strong contact zone are intentionally created by the difference in the cusp height. When a horizontal force is applied to the contact surface, each cusp is considered to have a load-displacement curve as shown in Figure 1(d) and (e). This curve has a hysteresis loop due to elasto-plastic deformation and slip of each cusp. At the weak contact area, the cusp slips and dissipate large energy. On the other hand, at the strong contact area, the cusp do not slip and maintain the stiffness. Therefore, the load-displacement curve of the entire contact surface (Figure 1(c)) should be wide hysteresis loop because of slip at the weak contact area and the inclination of hysteresis loop should be high because of no slip at strong contact area.

3. Simulation

In this chapter, simulations are performed to subject specimens with different cusp height differences to vibration. The possibility of the proposed method is verified by investigating the changes in damping and stiffness due to the different cusp height differences in the simulations.

3.1. Simulation method

Figure 2 shows a schematic of the simulation method. Two specimens were prepared: the upper specimen was a metal block with five cusps, and the lower specimen was a metal block with a flat surface. The cusps were designated as cusps ⅰ, ⅱ, ⅲ, ⅳ, and ⅴ, respectively.

Simulations were performed for four specimens by varying the height difference of the cusps on the upper specimen. Table 1 shows the specimen's cusp height distribution in simulation.A static structural analysis using the finite element method was used to simulate on the 2D model. The bottom edge of the lower specimen was fixed, and the load displacement was given to the upper specimen as a preload until the pressure on the top edge reached 300 MPa. After the vertical forced displacement was applied, horizontal forced displacement was applied to the left side of the upper specimen. The forced displacement was periodically varied to simulate the vibration of the specimen. Three vibration amplitudes of 3 μm, 5 μm, and 10 μm were investigated for the forced horizontal displacement.

The contact damping and contact stiffness were evaluated by the hysteresis loop in the tangential load–displacement diagram. The hysteresis loop was obtained by plotting the realative displacement on the contact surface and the holizontal load on the left side of the upper specimen. The energy dissipation ratio was calculated to evaluate the damping by dividing the dissipated energy by the energy input to the specimen. The contact stiffness was evaluated by the averaged slope of the hysteresis loop. The contact stiffness was evaluated for quasi static cases. The relative displacement on the contact surface d was calculated by following equation.

$$d = d_u - d_l \quad (1)$$

where d_u represents the displacement of the upper specimen, d_l represents the displacement of the lower specimen. Table 2 shows the simulation conditions.

3.2. Simulation result of entire specimen

Figures 3 and 4 show the energy dissipation ratio and contact stiffness for each specimen obtained from the simulations. In Figs. 3 and 4, the damping is high while the stiffness is low for 10 μm vibration amplitude. This is due to that the entire cusps slipped because the vibration amplitude is too large.

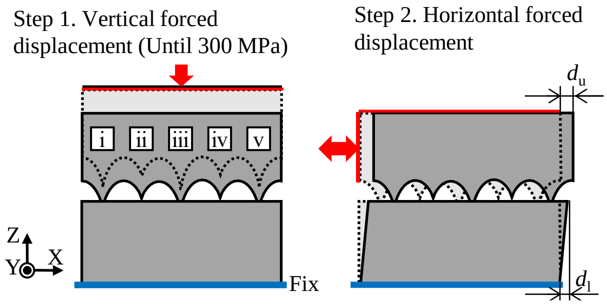

Fig.2 Simulation method

Table 1 Specimen's cusp height distributioin in simulation

Specimen	Height of Cusp ⅰ, ⅲ, ⅴ	Height of Cusp ⅱ, ⅳ
S-0	50 μm	50 μm
S-3	50 μm	47 μm
S-5	50 μm	45 μm
S-10	50 μm	40 μm

Table 2 Simulation condition

Cusp height difference	0, 3, 5, 10 μm
Vibration amplitude	3, 5, 10 μm
Vertical pressure	300 MPa
Coefficient of friction	0.36

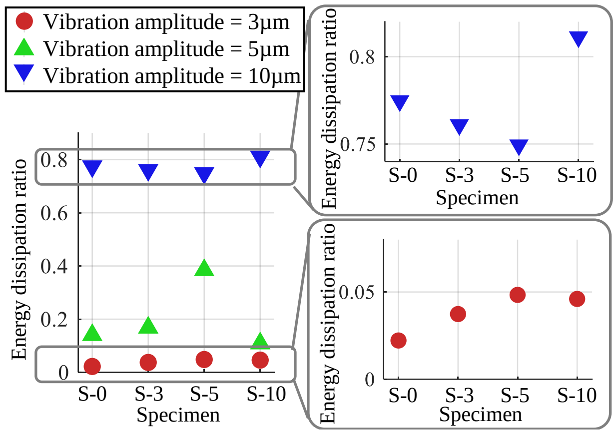

Fig.3 Energy dissipation ratio obtained by simulation

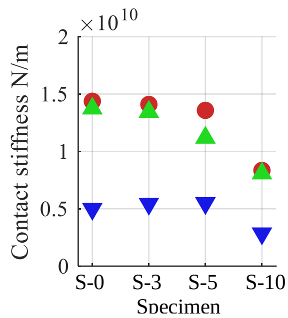

Fig.4 Contact stiffness obtained by simulation

Although the large amplitude condition is suitable to increase damping, it is not practical because unrecovered deformation remains.

In Fig. 3, specimen S-5 with the cusp height difference of 5 μm had the highest damping when the vibration amplitude was 3 μm and 5 μm. The damping for specimen S-10 with the cusp height difference of 10 μm is lower than that for specimen S-5 because the contact at the lower cusp is too weak. In Fig. 4, for vibration amplitudes of 3 and 5 μm, the stiffness of each specimen decreased as the difference in cusp height increased. However, the decrease rate of the stiffness for specimen S-5 compared to specimen S-0 is smaller than 19 % and not significant.

The damping for specimen S-5 at a vibration amplitude of 3 µm was about 117% higher than that of specimen S-0. On the other hand, the contact stiffness was reduced by only about 6%. Although there still exists the tradeoff between the stiffness and damping, it was found that the cusp height difference improved the damping without a significant decrease of the stiffness.

3.3. Simulation result of each cusps

The calculated hysteresis loop at each cusp was compared to verify that the damping was improved by the localized slip at the lower cusp. Figure 5 shows the hysteresis loops and dissipation energy of each cusp of specimen S-0 and S-5 at a vibration amplitude of 3 µm. The dissipation energy was calculated from the area enclosed by the hysteresis loops.

Figures 5(a) and (b) show the energy was dissipated by the mixture of small slip and plastic deformation at cusps ⅰ and ⅱ in specimen S-0. Because the horizontal load increased with the displacement increase, theses cusps did not completely slip. The reason why almost no energy was dissipated on cusps ⅲ, ⅳ, and ⅴ is considered to be smaller stress on these cusps resulting from ununiform stress distribution in the specimen.

In the results for specimen S-5 shown In Figs.5 (c) and (d), only cusp ⅱ slipped and large energy was dissipated at cusp ⅱ. Because the the horizontal load did not increase with the displacement increase in Fig.5(c), cusp ⅱ completely slipped. The hystelisis loops in Fig.5(c) also showed that the stiffness of cusps ⅰ, ⅲ, and ⅴ was higher than those of cusps ⅱ and ⅳ which contributes to maintain the stiffness of entire specimen. The simlulation results showed that the damping could be imprived by the localized slip only at the lower cusp.

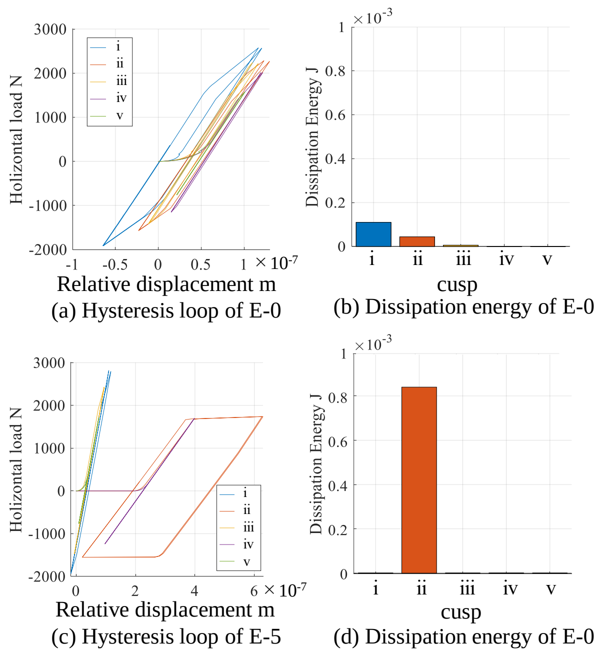

Fig.5 Hysteresis loop and dissipation energy of each cusp

4. Verification experiment

Experiments were conducted to verify the simulation result. The contact damping and stiffness were measured using specimens with different cusp height differences.

4.1. Experimental method

Figure 6 shows a schematic of the experimental setup. A vertical preload was applied to the upper specimen, and the upper specimen was pressed against the lower specimen using the bolt. The varied horizontal load was then applied using the piezoelectric actuator. The contact stiffness and damping properties were evaluated from the horizontal load and the relative displacements of the upper and lower specimens. The vertical preload was applied by a bolt on the top of the set up. The horizontal load and vertical preload were measured by piezoelectric force sensors. The difference between the horizontal displacement of upper and lower specimen, which was measured by capacitance displacement meters, is calculated as relative displacement between specimens.

Figure 7 shows a schematic diagram of the contact surface and the surface profile of the specimen before the experiment. As shown in Fig.7(a), the contact surface was finished by milling with a ball endmill and has cusp grooves. In order to reduce the influence of the waviness of the specimen surface, the specimens were placed so that the cusps intersected each other [6]. Three specimens with different cusp height differences were used for the upper specimen. Table 3 shows the specimen's cusp height distribution in experiment. To account for variations in measurements, three specimens each with similar processing were used in the experiment. The experiment was repearted three times for each specimen.

In this experiment, the vertical preload applied to the specimen was 8000N. The 0 – 150V of sign wave voltage was applied to the piezoelectric element, which was equivalent to 0-18 µm expansion without any external loads. The frequency of sign wave was 500 Hz. Thus, a dynamic effect may be included in this experiment while the quasistatic evaluation was conducted in the simulation. However, the vairiation of the contact damping due to the cusp height difference should oocur also in the experiment if the proposed method works.

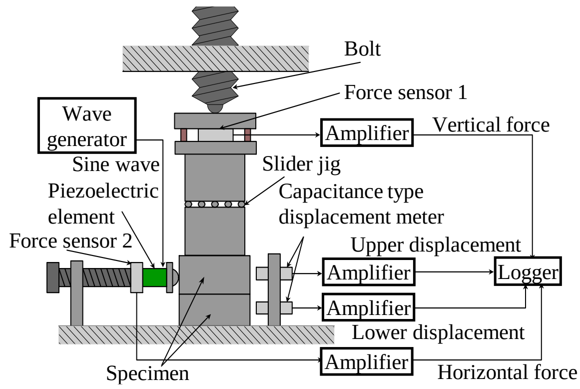

Fig.6 Schematics of experimental set up

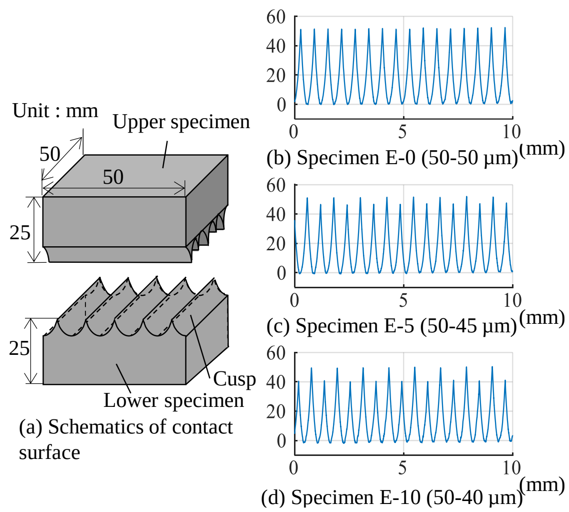

Fig.7 Schematics of contact surface and surface profile of specimen before the experiment

Table 3 Specimen's cusp height distributioin in experiment

Specimen	Height of High Cusp	Height of Low Cusp
E-0	50 μm	50 μm
E-5	50 μm	45 μm
E-10	50 μm	40 μm

4.2. Expeimental result

Figure 8 shows energy dissipation ratio and contact stiffness for each specimen obtained from the experiment. Figure 8 shows that the average values of energy dissipation ratio and stiffness are in the order of specimen E-0 > E-5 > E-10, which is different from the simulation result shown in Fig.3. However, specimen E-10 had a larger variation in damping. Specimen E-10_3 particuraly had better damping than those of specimens E-0 and E-5.

Figure 9 shows the hysteresis loops in the load-displacement diagrams for specimens E-0_1, E-0_3, E-10_1 and E-10_3. Figure 9 shows that specimen E-10_3 had a wider hysteresis loop which resulted in increased damping. Therefore, specimen E-10 with a large cusp height difference may have a good damping possibility.

4.3. Discussion of experimental result

The difference between the experimental and simulation results are discussed here. Figure 10 shows histograms of the cusp height distribution of specimens E-0 and E-5 obtained by the contact type surface roughness measurement machine. Figure 10 shows that the height of the cusps varied in about 3 μm range. This height variation could be caused by a machining error during end milling. In total of upper and lower specimens, a maximum hight error of about 6 μm could exist on the contact surface used in this experiment. Therefore, the real cusp height difference in specimen E-0 might be about 6 μm and suitable to increase the damping. In contrast, the real cusp height difference in specimen E-5 might be larger than targeted 5 μm due to the machining error which resulted in too large cusp height difference.

5. Conclusion

A method to improve the contact damping by cusp height difference was proposed. When the vibration amplitude is 3 μm and 5 μm, the cusp height difference improved the contact damping in the finite element simulation. However, in the experiment, the cusp height difference did not always improve the contact damping. The reason why the damping was not improved in the experiment may be that the targeted cusp height difference was not achieved because of the machining error. In our future work, coating on cusps with soft metal will be implemented to loosen the required manufacturing accuracy of cusp height differences.

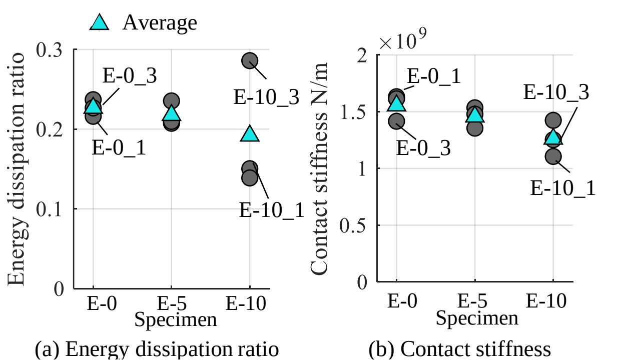

Fig.8 Energy dissipation ratio and contact stiffness obtained by experiment

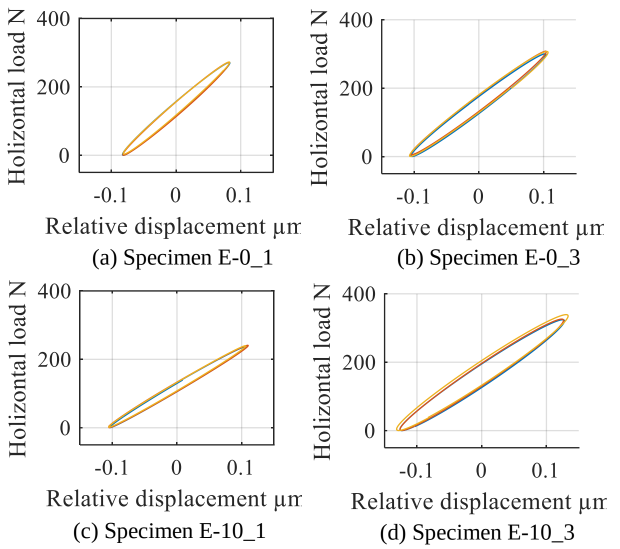

Fig.9 Hysteresis loop of specimen E-0_1, E-0_3, E-10_1 and E-10_3

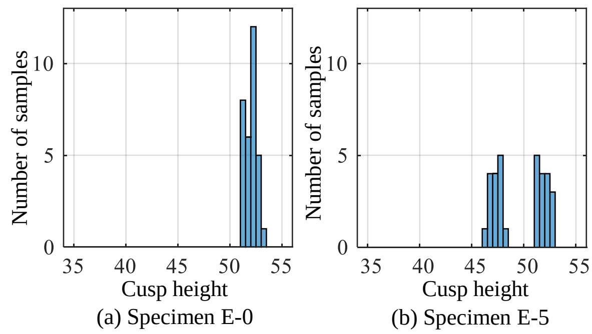

Fig.10 Histogram of cusp height

Acknowledgements

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