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On-site estimation of floor stiffness for modelling machine tool supports

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Abstract

This study proposes a simple on-site estimation method of the floor stiffness. The contact stiffness depending on the preload between the support and floor is identified. The model of the preload-stiffness relationship for the block on the floor is described. The natural frequency of the block for the translational vertical vibration is measured by the impact test. The measurement is conducted for several blocks with different mass to obtain the preload-stiffness relationship. The contact stiffness coefficient is identified by fitting the model to the experimental data. The stiffness of two floors are compared using the estimation method to investigate the influence of its surface finish on the contact stiffness. The surface reinforcement using the glass coating increased the contact stiffness to 455% of that for the general polymer painted floor. The natural frequency of the block which has three supports is measured on the painted floor for verification of the identified parameter. The estimation using the identified contact stiffness coefficient well agrees to the experimental results

Keywords: Stiffness; Machine; Contact; Vibration;

1. Introduction

High speed and high acceleration motions of machine tools are demanded for a high productive machining process. In such motions, vibrations in low frequencies caused by the driving force of feed axes can be often a problem. The machine's dynamic characteristic in low frequencies is dominated by the dynamic property of a machine support-floor system [1, 2]. It is difficult to estimate the dynamic property because of the influence of the contact stiffness between the support and floor [3].

The evaluation of the dynamic property of the machine support-floor system is expected to be utilized in the following cases. The first case is the quantitative evaluation of the floor. This evaluation contributes to the decision of machine installation location and determination of floor specifications such as the property of concrete and surface finishing. These decisions are currently done empirically. The second case is the dynamic simulation of the machine. The stiffness of supports should be tuned on the basis of dynamic performance evaluation of the machine [4]. Many studies do not consider the contact stiffness between the support and floor [5].

The contact stiffness between steel and concrete was measured using test pieces to estimate the support stiffness [6]. However, this method is not practical because it is often difficult to make a test piece from an existing floor. Thus, an on-site evaluation method is ideally required.

This study describes a simple on-site estimation method of the floor stiffness. The contact stiffness depending on preload between the support and floor is identified. The estimation method is described based on the stiffness model of machine tool support developed in our previous study. The stiffness of two floors are compared using the estimation method to

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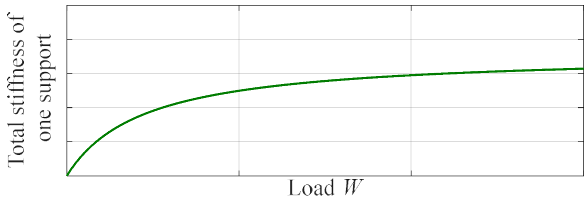


Fig.1. Preload-stiffness relationship of the support.

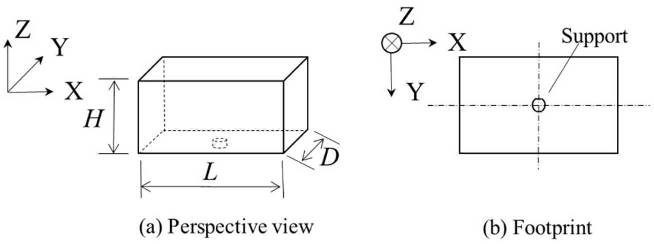


Fig.2. Schematic of block.

investigate the influence of its surface finish on the contact stiffness.

2. Estimation method of contact stiffness

A method to estimate the contact stiffness of the floor in the vertical direction is described in this section. The method is based on the contact stiffness model depending on the preload on the contact surface.

2.1. Contact stiffness model

Machine tools are generally installed on concrete floors using supports. The stiffness K between the machine and floor is modelled by the bulk stiffness and the contact stiffness connected in series [6], and determined as follows:

$$\frac{1}{K} = \frac{1}{k_b} + \frac{1}{k_c} \tag{1}$$

where k_b and k_c are the bulk stiffness and the contact stiffness, respectively.

The bulk stiffness can be calculated from the modulus of elasticity and the geometry of the support. The bulk stiffness is constant. The contact stiffness is assumed to be proportional to the vertical preload W [6, 7] in this study as follows:

$$k_c = \alpha W \tag{2}$$

where α is contact stiffness coefficient. Figure 1 shows the conceptual relationship between W and K. When the preload is small, the stiffness K increases linearly with W because the contact stiffness dominates the total stiffness. When the preload is increased enough, the stiffness saturates to the bulk stiffness. Although a similar stiffness model can be applied to the tangential stiffness, this study focuses on the vertical stiffness so far.

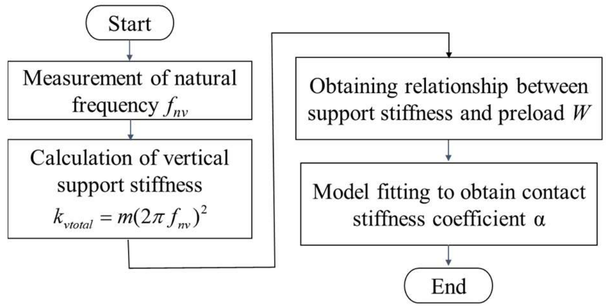


Fig.3. Flowchart of identification.

2.2. Identification method of contact stiffness coefficient

A method is proposed to identify the contact stiffness coefficient between the floor and support from the preload-stiffness relationship shown in Fig.1. A steel block is put on the objective floor to measure the stiffness between the block and floor. The measurement is conducted for several blocks with different mass to obtain the preload-stiffness relationship.

Figure 2 shows the schematic of the block used in this study. The lengths *L, D* and *H* are the dimensions of the block. The block has one support. The support is almost a cylinder with 3 mm height and 15 mm diameter. The tip of the support is slightly rounded with 500 mm radius to increase the repeatability of the contact.

In order to obtain the model of the preload-stiffness relationship for the block, the stiffness in the Z direction is calculated. The preload W on the support is determined by the mass of the block. The stiffness of the support is obtained by substituting Eq.(2) into Eq.(1) as follows:

$$K = \frac{k_b \alpha W}{k_b + \alpha W} \tag{3}$$

Figure 3 shows the flowchart of the identification. In the first step, the natural frequency f_{nv} of the block for the translational vibration in the Z direction is measured by the impact test. In the translational vibration in the Z direction, the experimental system can be assumed to be a single degree of freedom model consisting of one mass and one stiffness. Thus, in the second step, the vertical support stiffness k_{vtotal} can be obtained using the following equation:

$$k_{vtotal} = m(2\pi f_{nv})^2 \tag{4}$$

where m is the mass of the block. Then, the measurement is conducted for several blocks with different mass. The relationship between k_{vtotal} and the preload W is obtained. In the final step, the contact stiffness coefficient and bulk stiffness are identified by fitting Eq.(3) to the experimental data. The proposed method can be also applied for the contact stiffness model other than Eq.(2) when the stiffness depends on the preload.

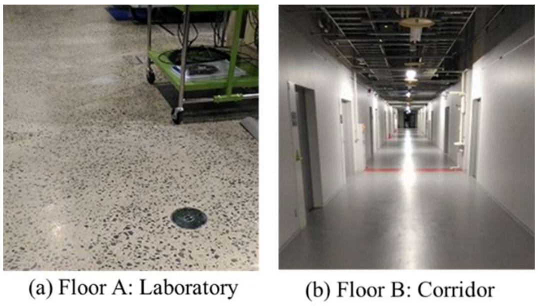


Fig.4. Appearance of floors.

Table 1 Block size

Block	$L \times D \times H$ mm
Large	180×120×100
Medium	180×120×75
Small	180×120×65

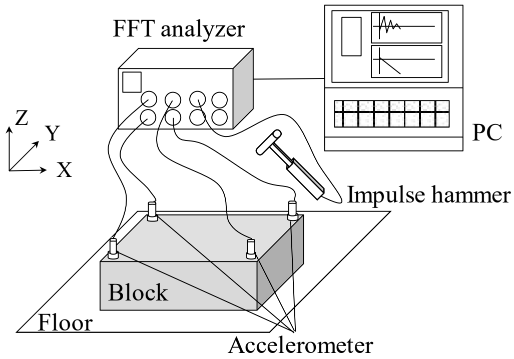


Fig.5. Experimental setup.

3. Identification experiment

3.1. Experimental method

The proposed method is applied to two types of floor to investigate the influence of their surface finish on the property. Figure 4 shows the appearance of the floors. Floor A is the floor of our laboratory. Because the floor is designed for machine tool installation and precise measurement, the concrete surface is polished and reinforced by a glass coating. Floor B is the floor of a corridor. It is a concrete floor covered by a polymer sheet.

The dimensions of blocks used in this study are summarized in Table 1. Three blocks with the same footprint are used. The material of the block and support is 304 stainless steel. The tip of the support was finished by cutting.

The natural frequency was measured by the impact test. The schematic drawing of the experimental setup is shown in Fig.5. The center of the block was excited in the Z direction using an impulse hammer (PCB Piezotronics). The response in the Z direction was measured using four acceleration sensors (PCB Piezotronics) attached on four corners of the block. The natural frequency was determined from the frequency response function calculated using a Fast Fourier Transform (FFT) analyzer (Ono-sokki). The lowest natural frequency having the same phase of four sensors was determined to be f_{nv}.

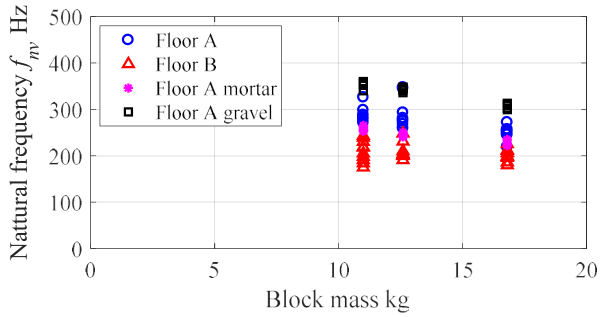


Fig.6. Relationship between block mass and f_{nv}.

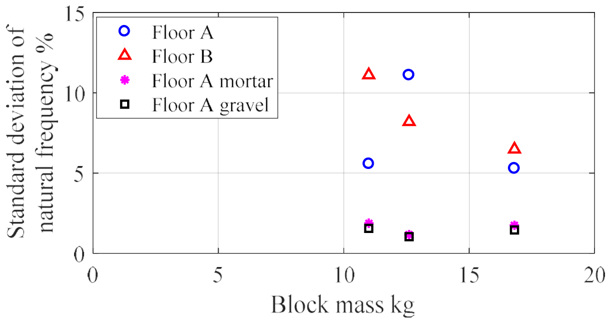


Fig.7. Relationship between block mass and standard deviation of f_{nv}.

The sensitivities of the impulse hammer and acceleration sensor are 2 mV/N and 10 mV/(m/s^2), respectively. The measurement frequency range was set to 500 Hz, and the number of sample points was 2048. Ten measurements were conducted while the block location was randomly changed in 300 mm ×300 mm area. The conventional averaging function of the FFT analyzer was not used because the natural frequency varied depending on the location. On Floor A, the measurement was conducted on selected gravel and mortar points to investigate their difference. In these measurements, a line tape on the floor was used to put the block back on the same location. The repeatability of the location is approximately 1 mm.

3.2. Experimental result

Figure 6 shows the relationship between the mass of the block and f_{nv}. The result shows the difference between two floors. The natural frequency for Floor A is higher than that for Floor B. It can be resulting from the surface finish by the glass coating. The glass coating increases the natural frequency by 23-36%. The natural frequency for Floor A is between those for gravel and mortar. It is because of the averaging effect by the random change of the block location.

Figure 7 shows the relationship between the block mass and standard deviation of f_{nv} to evaluate the repeatability of the measurement. The standard deviation is represented as the ratio to the mean value of f_{nv}. The standard deviation for gravel and mortar is smaller than that for Floors A and B. It shows the stiffness variation depending on the block location.

Figure 8 shows the relationship between k_{vtotal} and the preload W. The broken lines show the fitted curves. The obtained parameters are summarized in Table 2. The contact stiffness coefficient α is highest for the gravel. The coefficient α for Floor A is approximately 455% of that for Floor B.

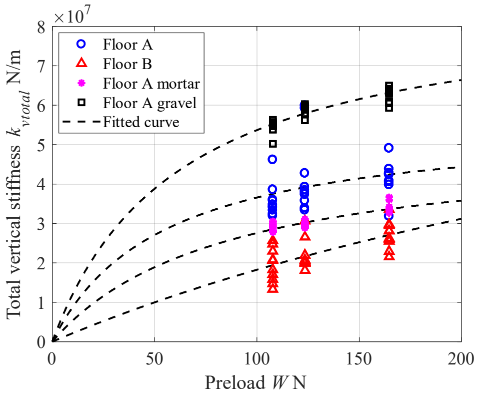


Fig.8. Relationship between preload and vertical stiffness.

Table 2 Identified parameters

Floor	α 1/m	k_b N/m
A	1.0×10^6	5.6×10^7
B	2.2×10^5	1.1×10^8
Mortar	6.0×10^5	5.1×10^7
Gravel	1.4×10^6	8.7×10^7

Although the stiffness of Floor B is highest in the bulk stiffness, the identified result for Floor B has a large uncertainty. This is because the influence of the bulk stiffness is small in this experiment. The small influence of the bulk stiffness is shown by the fitted curve for Floor B which looks almost linear.

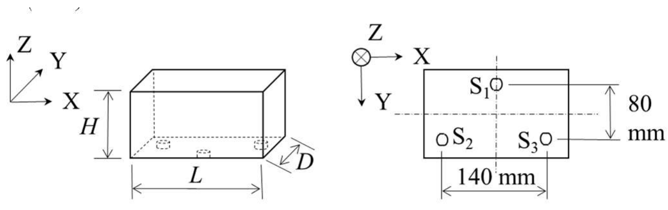
3.3. Verification

For brief verification of the identified parameter, the natural frequency of the block which has three supports was measured on Floor B. Figure 9 shows the schematic of the block. The dimensions of the block are similar to those summarized in Table 1. The natural frequency was also estimated from α of 2.2×10^5 1/m for comparison. The supports are modeled as three parallel springs in the vertical direction. Because the influence of the bulk stiffness looks small in Fig.8, the bulk stiffness was neglected in this estimation. Therefore, the natural frequency is theoretically constant regardless of the block mass because the vertical stiffness is proportional to the mass.

Figure 10 shows the comparison between measured and estimated natural frequencies. The estimation well agrees to the experimental results. Although the natural frequency is constant in the estimation, it slightly decreases while the block mass increases in the experimental result. This is caused by the small influence of the bulk stiffness which is neglected in this estimation.

4. Conclusions

This study proposed a simple on-site estimation method of the floor stiffness. The contact stiffness depending on preload between the support and floor was identified. The model of the preload-stiffness relationship for the block on the floor was described. The natural frequency of the block for the translational vibration in the Z direction is measured by the impact test. The measurement is conducted for several blocks with different mass to obtain the preload-stiffness relationship.



(a) Perspective view (b) Footprint

Fig.9. Schematic of block with three supports.

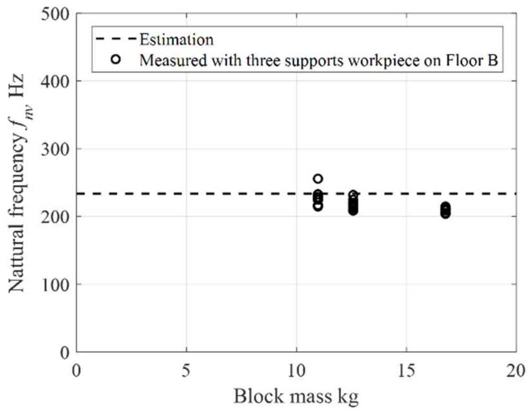


Fig.10. Comparison between measured and estimated natural frequencies.

The contact stiffness coefficient is identified by fitting the model to the experimental data. The stiffness of two floors were compared using the estimation method to investigate the influence of its surface finish on the contact stiffness. The surface reinforcement using the glass coating increased the contact stiffness to 455% of that for the general polymer painted floor. The natural frequency of the block which has three supports was measured on the painted floor for verification of identified parameters. The estimation using the identified contact stiffness coefficient well agreed to the experimental results.

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