Precision Engineering xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

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

Original paper

Modelling of viscoelastic damper support for reduction in low frequency residual vibration in machine tools

Kotaro Mori*, Daisuke Kono, Iwao Yamaji, Atsushi Matsubara

Kyoto University, C3 Kyotodaigaku-Katusra, Nishikyo-ku, Kyoto, 615-8540, Japan

ARTICLE INFO

Article history:
Received 15 May 2017
Accepted 5 June 2017
Available online xxx

Keywords:
Machine tool support structure
Viscoelastic damper
Vibration damping
Residual vibration
Low frequency vibration

ABSTRACT

Residual vibrations deteriorate the accuracy and productivity of precision machine tools. Rocking vibration is excited by feed motion. Rocking vibration is the mode in which the entire machine vibrates and is the main source of residual vibrations at low frequencies. The characteristics of rocking vibration are influenced by the characteristics of the machine support structure. Thus, it is necessary to increase the damping of the machine support structure to reduce the residual vibrations caused by rocking vibration. In addition, it is important for machine tools to be stiff to reduce vibrations caused by the acceleration of feed drives. Conventional passive damper supports decrease the stiffness of a machine support structure while increasing the damping. Consequently, a passive viscoelastic damper system is developed to increase support damping without decreasing stiffness by focusing on the horizontal component of rocking vibration. However, the proposed damper damping capacity has a magnitude dependency. This makes it difficult to quantitatively determine the damper area in machine tools to reduce rocking vibrations to the required level. In this study, the developed damper is modeled using a viscoelastic four element model. Because of the nonlinearity of the model, an iterative time domain calculation method is introduced for the simulation. This method enables us to quantitatively estimate the effect of the damper on the machine tool. Based on the model proposed in this study, the proposed damper system can be applied to various machine tools to reduce the residual vibration without adjusting the damper area on the machine tool by a trial and error method.

1. Introduction

Residual vibrations deteriorate the accuracy and productivity of precision machine tools. Rocking vibration, caused by axial movement and the vibration of the entire machine, is the main source of residual vibration at low frequencies [1–4]. Dampers that can be inserted in machine columns or jigs are proposed for a reduction in machine tool vibration [5,6]. However, the characteristics of rocking vibration are influenced by the vibration characteristics of the machine support structure [2]. Thus, it is assumed that these dampers are not effective for low frequency residual vibration.

To reduce low frequency residual vibrations caused by rocking vibration, it is necessary to increase the damping of the machine support structure (support damping) [7]. On the other hand, it is also important for machine tools to be stiff to reduce the vibration caused by the acceleration of feed drives. Thus, support damping should be increased without decreasing the stiffness of the machine support structure (support stiffness).

Support damping can be increased by two methods: improving the structure, and inserting dampers. As examples of structural improvement, Mahakalkar et al. introduced composite materials for machine structures [8]; Kashihara et al. used special castings [9]; and Yu et al. and Hiramoto et al. optimized machine structures to reduce vibrations [10,11]. However, it is difficult to apply them to existing machines [12,13].

Numerous studies have been conducted on active dampers [14–18]. However, active dampers are generally more expensive and complex than passive dampers. Some research has been conducted regarding passive damper support for machine tools: Okwudire et al. optimized isolator locations [19]; Geerts et al. used rubber and springs [20]; and Lee et al. introduced mode-coupling [21]. However, these methods affect support stiffness while increasing support damping.

Therefore, the authors propose a passive damper system that can increase support damping without decreasing stiffness by focusing on the horizontal component of rocking vibration [22]. This system is easy to install, even on existing machines. However,

* Corresponding author.
E-mail address: mori.kotaro.43z@kyoto-u.jp (K. Mori).

http://dx.doi.org/10.1016/j.precisioneng.2017.06.004
0141-6359/

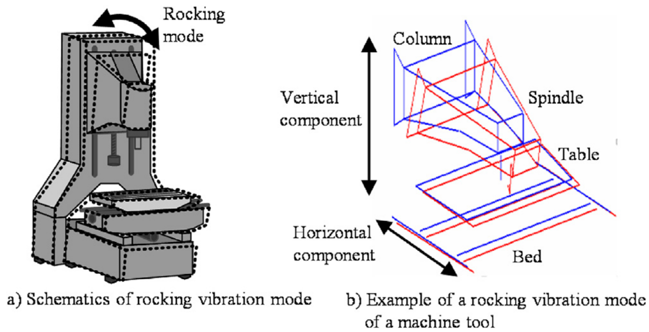

Fig. 1. Rocking vibration mode on a machine tool.
a) Schematics of rocking vibration mode
b) Example of a rocking vibration mode of a machine tool

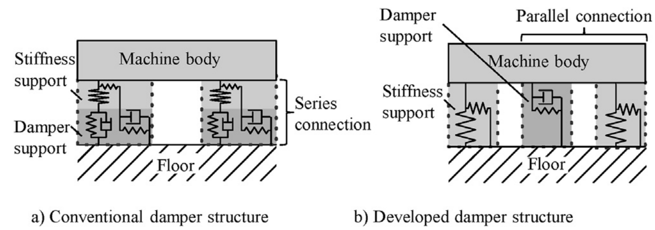

Fig. 2. Schematics of damper support structures.
a) Conventional damper structure
b) Developed damper structure

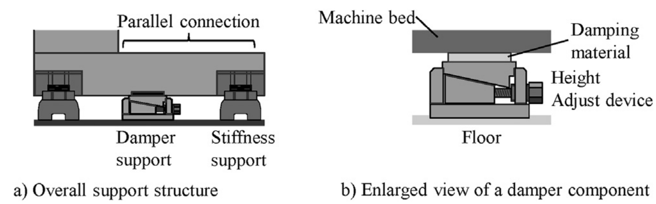

Fig. 3. Schematics of proposed damper support structure.
a) Overall support structure
b) Enlarged view of a damper support

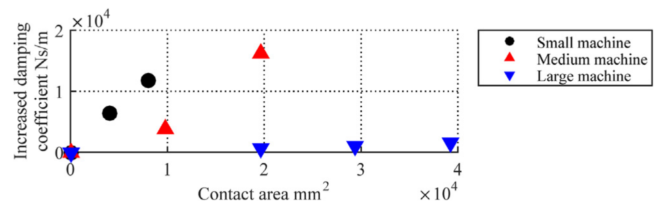

Fig. 4. Relationships between damper area and increased damping coefficient.

the damping ability of the proposed damper has magnitude dependencies, details on this are provided in Section 2. This makes it difficult to determine quantitatively the damper area in machine tools to reduce rocking vibration to the required level. Thus, the damper size for the new machine tool is currently determined by a trial and error method.

In some studies, dampers are modeled to estimate the damper behavior. Though, the behavior of entire machine tool is not modeled in most of the studies [14,16–18,21]. The behavior of an entire machine is modeled as a single degree-of-freedom model in [19]. However, a single degree-of-freedom model cannot simulate machine deformations. Thus, a two degrees-of-freedom model of machine tool is necessary for quantitative estimation of effect of the damper on tool-workpiece displacement.

Force-displacement hysteresis loops are mainly used to evaluate the elastic damper behavior in most studies as in reference [23]. In this method, the damper behavior in a steady-state vibration is evaluated. However, rocking vibration is a damped vibration and the damper has an amplitude dependency of damping. It makes difficult to use the conventional evaluation method in a damped vibration because the vibration amplitude changes in each vibration cycle.

In this study, the developed damper and the entire machine behavior are modeled. This model enables us to quantitatively estimate the behavior of the damper in the machine tool. It enables the estimation of the required damper size from the simulation. First, the relative vibration between the tool and workpiece caused by rocking vibration is modeled with a single degree-of-freedom model. Next, an iterative calculation method is implemented to the model for simulating the damper behavior under damped vibrations. Then, model parameters are obtained from experimental data on a three-axis vertical machining center. Following this, the damper behavior on a five-axis machining center is simulated based on the model. Finally, the simulated results are validated by experimental results from the machine.

2. Proposed damper

2.1. Fundamentals of the proposed damper

Rocking vibration contains both vertical and horizontal components [1,4]. Fig. 1 shows an example of a rocking vibration mode. Fig. 1a shows a schematic of a rocking vibration mode in a machine tool. Fig. 1b shows an example of a measured rocking vibration mode in a vertical machining center. Conventional dampers are designed for the vibration isolation of the machine tools. Thus, dampers require a series connection to the original machine's stiff support structure (stiffness support), as shown in Fig. 2a. By design, the damper support stiffness is lower than that of the stiffness support [24]. The total stiffness of the support is decreased by the low-stiffness damper in series connection.

Thereupon, our proposed damper is designed to reduce the horizontal component of the rocking vibration. The dampers are connected parallel to the stiffness support as shown in Fig. 2b. As a result, this damper avoids the reduction in total support stiffness caused by the low stiffness of the damper support.

Fig. 3a shows a schematic of the proposed damper support. The damper supports and stiffness supports are installed independently. Each damper support is composed of a damping material and a height adjusting device, as shown in Fig. 3b. The damping capacity of the damper is controlled by adjusting the number of damper supports.

Generally, bottom bed surfaces of machine tools have poor surface finishes. This damper requires a preload control, the details of which are described in Section 2.2. In this damper, the compressed thickness of the damping material determines the vertical preload. Thus, it is necessary to adjust the damper height according to the installation location. In this research, commercially available leveling blocks are used for this purpose.

A damping material that is effective for shear deformation is suitable for this purpose. In this research, a polyisobutylene thermoplastic elastomer is used as the damping material. This material was originally designed to prevent overturning of furniture during earthquakes. It is self-adhesive, which facilitates easy installation [25].

On the other hand, the damping ability of the proposed damper has magnitude dependencies. Because of this characteristics, the damping capacity added by the same amount of damper is different by machine, as shown in Fig. 4 in reference [22]. This makes it difficult to determine quantitatively the damper area in machine tools to reduce rocking vibration to the required level.