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Vibration control with active mass dampers in the milling process

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Abstract
Vibration generated during the milling process is divided into forced vibration, caused by cutting forces that occur when the tool cutter removes the workpiece, and self-excited vibration, caused by the weak vibration modes of the machine tool structure. To minimize the vibration generated during the milling process, various vibration reduction methods are applied, such as minimizing spindle imbalance and runout, reinforcing the machine structure, and applying passive and active vibration dampers. Among these, active mass dampers that utilize electromagnetic actuators for a wide frequency range and high controllability have been extensively studied. Most of the active mass dampers applied to machine tools are designed to improve the dynamic stiffness of the weak structural vibration modes, thereby suppressing chatter caused by self-excited vibration during the machining process and improving machining productivity. However, these methods have not focused on improving machining quality, such as surface roughness, through forced vibration reduction under stable cutting conditions. In this study, to improve both the machining productivity and surface quality of the milling process, both the virtual tuned mass damper (VTMD) and higher harmonic control methods were applied to active mass dampers. These actuators were installed in a 5-axis machine tool, and machining performance was evaluated. VTMD control was able to increase the dynamic stiffness by more than two times across the entire machining area of the machine and improve the critical cutting depth by over 40% by tuning the modal parameters of the VTMD to target the weak vibration modes of the structure. At the same time, higher harmonic control was also effective in improving the machined surface quality in the finishing process by reducing the forced vibration caused by cutting forces. We confirmed that both productivity and machining quality can be improved by applying the two control methods together.

Vibration control, VTMD, higher harmonic control, chatter, dynamic stiffness, active mass damper

1. Introduction

Vibration generated in milling can be divided into forced vibration caused by harmonic forces generated when operating machine tools, and self-excited vibration caused by the most flexible eigenmode of machine tool structure. In particular, chatter severely induces cutting instability and causes serious damage to tools and workpieces. Therefore, many studies have been conducted focusing on the prediction, detection, and suppression of chatter [1], [2]. In case of chatter suppression, to improve the dynamic stiffness of the most flexible eigenmode without changing the cutting parameters, methods of adding vibration damping devices on machine tools have been proposed. Especially, studies on active mass dampers that are effective in a wider frequency range and varying dynamics have been conducted. J.Munoa et al. proposed a biaxial active damper applying the direct velocity feedback (DVF) as a control law to increase the dynamic stiffness for a ram type moving column milling machine [3]. X. Beudaert et al. proposed a portable active damping system using an electromagnetic actuator for suppressing chatter of flexible workpieces [4].

Most active mass dampers applied to machine tools have tried to suppress chatter in roughing by improving the dynamic stiffness of the most flexible structural eigenmode [5][6]. Thus, the main purpose was to improve cutting productivity expressed as MRR, and the focus was not on improving surface quality through vibration reduction in stable finishing. However, in general, forced vibration dominates in stable milling. Even in stable milling, material removal rates (MRR) and surface quality can be degraded by forced vibration. However, the previously mentioned controllers may not be optimal for reducing forced vibration of harmonic vibration characteristics. Therefore, effective control methods for reducing the vibration of these harmonic characteristics were required [7]. Higher harmonic control (HHC) and least mean square (LMS) adaptive filtering are both useful techniques for reducing harmonic vibration and noise in various systems. Lisa et al. presented comparison of different control laws for periodic disturbances reduction including HHC and LMS adaptive filtering [8]. HHC is particularly effective in reducing low-frequency periodic disturbances, while LMS is useful for adaptive filtering and noise reduction [9].

In this paper, VTMD control method, which is effective for suppressing chatter, and HHC method, which is effective for reducing forced vibration, were investigated together to improve cutting depth in roughing as well as improve surface quality in finishing. The effects of each control law in milling were compared and analysed by conducting tap tests and cutting tests. In addition, a method combining the two control laws was investigated to be effectively applied to machine tools.

2. Active vibration control

We introduce in this section the overall configuration of the non-collocative active damping system for the ram type 5-axis milling machine in our testbed and analyze in detail the dynamic characteristics of the system in terms of the frequency response and verifies the effectiveness of active mass damper in the milling process.

2.1. System configuration

Fig. 1 shows the overall setup of our active damping system installed in the ram-type 5-axis milling machine (DVF5000 by DN Solutions Ltd.), which has a relatively weak torsional stiffness in the vertical ram structure due to its overhung configuration. Such insufficient dynamic stiffness makes the machining process susceptible to the structural chatter vibration, which is observed at around 100 Hz varying under machining operations with different Z-axis postures of the ram structure as shown in Fig. 2.

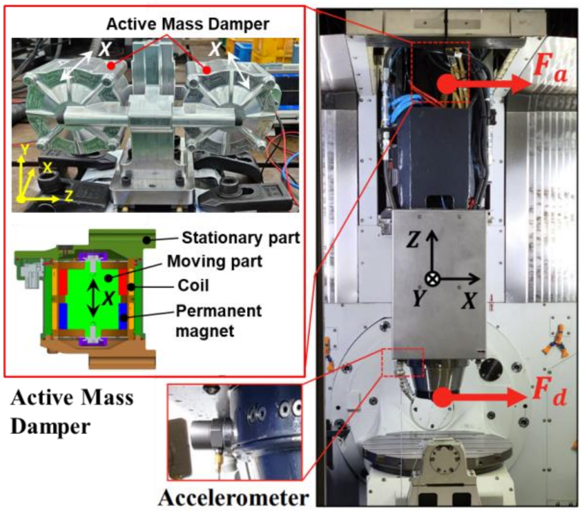


Figure 1. Configuration of the ram type 5-axis milling machine with active mass damper system

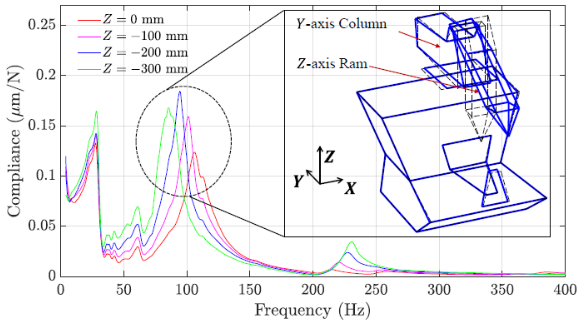


Figure 2. Compliance of the ram structure in X-direction, showing the weak mode at around 100Hz, depending on the Z-axis position

2.2. Virtual tuned mass damper for chatter suppression

In order to suppress the structural chatter vibration under such varying dynamic characteristics, we use our voice-coil type inertial actuator, as shown in Fig. 1, actively enhancing the dynamic stiffness of the ram structure using the control method presented in Section 3. In general, it is well known that the vibration energy is absorbed by the tuned mass damper (TMD) by matching the natural frequency of it with the target system. However, the performance of this passive TMD is proposed due to the problem of narrow suppression frequency range and difficulty in tuning due to the fixed damping and spring force. To solve this problem, we apply the Virtual TMD (VTMD) algorithm [4][5][6][7]. Thus, VTMD increases the critical depth of cut of chatter stability lobes by enhancing the dynamic stiffness of a specific weak vibration mode over a wider frequency range than a passive TMD and does not require chatter detection. In other words, the material removal rates in roughing is improved due to the increased dynamic stiffness by VTMD. First, the open loop machine tool dynamic response is required, and it can be obtained through tap tests at the tool tip. The actuator (active mass damper)-oriented head body acceleration is defined as the actuation path $G_a(s)$ in Eq.(2). Also, the VTMD transfer function which relates the inertial force of the active mass damper to measured acceleration at head body is given in Eq.(3). The VTMD has three tuning parameters to reduce the closed loop compliance magnitude at the dominant target mode: virtual damping ς, target frequency ω_n, and gain α. The virtual damping ς modifies the amplitude of the newly created resonances as well as the antiresonance depth, and target frequency ω_n matches the natural frequency of the weak vibration mode of a target machine. Finally, we can express the closed loop compliance in Eq.(1).

$$\frac{a_t(s)}{F_d(s)}_{closed\ loop} = \frac{\Phi_{open}(s)}{1+(C_{VTMD}(s)+C_{HHC}(s))G_a(s)} \quad (1)$$

where $$\Phi_{open}(s) = \frac{a_d(s)}{F_d(s)}_{open\ loop}, \quad G_a(s) = \frac{a_a(s)}{F_a(s)} \quad (2)$$

and $$C_{VTMD}(s) = \alpha\frac{2\varsigma\omega_n s+\omega_n^2}{s^2+2\varsigma\omega_n s+\omega_n^2} \quad (3)$$

2.3. Higher harmonic control for forced vibration reduction

The main idea of higher harmonic control(HHC) is to attenuate the harmonic forced vibrations, which are caused by periodic excitations such as spindle rotational speed and cutting forces induced by tool cutter. In this paper, cutting vibration is reduced by applying a control force with the frequency detected by the spindle encoder sensor. Therefore, instead of detecting chatter, the external excitation frequencies which are caused by spindle rotational speed and system transfer function information are required as shown in Eq.(4) and (5). [8][9]

$$C_{HHC}(s) = \frac{2}{T}\frac{as+b\omega}{s^2+2\varsigma\omega s+\omega^2} \quad (4)$$

where $$a = \frac{Real(\Phi_{open}(j\omega_d))}{|\Phi_{open}(j\omega_d)|^2}, \ b = \frac{Imag(\Phi_{open}(j\omega_d))}{|\Phi_{open}(j\omega_d)|^2} \quad (5)$$

where a and b represent the real and imaginary values of the target system transfer function, respectively, and T represents the period of external excitation.

Figure 3 shows a block diagram with the combination of the two control laws mentioned in section 2.2 and 2.3 to effectively reduce chatter and forced vibration in milling processes. And these two control laws do not require signal processing such as FFT from a vibration sensor to detect chatter.

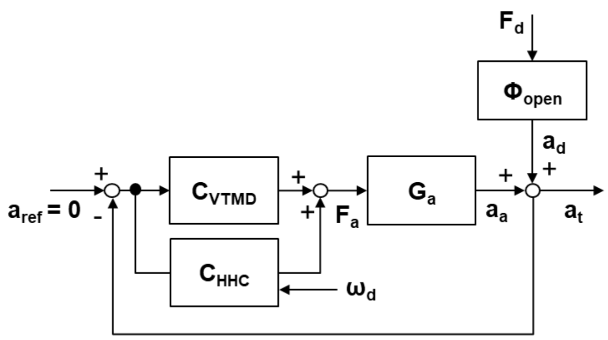


Figure 3. Block diagram of the active damping system. The tool tip acceleration response a_t is a combination of the disturbance response a_d to the cutting force F_d through the collocated path Φ_{open} and the actuator response a_a to the actuating force F_a through the non-collocated path G_a.

3. Experimental validation

Validation tests were conducted on the ram type 5-axis milling machine, DVF5000-5AX (DN-Solutions Ltd.). The performance of the active mass damper with the two control laws in roughing and finishing was validated in the DVF5000-5AX, which has a relatively large varying dynamic stiffness according to Z-axis position. In addition, tap tests on the head tip were conducted for the target machine. All the validation test set were in Table 1.

Table 1 Validation test set

	Note
FRF test	Tap test at head tip
Roughing	SM45C,ϕ80, z6, S1500RPM, Face milling, 100% immersion, ap3.5mm
Finishing	Al6061, ϕ10, z3, S6,000 & S12,000RPM, Side milling, ae0.1mm, ap5.0mm

3.1. Cutting depth improvement during rough milling process

A. Compliance Reduction Performance

To validate our active damping control method presented in Section 2, we measure the compliance of the ram structure with the active mass damper turned on and off as shown in Fig. 4. Both the open-loop (dotted curves) and the closedloop (solid curves) compliance curves are obtained from the measured impact hammer force (Type 8208 by Bruel & Kjaer) and the acceleration signals (Type 4533-B-001 by B&K) at the different ram postures of Z = -200 mm, and Z = -300 mm. As can be seen from the figure, we reduce the peak magnitude of the closed-loop compliance by 59 %, and 52 %, respectively, compared to the open-loop compliance, showing a promising performance of VTMD method, discussed in Section 2.2.

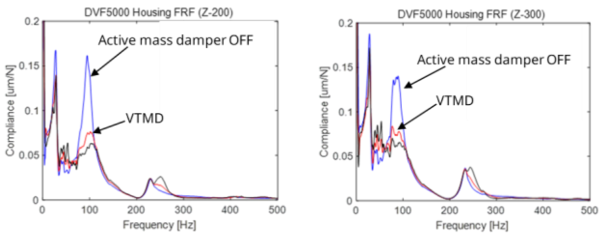
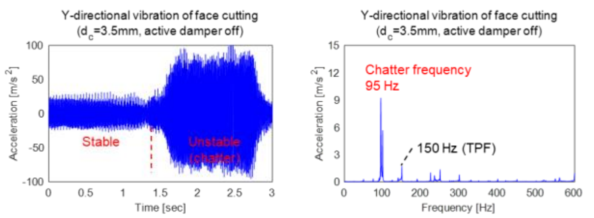


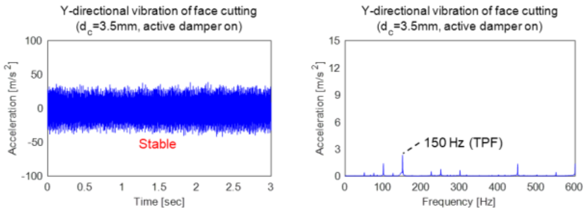
Figure 4. Measured compliance of the ram structure in X-direction with and without VTMD control at different Z-axis position

B. Machining Test

Fig. 5 shows the experimental results of the machining tests to validate the chatter suppression performance of active damping system. At roughing conditions without the active damping, the structural chatter vibration at 95 Hz is significantly induced, as shown in Fig. 5(a), due to the insufficient dynamic stiffness of the dominant mode dynamics as described in Section 2.1. Such chatter vibration leaves significant chatter marks, thereby degrading the machined surface as shown in the left picture of Fig. 6. And 150 Hz and its harmonic vibration in the FFT plots of Fig. 5 are the spindle frequency components which appear as the multiples of the spindle speed and number of tool blades and are independent to the occurrence of the structural chatter vibrations. With our active mass damper turned on, on the other hand, the chatter vibration does not occur as shown in Fig. 5(b), due to the significantly increased dynamic stiffness of the ram structure. The machined part shows a highly uniform surface as can be seen in the right picture of Fig. 6, validating the machining performance of our active damping system with VTMD control method.



(a) active mass damper OFF



(b) active mass damper ON

Figure 5. Measured acceleration at head body (a) VTMD control OFF and (b) VTMD control ON

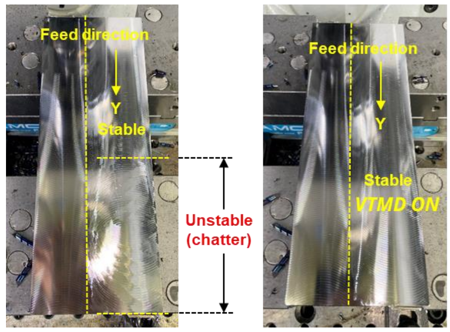
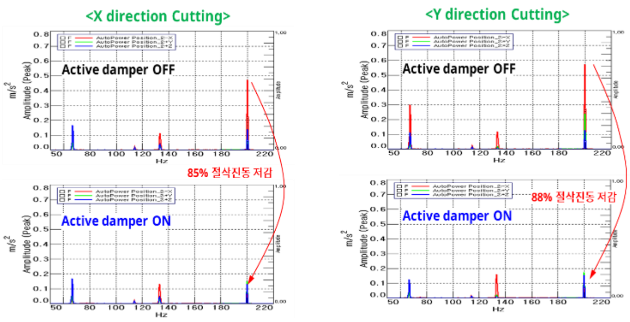


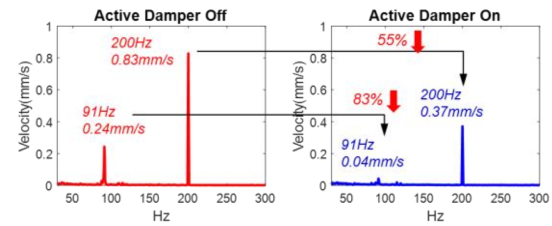
Figure 6. Comparison of surface quality according to applying the active damping system in roughing

3.2. Surface quality improvement during finish milling process

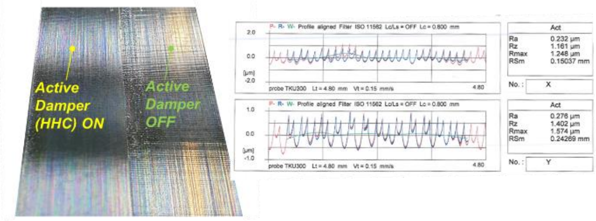
The performance of forced vibration suppression of the active mass damper using the HHC control law was validated through the finishing conditions in Table 1. The VTMD control mentioned in Section 3.1 has an excellent performance in reducing chatter vibration by improving the dynamic stiffness of the target mode, but the ability to reduce a non-resonant forced vibration under stable machining process is not effective. To handle this issue, the HHC control technique using the information of frequency response function of the target system and external excitation frequency was applied to confirm the effect of forced vibration reduction in the non-resonant condition. Cutting vibration was compared at 4k RPM, while both cutting vibration and surface finish were evaluated at 12k RPM during aluminium finishing with HHC on and off. The harmonic vibrations related on the spindle rotational speed have been significantly reduced by more than 50%, resulting in a 20% improvement in surface roughness from R_z 1.57µm to 1.25µm and the pattern of cutter mark is also changed regularly as shown in Fig. 7.



(a) Comparison of cutting vibration according to HHC at 4k RPM



(b) Comparison of cutting vibration according to HHC at 12k RPM



(c) Comparison of surface roughness according to HHC at 12k RPM

Figure 7. The measured vibration(velocity) at head body and surface roughness in finishing: (a) Comparison of cutting vibration according to HHC at 4k RPM, (b) Comparison of cutting vibration according to HHC at 12k RPM, (c) Comparison of surface roughness according to HHC at 12k RPM

4. Conclusions

In this paper, the effects of the two control laws, VTMD and HHC, were examined in roughing and finishing. First, the VTMD control set three tuning parameters which are modified gain, virtual damping and target frequency with the most flexible eigenmode of the structure as the region of interest. It has the advantage of being able to set control parameters more easily than the loop shaping method of DVF control. Then, by designing the VTMD controller through parameters tuning process for the region of interest, the dynamic stiffness of the resonance region was improved at different Z axis position, and it was effective in increasing the chatter stability. Therefore, we determined that the VTMD control was suitable for improving MRR through improvement of critical depth of cut by suppressing chatter. On the other hand, generally VTMD control method is not effective in reducing vibration due to periodic forced excitation in the non-resonant range.

The HHC method was effective in reducing forced vibration in the non-resonant region since it utilizes information on the frequency of excitation source, and system dynamics. However, because the HHC generates control force with the frequency of the excitation source, this technique was impossible to mitigate vibration when chatter occurs. Therefore, we confirmed HHC was effective in reducing forced vibration caused by spindle rotation and stable cutting and was particularly suitable for improving the machined surface quality in finishing.

Thus, there is a more suitable control method according to the milling process, and it is expected that the effectiveness of the active mass damper can be further increased through the combination of these control laws.

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