Precision Engineering 37 (2013) 650–657

Contents lists available at SciVerse ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Stiffness model of machine tool supports using contact stiffness

Daisuke Kono*, Takahiro Inagaki, Atsushi Matsubara, Iwao Yamaji

Department of Micro Engineering, Graduate School of Engineering, Kyoto University, Kyotodaigaku Katsura, Nisikyo-ku, Kyoto 615-8540, Japan

ARTICLE INFO

Article history:
Received 19 September 2012
Received in revised form
19 December 2012
Accepted 8 January 2013
Available online 13 February 2013

Keywords:
Stiffness model
Support stiffness
Contact stiffness
Concrete
Machine tool

ABSTRACT

The stiffness of machine tool supports should be properly designed for reducing both the ground disturbance vibration and the drive disturbance vibration. However, the stiffness cannot be easily calculated from the geometry and material properties of the support. In this paper, a 3D stiffness model of a machine tool support is proposed using contact stiffness. The stiffness in each direction is assumed to be determined by the contact stiffness at the interfaces and the bulk stiffnesses of the supports and the floor. The contact stiffness model proposed by Shimizu et al. is expanded to determine the contact stiffness in the normal and tangential directions of an interface. In the proposed model, the contact stiffness is obtained by multiplying the unit contact stiffness by the real contact area. The contact stiffness of concrete is experimentally investigated to estimate the stiffness between machine tool supports and the floor, and it was observed to be the primary determinant of the stiffness of interfaces between metal and concrete. Moreover, the unit contact stiffness of concrete is discovered to be less than 1/10 of those of the metals that were used for the study. The natural frequency and vibration mode shape of a model machine tool bed are also experimentally measured and used to verify the proposed stiffness model. The comparison of the results obtained from the two procedures shows that the natural frequency and vibration mode shape of a machine tool bed can be predicted using the proposed stiffness model.

1. Introduction

There has been a demand for higher efficiency in high-precision machining in recent times. Vibration of machine tools, such as those that result in the relative displacement of the tool and the table, pose a huge challenge to high-precision machining. Machine tool vibrations are classified into two types, namely: (1) ground disturbance vibration transmitted by the floor on which the machine is installed and (2) drive disturbance vibration generated by the feed drives. Both types of vibrations are greatly determined by the stiffness of the machine tool supports.

Ground disturbance vibration can be reduced by using soft supports such as rubbers and air springs [1–4]. Unfortunately, soft supports also cause the entire machine to rock, thereby increasing the drive disturbance vibration [1]. The stiffness of machine tool supports should therefore be designed by taking into consideration the amplitudes of both types of vibration.

However, owing to the fact that the factors that determine the stiffness of machine tool supports have not been clarified, they have only been designed empirically by most machine tool builders. Moreover, since the stiffness of the support cannot be easily calculated from its geometry and material properties, it would have to be modeled on the basis of other factors to aid systematic design.

Some studies have shown that the stiffness at the interface (contact stiffness) of a support significantly affects the overall stiffness of the support [5,6]. Hoshi particularly noted that contact stiffness with the concrete floor is the most important factor that determines the stiffness of a support [5].

There have actually been many studies on contact stiffness. Theoretical models have been proposed on the basis of the Hertz theory, and the governing equation of the contact stiffness was derived [7,8]. The contact stiffness has also been measured in directions normal and tangential to the interface to verify proposed models [9–11]. Furthermore, the influence of surface topography on contact stiffness has been investigated [12]. While these experimental studies examined contact stiffness between the same type of materials (mostly steel), machine tool supports usually involve contact between different types of materials such as cast iron, steel, and concrete. The contact stiffness between metals and concrete is particularly of interest because concrete is the usual material used for the floor of workshops and factories. Shimizu et al. proposed a simple model of the contact stiffness at the interface of different materials and measured the stiffness normal to the interface for several combinations of materials [13].

In this paper, a model of the stiffness of a machine tool support is proposed on the basis of Shimizu et al.'s contact stiffness model. The model is then used to estimate the contact stiffness of

---

* Corresponding author. Tel.: +81 75 383 3677; fax: +81 75 383 3677.
E-mail address: kono@prec.kyoto-u.ac.jp (D. Kono).

0141-6359/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.precisioneng.2013.01.010

Nomenclature

W	normal load
W_{pre}	normal preload
W_v	variable normal load
F	tangential load
k_n	normal contact stiffness
k_t	tangential contact stiffness
k_{nmc}	normal contact stiffness between the middle specimen and the lower specimen of the metal–concrete specimen set
k_{nmm}	normal contact stiffness between the middle specimen and the lower specimen of the metal–metal specimen set
δk_n	unit normal contact stiffness
δk_t	unit tangential contact stiffness
δk_{nc}	unit normal contact stiffness of concrete
δk_{nm}	unit normal contact stiffness of metal
δk_{tc}	unit tangential contact stiffness of concrete
δk_{n1}, δk_{n2}	unit normal contact stiffnesses of materials 1 and 2
δk_{t1}, δk_{t2}	unit tangential contact stiffnesses of materials 1 and 2
i	subscript representing normal and tangential directions
K_{nl}	normal stiffness of the lower specimen
K_{nu}	normal stiffness of the upper specimen
K_{nmc}	normal stiffness between the upper specimen and the lower specimens of the metal–concrete specimen set
K_{nmm}	normal stiffness between the upper specimen and the lower specimen of the metal–metal specimen set
p_m	yield pressure
A_r	real contact area
A_{rmc}	real contact area between the middle specimen and the lower specimen of the metal–concrete specimen set
A_{rmm}	real contact area between the middle specimen and the lower specimen of the metal–metal specimen set
d_{nl}	normal displacement of the lower specimen
d_{nu}	normal displacement of the upper specimen

interfaces between several metals and concrete in directions normal and tangential to the interface. Finally, the estimates of the proposed model are experimentally verified using a small model of a machine tool bed.

2. Model of machine tool supports and contact stiffness

2.1. Stiffness model of machine tool supports

Fig. 1 shows examples of machine tool supports. Medium- and small-sized machine tools are generally mounted on concrete floors with the aid of screw jacks or leveling blocks. Such height adjustment supports are used to ensure that the machine is leveled when installed.

In this study, the stiffness of one support is modeled in 3D as shown in Fig. 1(b). The stiffness in each direction is assumed to be determined by the contact stiffness at the interface and the bulk stiffnesses of the support and floor. Hence, the stiffness in each direction is modeled by the bulk stiffness and the contact stiffness connected in series, as shown in Fig. 1(c). The bulk stiffness can be calculated from the modulus of elasticity and the geometry of the support. In this study, the contact stiffness is treated as a linear stiffness. A model of the contact stiffness is described in the following section.

2.2. Model of contact stiffness

The contact stiffness model proposed by Shimizu et al. [13] is modified here. Fig. 2(a) shows a schematic of two materials in contact at the machine tool support. The load W acts on the interface; k_n and k_t are the contact stiffnesses in directions normal and tangential to the interface, respectively.

In Shimizu et al.'s model, k_n is considered to be the contact stiffness associated with a series of coupled springs spread over the interface. In this study, this model is expanded to obtain k_t as shown in Fig. 2(b). δk_{n1} and δk_{n2} are the normal contact stiffnesses per unit real contact area (unit normal contact stiffness) of materials 1 and 2, respectively; and δk_{t1} and δk_{t2} are the tangential contact stiffnesses per unit real contact area (unit tangential contact stiffness). The real contact area is determined by the contacting roughness asperity of the interface. k_i ($i = n, t$) is given by

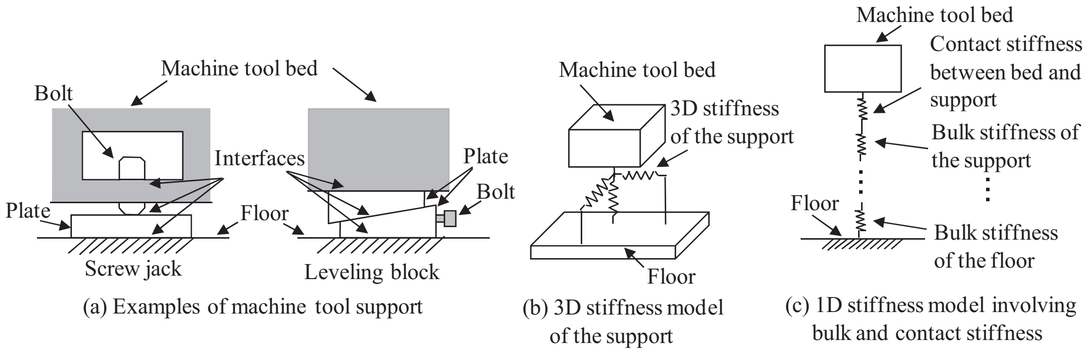
$$k_i = \frac{\delta k_{i1} \delta k_{i2}}{(\delta k_{i1} + \delta k_{i2})} A_r \tag{1}$$

where A_r is the real contact area and the subscript i represents the normal or tangential direction. A_r is given by

$$A_r = \frac{W}{p_m} \tag{2}$$

where p_m is the lower of the yield pressures of materials 1 and 2 [14]. In this study, the yield pressure is assumed to be equal to the Vickers hardness.

From Eqs. (1) and (2), we see that k_i is a nonlinear stiffness dependent on W. This is because the plastic deformation of the interface increases A_r. In the machine tool support, W is determined



(a) Examples of machine tool support (b) 3D stiffness model of the support (c) 1D stiffness model involving bulk and contact stiffness

Fig. 1. Machine tool support and its model. (a) Examples of machine tool support. (b) 3D stiffness model of the support. (c) 1D stiffness model involving bulk and contact stiffness.