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Implementation of jack bolts with built-in preload sensors for level condition monitoring of machine tool

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Abstract

Precision machine tools are usually installed on foundations via supporting elements. In this configuration, errors because of inappropriate support lengths (level error) have to be adjusted during the installation to align the level of the machine tool. Consequently, a quantitative indication of level errors is a necessity for levelling works. Therefore, a model-based approach for level condition monitoring, which can identify level errors, is proposed. In the model, machine supports are modeled as linear springs. The relationship between the level error and preload distribution is modeled in matrix form. This report verifies the fundamentals of the proposed approach through experiments performed on a machining center.

Keywords: Machine tool; Condition monitoring; Sensor; Installation; Level control;

1. Introduction

Precision machine tools are often installed on foundations via supports, such as levelling blocks or jack bolts. However, this configuration can induce a number of geometrical errors on the machine structure because of inappropriate support lengths (level error). Thus, the support length should be adjusted during the installation and daily maintenance (level adjustment) [1]. In low stiffness machine tools, which have several supports to prevent deformations in the machine, level adjustment becomes complex. Moreover, because level adjustment requires highly skilled installers, it is difficult for machine tool users to perform levelling on their own. Therefore, a model-based adjustment method for level errors is required for the easy installation and maintenance of machine tools [2].

A number of methods have been proposed to overcome this levelling problem [2–4]. These methods require several measurement devices, such as levels or displacement sensors. Moreover, these techniques are based on the trial-and-error method. Thus, a numerical compensation method, using support preload measurement is proposed [5]. However, the level error should be compensated mechanically.

A level error identification method, which can compensate mechanically for level errors, is proposed in this paper. In this method, supports are considered as linear springs, in which the relationship between changes in the support length and preload is modeled. This report explains the verification fundamentals of the proposed approach. The approach and model are described in section 2 below, whereas the experimental verification is reported in sections 3 and 4.

2. The approach and model

Figure 1 shows a two-dimensional machine tool levelling model, where each support is assumed to be a linear spring.

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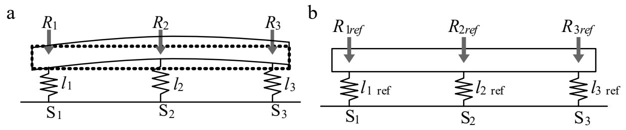

Fig. 1. Simplified machine tool level model; (a) Unlevelled condition; (b) Levelled condition.

The parameters R_i and l_i represent the supporting preload and free length of the support S_i, respectively. The horizontal beam represents a machine tool bed. In a real machine tool, the linear movements of the horizontal axes should be sufficiently straight. The straightness of axes movements is mainly influenced by the straightness of the guideways, which are fixed on the machine bed. Thus, the bed, including the guideways, is modelled as a beam and its deformation because of supports length change is considered in this model.

When the machine is first installed, supports are not adjusted and the beam is deformed (unlevelled condition), as shown in Fig. 1(a). The free length of each support is defined as $l_i(i = 1 - 3)$. Here, the free length is the jack length without any preload, and is different from the apparent length, which is directly observed under a preload because of the stiffness of the support.

By adjusting the support lengths, the beam becomes straight (levelled condition) as shown in Fig. 1(b). Moreover, the free length of each support is adjusted to $l_{i\,\mathrm{ref}}(i = 1 - 3)$. The support length should be adjusted is as follows:

$$\Delta l_i = l_i - l_{i\,\mathrm{ref}}\ (i = 1 - 3) \quad (1)$$

In the machine tool installation, a vertical translation of the machine does not induce a level error but relative length differences between supports are important. Thus, the free length change, Δl_1, of support S_1 can be neglected.

The preload changes in the supports shown in Figs. 1(a) and 1(b) are expressed as follows:

$$\Delta R_i = R_i - R_{i\,\mathrm{ref}} \quad (2)$$

where $R_{i\,\mathrm{ref}}$ represents the supporting preload in supports, S_i $(i = 2, 3)$, at the levelled condition.

When the free length changes only in support S_2, the preload change in each support can be expressed as follows:

$$\Delta R_i = dR_{i2} \times \Delta l_2 \quad (3)$$

where dR_{i2} represents the preload change in supports caused by a unit of free length change.

Linear models conform with the rules of superposition. Thus, the preload change in supports caused by free length changes in multi supports can be expressed as follows:

$$\Delta R_i = dR_{i2} \times \Delta l_2 + dR_{i3} \times \Delta l_3 \quad (4)$$

When the model is extended to n jacks, the preload changes caused by the support length change can be expressed as follows:

$$\begin{bmatrix} \Delta R_1 \\ \vdots \\ \Delta R_n \end{bmatrix} = \begin{bmatrix} dR_{12} & \cdots & dR_{1n} \\ \vdots & \ddots & \vdots \\ dR_{n2} & \cdots & dR_{nn} \end{bmatrix} \begin{bmatrix} \Delta l_2 \\ \vdots \\ \Delta l_n \end{bmatrix} \quad (5)$$

Hereinafter, the coefficient matrix of the Eq. (5) is called as stiffness matrix.

When the beam is replaced by a plate, which is more similar to the bed, the model becomes a three-dimensional model. Nevertheless, the model remains linear. Thus, it is assumed that Eq. (5) can be applied to the three-dimensional case. Therefore, when the supporting preload under the levelled condition and the stiffness matrix are known, free length changes in the unlevelled condition can be obtained from the supporting preload using the following equation:

$$\begin{bmatrix} \Delta l_2 \\ \vdots \\ \Delta l_n \end{bmatrix} = \begin{bmatrix} dR_{12} & \cdots & dR_{1n} \\ \vdots & \ddots & \vdots \\ dR_{n2} & \cdots & dR_{nn} \end{bmatrix}^{-1} \begin{bmatrix} \Delta R_1 \\ \vdots \\ \Delta R_n \end{bmatrix} \quad (6)$$

By utilizing this method, the levelling work can be done without the use of the trial-and-error method.

3. Identification of the stiffness matrix

3.1. Machine tool used in the experiment

Experiments are conducted on a vertical machining center prototype shown in Fig. 2(a) to identify the stiffness matrix. Table 1 summarizes the major specifications of the machine tool, and a schematic of the support is shown in Fig. 2(b). The machine, whose footprint is shown in Fig. 3, has eight jack-bolt-type supports (S_1–S_8).

The supports are equipped with rotary encoders and strain gauge type load cells, which can measure the preloads in the Z-direction on each support approximately every 6 seconds. Its measurement repeatability is approximately ± 0.1 kN. The rotary encoders are attached to the jack bolts via reduction gears to measure the rotation angle, $\Delta\theta_i$, of the jack bolts. Because it is difficult to measure the free length of a support, support free length changes, Δl_i, are measured by way of the rotation angle, $\Delta\theta_i$, in the jack bolt and then the free length change is calculated using the following equation:

$$\Delta l_i = L \times \frac{\Delta\theta_i}{360} \quad (7)$$

where L is the lead of the jack bolt screw and is 2 mm in this jack bolt. The resolution of the rotary encoder is 3.75° per pulse and the rotations of the jack bolts are amplified for 10 times by the reduction gears. Thus, the measurement resolution of the free length change is approximately 2 μm.

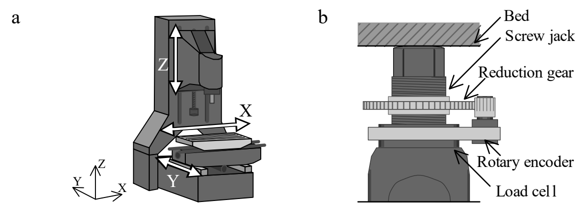

Fig. 2. Schematic of the machine tool: (a) Entire machine tool; (b) Jack bolt.

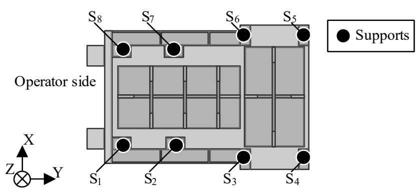

Fig. 3. Machine tool footprint.

Table 1. The specifications of the machine tool.

	Machine type	Vertical machining center
Body size	Width	0.5 m
	Length	0.9 m
	Height	1.5 m
Axes travel	X-axis	600 mm
	Y-axis	530 mm
	Z-axis	510 mm
	Machine weight	5800 kg
	Number of support	8

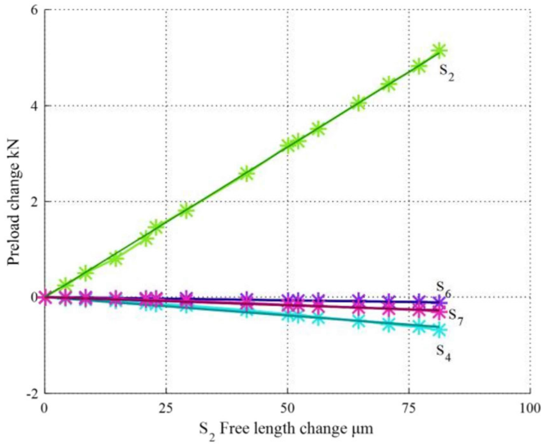

Fig. 4. Measured relationships between free length and preload changes in support S_2; the slope of a regression line responds as a component of the stiffness matrix.

3.2. Identification of the stiffness matrix

The stiffness matrix of the machine tool is obtained by the following procedure based on the relationship between the free length change, Δl_i, and preload change, ΔR_i. First, the preload on supports S_1–S_8 are measured as the free length of support S_k is being changed. Thereafter, relationships between free length changes, Δl_k, and preload changes, ΔR_i, are obtained for each of the supports. Then, the stiffness matrix elements, dR_{ki}, are obtained from the relationships by using the least square method. This procedure is applied for each support.

In the experiment, to simplify the problem, free length changes caused by three supports (S_2, S_6, and S_7) and preload changes in four supports (S_2, S_4, S_6, and S_7) are investigated. The free length of a support is extended by several steps up to approximately 125 μm. In order to avoid the effect of the jack bolt backlash, the free length change is extended only in one direction. The load on each support is measured for 5 minutes under each free length condition. Approximately 50 measurement data are collected in each condition, and the collected data are averaged. Throughout all experiments, the position of each axis is fixed at the center of travel to neglect the effect of mass movement.

Examples of obtained relationships between the free length and preload changes in the support are shown in Fig. 4. Each asterisk represents measured results and each line represents a regression result. The slope of each regression line responds to a component of the stiffness matrix. According to the figure, the linear assumption of the relationship between the free length and preload changes is satisfied. It is presumed that this model can be extended to be three-dimensional. The stiffness matrix obtained from the experimental results is as follows:

$$\begin{bmatrix} dR_{22} & dR_{26} & dR_{27} \\ dR_{42} & dR_{46} & dR_{42} \\ dR_{62} & dR_{66} & dR_{62} \\ dR_{72} & dR_{76} & dR_{77} \end{bmatrix} = \begin{bmatrix} 63.4 & -1.0 & -2.8 \\ -7.3 & 1.5 & 2.8 \\ -1.3 & 52.0 & -14.5 \\ -2.9 & -12.8 & 57.9 \end{bmatrix} \text{[N/μm]} \tag{8}$$

4. Method verification

For the verification of the method, the superposition theory is investigated by comparing the experimental and estimated results based on the stiffness matrix obtained in subsection 3.2.

4.1. Experimental method

The investigation of superposition theory is described in this section. First, the machine tool is set to a levelled condition by a conventional method. Then, free length of three supports (S_2, S_6, and S_7) are changed randomly in the extension direction, and the preload on supports are measured under each level error condition. Finally, experimental results are compared with the stiffness matrix.

4.2. Obtained results

The experimental results are shown in Figs. 5, 6, and 7. Figure 5 shows the relationships between preload changes and the free length change, Δl_2, whereas Figs. 6 and 7 show the relationship between the preload and free length changes, Δl_6 and Δl_7, respectively. In the figure, asterisks connected by solid lines represent the measured values. Dashed lines represent the estimated change ratios calculated from the stiffness matrix, shown in Eq. (8). The horizontal shift of the preload (sections A and B) represents the preload changes induced by the free length change of the support, which corresponds to the horizontal axis. The vertical shift of the preload (section C) represents the preload changes induced by the free length change of the support, which does not correspond to the horizontal axis.

In section A, the slopes between the estimated and experimental results basically agree. Thus, it can be said that the stiffness matrix does not change under multi free length changes conditions.

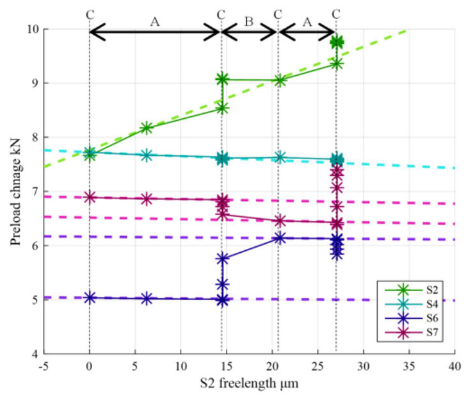

Fig. 5. Relationships between S_2 free length changes and preload changes of support S_2, S_4, S_6, and S_7.

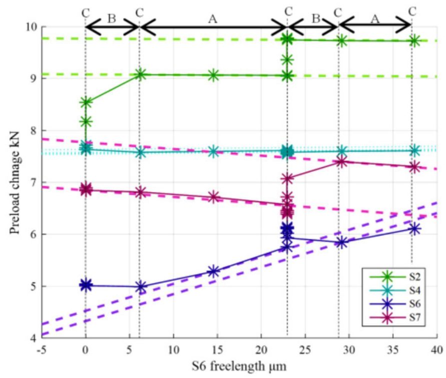

Fig. 6. Relationships between S_6 free length changes and preload changes in supports S_2, S_4, S_6, and S_7.

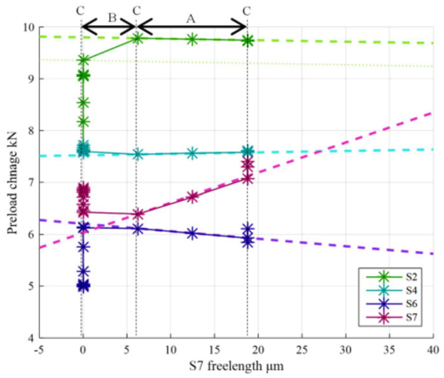

Fig. 7. Relationships between S_7 free length changes and preload changes of support S_2, S_4, S_6 and S_7.

The average of each component of the stiffness matrix obtained from the experimental results are as follows:

$$\begin{bmatrix} dR_{22} & dR_{26} & dR_{27} \\ dR_{42} & dR_{46} & dR_{42} \\ dR_{62} & dR_{66} & dR_{62} \\ dR_{72} & dR_{76} & dR_{77} \end{bmatrix} = \begin{bmatrix} 45.8 & -0.7 & -3.0 \\ -4.4 & 1.8 & 3.3 \\ -1.3 & 41.3 & -14.8 \\ -3.2 & -13.3 & 54.4 \end{bmatrix} \text{[N/μm]} \quad (9)$$

In this setup, the uncertainty in the stiffness matrix originating from measurement errors of the preload and free length is approximately ±2 N/μm. Thus, it is considered that the difference between component values in Eqs. (8) and (9) are induced by measurement errors. Under each condition, the results have large uncertainties in the preload measurement in the support, whose free length is changed at that measurement. This is caused by the characteristics of the measurement setup.

On the other hand, in section B, the slopes of the estimated and experimental results do not match. It is assumed that the backlash in the jack bolts and gears deteriorate the measurement accuracies. Consequently, a larger difference is observed with a larger preload change. Apparently, the backlash in the jack bolt is more important. Thus, improvements in the measurement equipment are essential.

4.3. Inverse identification

From the obtained preload changes and stiffness matrix in Eq. (8), the free length change can be estimated by utilizing Eq. (6). Table 2 summarizes the obtained differences between the applied free length and estimated free length changes. From the table, the identification errors are less than ±2 μm under all conditions, except condition 4, which has a large backlash. The 2 μm free length change means a jack bolt rotation of approximately 0.4°, which is sufficiently small for level adjustments. The result suggests that this inverse identification approach can quantitatively estimate level errors.

Table 2. Estimation errors of free length changes

	Free length change from previous condition [μm]			Estimation errors [μm]		
Condition	Δl_2	Δl_6	Δl_7	Δl_2	Δl_6	Δl_7
1	0.0	0.0	4.2	0.2	–0.2	1.4
2	0.0	0.0	8.3	0.4	–0.5	1.7
3	0.0	6.3	0.0	0.1	0.8	0.1
4	2.1	0.0	0.0	–2.4	0.0	0.0
5	0.0	0.0	4.2	0.5	–0.2	–2.0
6	0.0	0.0	8.3	0.6	–0.1	1.2
7	0.0	0.0	8.3	0.6	0.2	1.4
8	8.3	0.0	0.0	0.4	0.2	0.1
9	6.3	0.0	0.0	0.5	0.0	0.0
10	8.3	0.0	0.0	–0.2	0.2	0.2
11	0.0	6.3	0.0	0.0	0.7	0.5
12	0.0	8.3	0.0	–0.1	–0.6	0.4
13	0.0	8.3	0.0	0.0	1.1	0.4
14	6.3	0.0	0.0	1.5	0.1	0.3
15	6.3	0.0	0.0	–0.5	0.2	0.3
16	0.0	0.0	6.3	0.6	0.3	0.7
17	0.0	0.0	6.3	0.6	0.1	0.2
18	0.0	0.0	6.3	0.5	0.1	0.7
19	0.0	6.3	0.0	0.0	1.2	0.5
20	0.0	8.3	0.0	0.0	1.1	0.3

5. Conclusion

A model-based level error identification method is proposed in this study, in which supports are modeled as linear springs. The relationships between the free length and preload changes in the supports are expressed as a matrix. By utilizing this method, the levelling work can be done without using the trial-and-error method. The model and approach are verified on a vertical machining center. The results suggest that this approach can quantitatively estimate level errors. However, under certain conditions, the backlash in jack bolts or gears deteriorate the measurement accuracies. Moreover, improvements in the measurement equipment are essential.

Acknowledgements

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