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LOW-FREQUENCY CHATTER SUPPRESSION USING TUNED MASS DAMPER IN ROBOTIC MILLING

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Abstract

Low-frequency chatter severely limits robotic milling efficiency. In this paper, tuned mass dampers (TMDs) are introduced to suppress low-frequency chatter based on robotic modal directionality. A TMD model with mounting angle is established, and the suppression effect of TMD on the robotic low-frequency dynamic compliance with different mounting directions is analyzed together with experiments. Then, low-frequency chatter is further suppressed by suppressing side-frequency dynamic compliance. The milling experiments show that the TMD can significantly suppress low-frequency chatter and improve cutting amount, and a better effect can be achieved when TMDs act at both the low-frequency mode and side frequencies.

Keywords:

Robotic milling, Chatter suppression, Modal directionality, Tuned mass damper (TMD)

1 INTRODUCTION

Robotic milling chatter is a significant obstacle to machining efficiency, especially the low-frequency chatter caused by the weak stiffness of the robot body structure [Zhu, 2021]. The low-frequency chatter often leads to high-amplitude vibration at the robot end and a surge in cutting forces, interrupting machining and easily causing damage to the workpiece and robot machining system.

The low-frequency chatter in robotic milling can be avoided to some extent by machining planning. Cen et al. [Cen, 2017] used the conservative congruence transformation stiffness model to minimize the angle between the average cutting force direction and robotic maximum principal stiffness direction as a way to avoid the low-frequency chatter. Gienke et al. [Gienke, 2019] extended the mode coupling chatter theory using robot kinematics and developed a software to help plan the machining parameters. He et al. [He, 2020] avoided the low-frequency chatter by selecting the machining feed direction. Another popular method is to apply additional forces to robot machining systems through specific devices. Yuan et al. [Yuan, 2019] proposed a semi-active vibration suppression device based on magnetorheological elastomers with variable suppression frequency. Guo et al. [Guo, 2019] proposed a rotating ultrasonic-based method for robotic milling, and the experimental results showed that ultrasonic vibration can reduce the milling forces and chatter amplitude. Nguyen et al. [Nguyen, 2020] solved the linear quadratic regulator optimal control problem to obtain the pose-dependent controller gain and suppress the chatter by controlling the drive joints. Xiao et al. [Xiao, 2020] proposed an active vibration suppression solution using robot follow-up support.

Tuned mass dampers (TMDs) are absorbers consisting of auxiliary masses, dampers, and springs, whose own resonances act on the main structure and can achieve a good dynamic compliance suppression with a small mass ratio [Soto, 2013]. TMDs have been used for chatter suppression in boring [Iklódi, 2021] and turning [Wang, 2010]. This paper introduces TMDs to suppress the low-frequency chatter in robotic milling. The low-frequency TMD and high-frequency TMD are used to address the low-frequency and side-frequency vibrations, respectively. Based on the established TMD model with mounting angle and the modal directionality of milling robots, the effect of TMD mounting direction on the dynamic compliance suppression effect is analyzed theoretically and experimentally. The milling experiments show that the TMD can significantly increase the robot's chatter-free cutting amount (by about 1 time). And it is found that the TMDs are more effective for both low and side frequencies.

2 SUPPRESSING MILLING ROBOT DYNAMIC COMPLIANCE WITH TMD

When modal vibration occurs, the tool center point (TCP) of milling robots moves linearly, reflecting the modal directionality at the robot end, which has been discussed in a recent study [Wu, 2022]. Since the robot's modal direction changes during machining, this section establishes a TMD model with mounting angle. The dynamic compliance suppression effect is analyzed when the TMD mounting direction is at different angles to the robot's modal direction, and corresponding experiments are conducted.

2.1 TMD model with mounting angle

Fig. 1 shows the dynamics model of the TMD with mounting angle, consisting of a main system with mass, damping, and stiffness of *M*, *C*, and *K*, and a TMD with *m*, *c*, and *k*. *α* represents the angle between the main system and TMD system, and it is specialized to the classical TMD model when *α* = 0°. Its dynamics equation is:

$$\begin{cases} M\ddot{x}_1 + C\dot{x}_1 + Kx_1 + c\left(\dot{x}_1\cos\alpha - \dot{x}_2\right)\cos\alpha \\ \quad +k\left(x_1\cos\alpha - x_2\right)\cos\alpha = F\cos\omega t \\ m\ddot{x}_2 + c\left(\dot{x}_2 - \dot{x}_1\cos\alpha\right) + k\left(x_2 - x_1\cos\alpha\right) = 0 \end{cases}, \qquad (1)$$

where F is the excitation amplitude, ω is the angular frequency, and x_1 and x_2 are the displacements of the main system and TMD system, respectively.

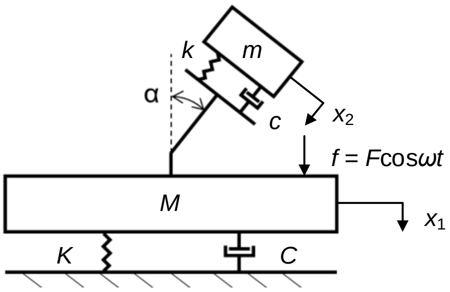

Fig. 1: Dynamics model of the TMD with mounting angle.

Denote the excitation force as $Fe^{j\omega t}$, x_1 as $x_1 = X_1e^{j\omega t}$, and x_2 as $x_2 = X_2e^{j\omega t}$, where X_1 and X_2 are complex numbers. Substituting them into Eq. (1) and simplifying gives:

$$\begin{cases} X_1\left(-\omega^2M + j\omega C + K + cj\omega\cos\alpha\cos\alpha + k\cos\alpha\cos\alpha\right) \\ \quad +X_2\left(-cj\omega\cos\alpha - k\cos\alpha\right) = F \\ X_1\left(-cj\omega\cos\alpha - k\cos\alpha\right) + X_2\left(-\omega^2m + cj\omega + k\right) = 0 \end{cases}. \qquad (2)$$

Eq. (2) can be solved as:

$$\frac{X_1}{F} = \frac{-\omega^2m + cj\omega + k}{\left\{\begin{matrix}\left(-\omega^2M + j\omega C + K\right)\left(-\omega^2m + cj\omega + k\right) \\ -\omega^2m\left(cj\omega + k\right)\cos^2\alpha\end{matrix}\right\}}. \qquad (3)$$

Fig. 2 shows the simulation results of the frequency response function (FRF) of the main system at different *α* under optimal tuning [Seto, 2010] according to Eq. (3). The simulation parameters are as follows. $M = 100\,\text{kg}$, $C = 600\,\text{N/(m/s)}$, $K = 10^6\,\text{N/m}$. Then the static flexibility is $10^{-6}\,\text{m/N}$ and the natural frequency is 15.9 Hz, all of which are quite comparable to that of milling robots. The mass ratios are set to 0.05 and 0.1, i.e., $m = 5\,\text{kg}$ and $m = 10\,\text{kg}$, respectively. To satisfy the optimal tuning condition, the TMD damping and stiffness are $c = 305\,\text{N/(m/s)}$ and $k = 82628\,\text{N/m}$, respectively. The natural frequency of the TMD is 14.5 Hz, which is close to that of the main system.

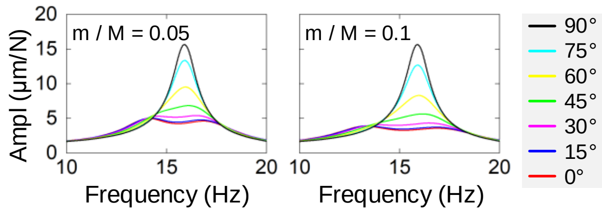

Fig. 2: The simulated FRFs of the main system at different TMD mounting angles, *α*. The smaller *α* is, the better the TMD suppresses the dynamic compliance of the main system. The suppression effect does not become significantly worse (less than 2 % difference) until *α* increases to 30°.

The simulation results show that the smaller the angle *α* is, the better the TMD suppresses the dynamic compliance of the main system. Table 1 shows the suppression ratio of the TMD on the maximum dynamic compliance of the main system at different mass ratios and *α*. The best dynamic compliance suppression is achieved at *α* = 0°, reaching 68 % and 75 % at mass ratios of 0.05 and 0.1, respectively. As *α* increases, the suppression effect becomes gradually worse. The TMD completely loses its effect at *α* = 90°. This is consistent with expectations because the principle of TMDs is to use their own resonance to act back on the main structure. The increase in *α* means that the TMD deviates from the modal direction and the transmission of vibration and force between the main system and TMD is reduced. But it is worth noting that the suppression effect does not get significantly worse until *α* increases to 30° (less than 2 % difference). This means that the mounting direction of the optimal tuning TMD is not required to be precisely consistent with the robot's modal direction. As long as the angle does not exceed 30° or even 45°, a considerable suppression effect can still be achieved.

Table 1: Suppression ratio of the optimal tuning TMD to the maximum dynamic compliance of the main system at different mass ratios and mounting angles, *α*.

	α						
	0°	15°	30°	45°	60°	75°	90°
m / M = 0.05	0.68	0.68	0.65	0.56	0.39	0.15	0
m / M = 0.1	0.75	0.75	0.72	0.64	0.47	0.19	0

2.2 Experiment of dynamic compliance suppression

This section first introduces the low-frequency TMD (LFTMD) based on the electromagnetic damping principle. Then the modal tests are carried out at different mounting angles to verify the suppression effect of the LFTMD on the modal dynamic compliance at the robot end.

Fig. 3 shows the structural design of the LFTMD. The stiffness is provided by the full inner spring and the outer spring in parallel, the length of the latter can be adjusted by changing the position of the stiffness adjuster to achieve variable stiffness. The NdFeB magnet is sandwiched between the back iron A and B. When the back irons vibrate up and down, the magnetic flux of the coil changes. According to Faraday's principle of electromagnetic induction, an induced current is generated in the closed coil, which creates a magnetic field that hinders the change of the magnetic flux, thereby generating a damping force proportional to the vibration velocity. The damping can be adjusted by adding a resistance to the coil.

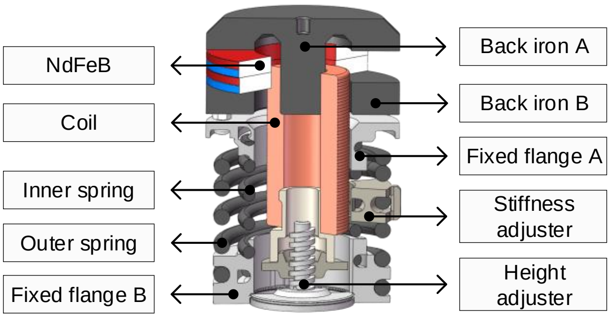

Fig. 3: Structural design of the LFTMD.

Fig. 4a shows the site of the robotic modal test. The Dytran 5802A impulse sledge hammer and DYTRAN 3263A2 triaxial accelerometer are used. The pose of the ABB IRB6660 robot is [27.8°, -4.6°, 49.7°, 34.7°, -55.1°, 158.4°]. Fig. 4b gives the direct and cross FRFs at the robot end, referenced to the robot base coordinate system (the base coordinate system is used as the reference unless otherwise stated later). H_{xy} represents the FRF with Y-direction excitation and X-direction response, while others are similar. The 11.25 Hz mode is chosen to be suppressed, whose modal direction at the LFTMD mounting point is [-0.21, -0.23, 0.95], and the rest of the modal parameters are shown in Table 2. Fig. 5a and Fig. 5b show the modal test and FRF of LFTMD, respectively. The hammer is PCB 086C03. The modal parameters of the LFTMD are shown in Table 2, which are close to the optimal tuning.

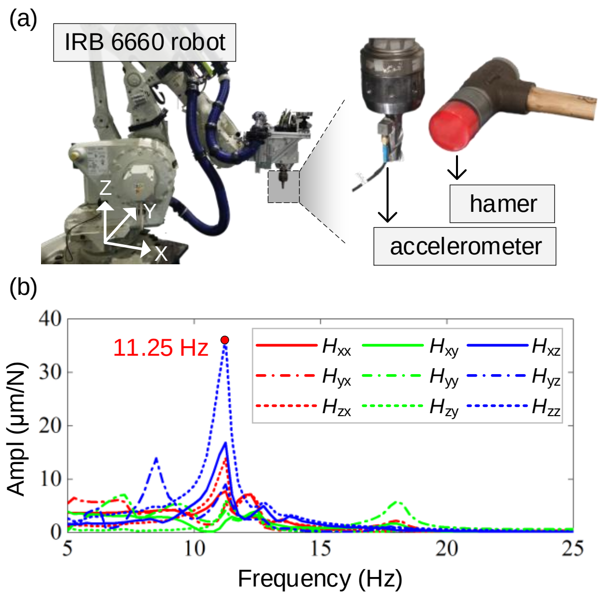

Fig. 4: Modal test of the milling robot.

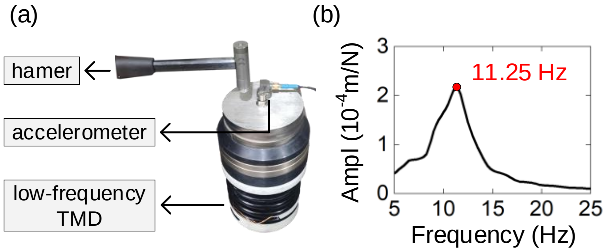

Fig. 5: Modal test of the LFTMD.

Table 2: Modal information of the robot and LFTMD in their modal directions.

Mode	Frequency (Hz)	Damping ratio (%)	Residue (s/kg)	Mass (kg)
Robot	11.25	2.5	-1.32e-6 - 6.45e-5j	107.7
LFTMD	11.25	13.3	-2.70e-4 - 2.11e-3j	3.3

Fig. 6 shows the robot's modal test results at different LFTMD mounting angles. For brevity, only H_{zz} is shown (according to the robotic modal directionality principle [Wu, 2022], the dynamic compliance is equally suppressed in each direction). It can be seen that the best suppression is achieved at α = 0°. The maximum dynamic compliance of the 11.25 Hz mode decreases from 36.3 μm/N to 10.0 μm/N, with a decrease of 72.4%. As α increases, the suppression effect becomes gradually worse. This meets the expectations from the simulation. Overall, the experimental results show that the LFTMD can effectively suppress the modal dynamic compliance at the robot end.

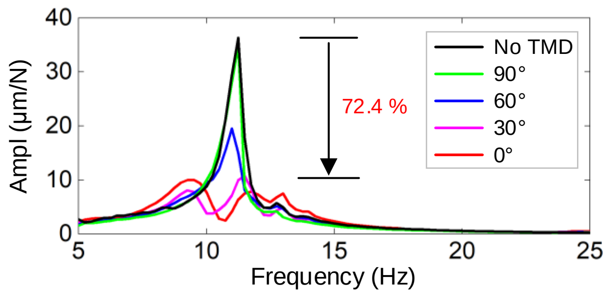

Fig. 6: Experiments of suppressing the dynamic compliance at the robot end. H_{zz} of the robot with the LFTMD at different mounting angles is displayed. The best suppression is achieved at α = 0°, with a 72.4 % reduction in dynamic compliance of the 11.25 Hz mode. As α increases, the suppression effect becomes gradually worse, which meets the expectations from the simulation.

3 SUPPRESSING LOW-FREQUENCY CHATTER IN ROBOTIC MILLING WITH TMD

The low-frequency chatter is dominated by robotic structural modes, whose frequencies are close to robotic natural frequencies. Suppressing robotic modal dynamic compliance can therefore suppress the low-frequency chatter. When the low-frequency chatter occurs in robotic milling, in addition to the modal frequency and the harmonic frequencies of the spindle, the vibration signal also has significant amplitudes on both sides of the harmonic frequencies away from the modal frequency, which is called the side-frequency signal. As pointed out in the recent literature [Xin, 2022], the side-frequency signals originate from the modulation effect between the low-frequency vibrations dominated by robotic structural modes and the forced vibrations in the harmonic frequencies. Meanwhile, this is not a one-way process; the side-frequency vibrations are also modulated with the forced vibrations to produce new low-frequency vibrations. Therefore, it can be conjectured that not only suppressing the low-frequency modal dynamic compliance would suppress the low-frequency chatter, but also suppressing the side-frequency vibrations can be effective.

In this section, milling experiments are conducted to verify the suppression of the low-frequency chatter and the improvement of stability by TMDs. Robotic milling is carried out with no TMD, the LFTMD only, the side-frequency TMD (SFTMD) only, and the combined TMDs (i.e., both the LFTMD and SFTMD), respectively. And their low-frequency amplitudes are compared. Then, with the combined TMDs, the variation of the low-frequency amplitudes with the cutting parameters is observed and the critical stable cutting parameters are judged.

3.1 Suppressing low-frequency chatter with different TMDs

In this section, milling experiments are conducted with different TMDs to verify the suppression effect of the LFTMD and SFTMD on the low-frequency chatter.

It should be noted that the configuration of the LFTMD and SFTMD are different. A TMD with a very low damping ratio can make the FRF peak of the main system greatly reduced (close to 0), but its sides rise (the smaller the TMD damping, the more they rise). The LFTMD aims to reduce the dynamic compliance of robot modes and therefore requires some damping to achieve or approach optimal tuning. The increased dynamic compliance in the sides caused by the too low damping may trigger new low-frequency chatter. In contrast, the SFTMD targets only the dynamic compliance at the side frequency. Since the side frequency is fixed, the damping ratio of the SFTMD should be as small as possible.

Fig. 7 shows the experimental site. The SFTMD consists of a spring and a mass block, with a mass of 1.88 kg, a spring stiffness of 470 kN/m, a natural frequency of 79.5 Hz, and a damping ratio of 0.80 %. The nearest modal frequency to 79.5 Hz is 74 Hz, and the corresponding modal direction is measured as [0.14, -0.97, 0.17], which is close to the mounting direction of the SFTMD. The robot pose is close to that in Section 2.2. The LFTMD direction is close to the direction of the 11.25 Hz mode.

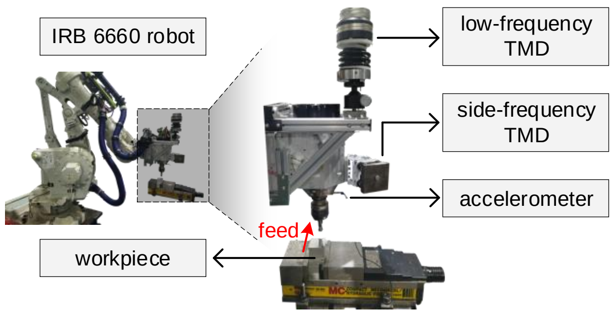

Fig. 7: Experimental site of robotic milling.

When the LFTMD and SFTMD work together, the dynamic compliance of the low-frequency mode and at the side frequency are both suppressed. Due to the large frequency interval, the suppression effects of the two TMDs do not affect each other. The suppression effect of the LFTMD has been shown in Section 2.2. Fig. 8 shows the suppression effect of the SFTMD on the dynamic compliance at the side frequency. Since the modal compliance at the side frequency exists mainly in the Y direction, only H_{yy} is shown for brevity. The SFTMD results in a 60.3 % decrease in dynamic compliance at 79.5 Hz.

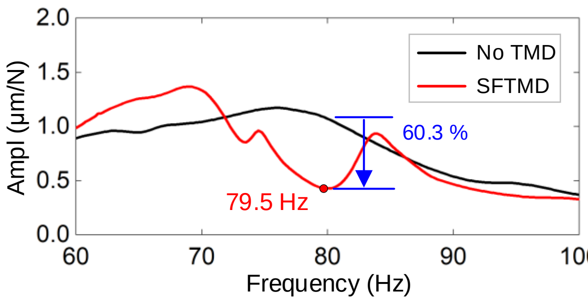

Fig. 8: Suppression effect of the SFTMD on the dynamic compliance at the side frequency (H_{yy}).

The milling conditions are described below.

Table 3 shows the tool parameters and cutting parameters. The spindle speed is set to 5445 rpm to make the side frequency the same as the natural frequency of the SFTMD. The feed direction is shown in Fig. 7. The workpiece is 6061 aluminum alloy. The accelerometer is the same as in Section 2.2. Fig. 9 shows the Z-direction milling vibration spectra under four TMD conditions. It can be seen that in the absence of TMD, the low-frequency chatter occurs at 11 Hz and 17.5 Hz with amplitudes of 318.4 μm and 91.7 μm, respectively. From the amplitudes at 11Hz, it is known that both SFTMD, LFTMD, and combined TMDs can suppress the low-frequency chatter. The LFTMD is more effective than the SFTMD, and the best effect is achieved when they work together. In addition, the chatter at 17.5 Hz is unexpectedly suppressed, probably because the occurrence of the 17.5 Hz chatter involves the coupling with the dynamic compliance of the 11.25 Hz mode.

In summary, both the LFTMD and SFTMD are effective in suppressing the low-frequency chatter in robotic milling, and a better effect can be achieved when they work together. In addition, it should be noted that the chatter modes may be different for different robot poses and machining conditions. For side milling, chatter may be more inclined to occur in the X and Y directions. It is necessary to select the TMD configuration according to the frequency and direction of chatter.

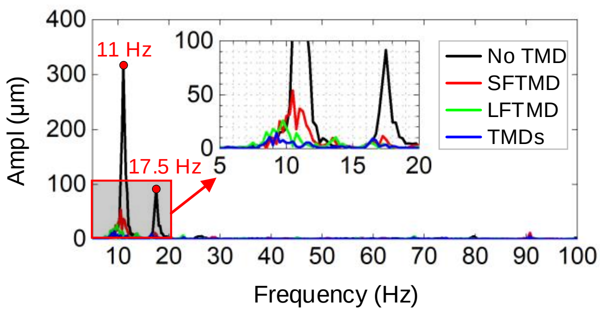

Fig. 9: Z-direction vibration spectra of robotic milling with different TMDs. Both the LFTMD, SFTMD and combined TMDs are effective in suppressing the low-frequency chatter, with the combined TMDs being the most effective.

3.2 Improving milling stability with combined TMDs

This section carries out milling experiments at different cutting depths and cutting widths, with the rest of the cutting parameters being the same as in section 3.1. The low-frequency vibration amplitudes are observed to evaluate the improvement of the critical cutting parameters of the low-frequency chatter stability by the combined TMDs.

The milling experiments are carried out without TMD and with the combined TMDs, respectively, and the TMDs are mounted in the same way as in Fig. 7. The cutting depth is gradually increased from 1 mm to 6 mm with 1 mm interval.

The cutting width is gradually increased from 2 mm to 20 mm with 2 mm interval. The case of low-frequency vibration amplitude in any direction greater than 30 μm is judged as chatter. Fig. 10 shows the low-frequency amplitudes of different cutting parameters and the chatter boundaries without TMD and with combined TMDs. It can be seen that the combined TMDs have a significant suppression effect on the low-frequency chatter in robotic milling, the stability boundary is improved, and the chatter-free material removal rate can be nearly doubled.

Table 3: Tool parameters and cutting parameters.

Tool parameters				Cutting parameters				
Type	Diameter	Number of teeth	Helical angle	Spindle speed	Cutting depth	Cutting width	Feed speed	Cutting mode
Flat	20 mm	2	30°	5445 rpm	4 mm	10 mm	18 mm/s	Down milling

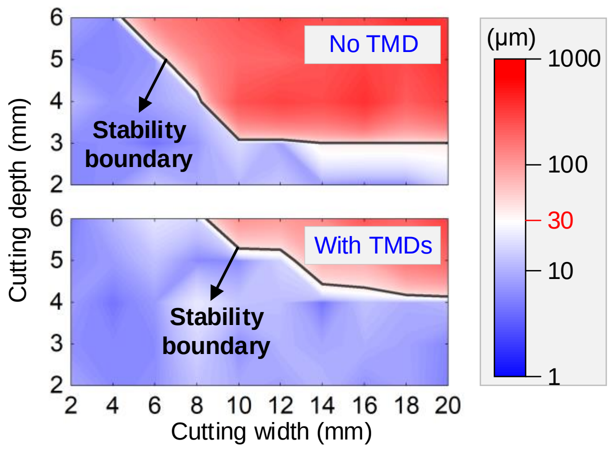

Fig. 10: Low-frequency vibration amplitudes of different cutting parameters and the chatter boundaries without TMD and with the combined TMDs. The combined TMDs have significant suppression of the low-frequency chatter in robotic milling and can nearly double the chatter-free material removal rate.

4 SUMMARY AND OUTLOOK

The low-frequency chatter in robotic milling greatly limits machining efficiency. This paper introduces the TMD to suppress the low-frequency chatter based on the modal directionality of milling robots. A TMD model with mounting angle is established, and the experiments are conducted to verify the suppression effect of the TMDs on the robot dynamic compliance and low-frequency milling chatter. The main conclusions are as follows.

- The LFTMD can greatly suppress the low-frequency modal dynamics compliance of the robot, with a mass ratio of 3 % achieving a suppression rate of 70 %. The suppression effect becomes worse with the increase of the angle between the LFTMD direction and modal direction, but there is almost no loss of suppression effect when the angle is within 30°.
- Both the LFTMD and SFTMD are effective in suppressing the low-frequency chatter, and a better effect can be achieved when they work together.
- The milling experiments show that the TMDs can significantly suppress the low-frequency chatter and improve the chatter-free cutting amount (about 1 times improvement in the experiments of this paper).

Further application of TMDs in robotic milling still faces some challenges. For example, (1) when machining large parts, the change of robot pose will make the frequency and direction of the low-frequency chatter change, which requires the frequency and direction of the TMD to follow this change so as to effectively suppress chatter; (2) The side frequency may be at the superposition of multiple modes, with multiple modal directions, at which time the effect of the one-way TMD is limited; (3) A chatter stability prediction model with TMD action should be established to plan the machining parameters and further improve the machining efficiency.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[Zhu, 2021] Z. Zhu, et al., High precision and efficiency robotic milling of complex parts: Challenges, approaches and trends, Chinese Journal of Aeronautics, 35 (2021) 22-46. https://doi.org/10.1016/j.cja.2020.12.030.

[Cen, 2017] L. Cen, et al., CCT-based mode coupling chatter avoidance in robotic milling, Journal of Manufacturing Processes, 29 (2017) 50-61. https://doi.org/10.1016/j.jmapro.2017.06.010.

[O. Gienke, et al., 2019] O. Gienke, et al., Mode coupling chatter prediction and avoidance in robotic machining process, International Journal of Advanced Manufacturing Technology, 104 (2019) 2103-2116. https://doi.org/10.1007/s00170-019-04053-x.

[He, 2020] F. He, et al., Three-dimensional stability analysis of robotic machining process, Industrial Robot-the International Journal of Robotics Research and Application, 47 (2020) 82-89. https://doi.org/10.1108/ir-02-2019-0036.

[Yuan, 2019] L. Yuan, et al., Mode coupling chatter suppression for robotic machining using semi-active magnetorheological elastomers absorber, Mechanical Systems and Signal Processing, 117 (2019) 221-237. https://doi.org/10.1016/j.ymssp.2018.07.051.

[W. Guo, et al., 2019] W. Guo, et al., Experimental research on rotating ultrasonic milling aluminum alloy by robot, Journal of Nanjing University of Science and Technology, 43 (2019) 159-164.

[Nguyen, 2020] V. Nguyen, et al., Active vibration suppression in robotic milling using optimal control, International Journal of Machine Tools and Manufacture, 152 (2020) 103541. https://doi.org/10.1016/j.ijmachtools.2020.103541.

[Xiao, 2020] J. Xiao, et al., Research on vibration suppression by a multi-point flexible following support head in thin-walled parts mirror milling, The International Journal of Advanced Manufacturing Technology, 106 (2020) 3335-3344. https://doi.org/10.1007/s00170-019-04728-5.

[Soto, 2013] M.G. Soto, et al., Tuned Mass Dampers, Arch. Comput. Method Eng., 20 (2013) 419-431. https://doi.org/10.1007/s11831-013-9091-7.

[Z. Iklódi, et al., 2021] Z. Iklódi, et al., Bi-stability induced by motion limiting constraints on boring bar tuned mass dampers, Journal of Sound and Vibration, 517 (2021) 116538. https://doi.org/10.1016/j.jsv.2021.116538.

[M. Wang, et al., 2010] M. Wang, et al., Design and implementation of nonlinear TMD for chatter suppression: An application in turning processes, International Journal of Machine Tools & Manufacture, 50 (2010) 474-479. https://doi.org/10.1016/j.ijmachtools.2010.01.004.

[Wu, 2022] J. Wu, et al., Characterization of milling robot mode shape and analysis of the weak parts causing end vibration, Measurement, 203 (2022) 111934. https://doi.org/10.1016/j.measurement.2022.111934.

[Seto, 2010] K. Seto, Dynamic vibration absorber and its application, Corona publishing Co., Ltd, Tokyo, Japan, 2010.

[S. Xin, et al., 2022] S. Xin, et al., Research on the influence of robot structural mode on regenerative chatter in milling and analysis of stability boundary improvement domain, International Journal of Machine Tools and Manufacture, 179 (2022) 103918. https://doi.org/10.1016/j.ijmachtools.2022.103918.