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Research Article

Suppressing Milling Chatter of Thin-Walled Parts by Eddy Current Dampers

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Machining vibrations often occur when working with thin-walled workpieces. One effective method to mitigate these vibrations is by using a damper, which can enhance machining accuracy, surface finish, and tool life. However, traditional contact dampers have a drawback in that they require direct contact with the workpiece, leading to friction, wear, increased cutting forces, and reduced machining accuracy. In contrast, electromagnetic eddy current dampers are noncontact dampers that can effectively suppress machining vibrations without the need for physical contact. In this study, a method to suppress machining vibrations in thin-walled workpieces using electromagnetic eddy current dampers is proposed. By establishing a theoretical model for the electromagnetic damper, the damping force and equivalent damping of the damper are determined. Subsequently, the impact of electromagnetic dampers on frequency response functions and machining vibrations are investigated through hammer impact tests. The results indicate that increasing the surface damper voltage and reducing the air gap both enhance the equivalent damping of the electromagnetic eddy current damper. Moreover, cutting experiments are conducted to analyze the surface roughness of thin-walled workpieces with and without dampers. The results demonstrate that the eddy current damper can effectively increase the equivalent damping and provide the necessary damping force to suppress machining chatter. Overall, the proposed method utilizing electromagnetic eddy current dampers presents a promising solution for suppressing machining vibrations in thin-walled workpieces.

1. Introduction

Thin-walled structures utilized in aerospace spacecraft design are commonly employed to minimize part mass and decrease fuel consumption. However, the reduction in mass is often accompanied by a decrease in the structure's stiffness, making it prone to machining chatter [1, 2]. Machining chatter, when it occurs, gives rise to various issues, including increased tool wear, diminished machining quality, and reduced machining efficiency [3–6]. Consequently, finding effective methods to suppress machining chatter has become a significant focus for researchers.

Controlling machining parameters is the traditional method for suppressing machining chatter. Based on a stability prediction model and stability lobe diagram, the cutting parameters are set in the stable cutting zone of the stability lobe diagram by controlling the axial cutting depth and spindle speed. In the turn-milling process, the turning spindle and milling spindle rotate simultaneously, resulting in constant changes in the axial cutting depth. Yan et al. [7] proposed a stability prediction model for turn milling that considered changing axial cutting depth and coupled structural modes. Ozkirimli et al. [8] proposed a milling stability prediction method suitable for use in five-axis milling and complex part machining. The stability limits can be predicted using the zeroth-order approximation frequency domain method. Li et al. [9] designed a new type of tool holder and developed a time-varying model to control the stability of machining systems. Zhao et al. [10] proposed a time-varying information model for controlling the machining stability of thin-walled parts, which is predicted based on time-varying information during machining. The method for controlling machining parameters can be carried out during the machining process; therefore, the efficiency of this method is higher. However, when original modal parameters such as the stiffness and damping of the system are weak, the stable cutting area of the parts is small in the stability lobe diagram. Therefore, for thin-walled parts, it is difficult to achieve effective control of machining chatter by controlling machining process parameters. This method cannot satisfy the requirements of machining chatter control of thin-walled parts.

Another effective strategy to control the vibration of thin-walled parts is to employ dampers on the parts or machining tools. The mass, stiffness, and damping of the machining system can be effectively improved by applying a damper to the system to increase the range of the stable cutting area; thus, machining chatter can be suppressed, as shown in Figure 1. Tuned mass dampers are widely used compared to other passive devices, and they are easy to implement and effective in controlling machining chatter [11]. Kolluru et al. [12] proposed a novel surface damping solution to realize the goal of suppressing high- and low-frequency vibrations. In this solution, a thin flexible layer is added to the surface of the workpiece and a discrete mass is added to the surface of the flexible layer. Thus, the damping of the workpiece is modified.

Brecher et al. [13] presented an analytical method for a multistage multimass damper to increase the robustness and effective frequency range of a system. The performance was excellent at low damping values. The reliability of the results was verified using finite element simulations and measurements. Yang et al. [14] designed a two-degree-tuned mass damper that has two degrees and can be utilized in machining chatter suppression of aluminum thin-frame workpieces. The design, modelling, and analysis of a new magnetic spring damper were carried out by Ebrahimi et al. [15]. The electromagnetic force was estimated through electromagnetic theory analysis, and the moving magnet and conductor jointly acted as a viscous damper. Ma et al. [16] proposed a tuned mass damper that is imposed on the tool shank and can rotate with the tool. The frequency response function of the tool can be predicted when the damper is applied, and the stability can be improved by optimizing the natural frequency and damping ratio of the mass damper. Receptance coupling substructure analysis was applied by Duncan et al. [17] to develop a model and investigate the effect of a dynamic absorber on the spindle-holder-tool assembly. It was demonstrated that the dynamic absorber can improve the system dynamic stiffness and critical stability limit of machining. To enhance the dynamic characteristics of fixtures for a large workpiece, Munoa et al. [18] presented variable-stiffness tuned-mass dampers to improve the dynamic stiffness of the fixtures. The stiffness and damping were varied using spring and eddy currents to achieve optimal tuning. Habib et al. [19] presented a new type of nonlinear tuned vibration absorber to mitigate the nonlinear resonance of mechanical systems. Den Hartog's equal-peak method was employed to determine the

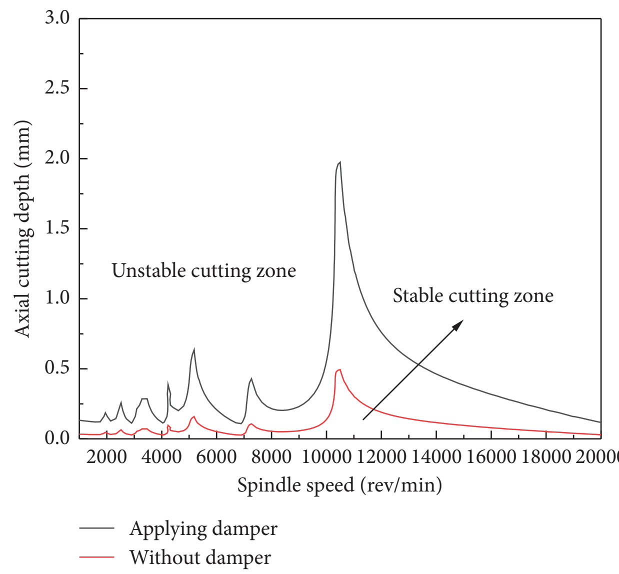

Figure 1: Influence of a damper on the stability lobe diagram.

parameters of the absorber, and the results showed that the nonlinear tuned vibration absorber is superior to the classical linear tuned vibration absorber. Wan et al. [20] presented a method for controlling vibrations during milling using a dynamic vibration absorber. The modal parameters of the workpiece were predicted, and the effects of the dynamic vibration absorber on the dominant modes and response displacements of the workpiece were also studied. Subsequently, the dynamic displacements were minimized using an optimization algorithm.

According to the above analysis, it can be concluded that a tuned mass damper can be easily applied at low cost. While the tuning mass damper is often fixed on the workpiece, the surface of the workpiece or tool cannot be destroyed to fix the damper and fixture, and the system quality cannot be altered. Therefore, one of the difficulties in applying contact dampers is installation and fixation. This problem can be solved by a noncontact damper, which does not need to come into contact with the workpiece or destroy the workpiece surface. When a conductor moves in an electromagnetic field, the magnetic flux through the conductor changes, and an eddy current is produced in the conductor. The conductor is not in contact with the electromagnet during the moving process, and equivalent damping appears with the eddy current. Because of the aforementioned advantages of magnetic dampers, many scholars have conducted research on magnetic and electromagnetic dampers. An eddy current damper with a rack and gear was proposed by Li et al. [21], and the linear relationship between the damping torque and damping velocity was obtained through a theoretical model. The accuracy of the theoretical model was evaluated using COMSOL Multiphysics, and the influence of plate thickness, position, and number of magnetic poles on the damping torque was analyzed. Butt et al. [22] designed a two-degree magnetic damper to provide an eddy current damping force against machining chatter caused by the cutting force and only the experimental studies were carried out. Eddy current damping is related to the magnetic flux density, which is caused by the neodymium magnets. The damping force can resist the chatter caused by the cutting force. An electromagnetic damper that suppresses vibration in aluminum machining processes was designed by Sodano et al. [23]. The damping is generated by the damping force when the radial magnetic flux changes. The damping force on the structure can be predicted by a theoretical model based on the electromagnetic theory. The proposed electromagnetic damper can improve the damping ratio of the workpiece. Ebrahimi et al. [24] proposed a novel eddy current damper that can produce damping owing to eddy currents based on the electromagnetic theory. When the conductor moves relative to the permanent magnets, electromagnetic forces and eddy currents are generated. Simulations were conducted to optimize the damper. It can be concluded from the above analysis that much of the research is concentrated on mass dampers, whereas magnetic and electromagnetic dampers are less studied.

Based on previous studies, it can be inferred that contact dampers require physical contact with the workpiece, necessitating direct installation on the workpiece itself. Hence, a noncontact electromagnetic eddy current damper, capable of being adjusted to accommodate the various modes of the machining system, is better suited for the machining requirements of thin-walled parts. Additionally, adjusting the modal parameters of the system using dampers is closely linked to the inherent modal parameters of the system. Consequently, the damper parameters should be tailored to the specific modes of the tool and parts. The use of nonadjustable dampers restricts their application range and presents significant limitations. Meanwhile, existing eddy current dampers are mostly designed with permanent magnets, and the equivalent damping of the damper is closely related to the magnetic properties of the permanent magnets, making it difficult to adjust. Therefore, designing eddy current dampers with electromagnets allows for online adjustment of their equivalent damping, which is beneficial for controlling machining chatter. Therefore, studying the influence of electromagnetic eddy current damper parameters on the equivalent damping is helpful to select the appropriate damper parameters and improve the machining flutter suppression effect.

This paper introduces a novel damper design that utilizes an electromagnetic damper to generate a magnetic field, thereby inducing eddy currents in a conductor. This damper effectively alters the stiffness and damping of the system, providing a means to mitigate machining chatter. The theoretical analysis begins by examining the mechanism of electromagnetic field generation and eddy current induction. By applying electromagnetic theory, the relationship between the equivalent damping caused by the electromagnetic eddy current and the electrical parameters of the electromagnet is established. Impact experiments are then conducted to obtain the frequency response functions. The resulting equivalent damping values from both theoretical analysis and experiments are compared, considering variations in voltage and air gap. Finally, machining experiments are performed on thin-walled parts made of aluminum alloy. The surface condition and roughness of the workpiece are measured to validate the reliability of the theoretical analysis.

2. Eddy Current Damper Model

According to the electromagnetic theory, electromagnets generate an electromagnetic field under the influence of an electric field when a voltage is applied to the electromagnet. When the conductor moves in the electromagnetic field in Y direction, an eddy current is generated in the conductor along with an electromagnetic force. The electromagnetic force hinders the movement of the conductor and equivalent damping is generated. The electromagnet is installed near the conductor such that the thin-walled conductor is within the range of the electromagnetic field. When the conductor is machined using the machining tool, it moves in Y direction. Given that the conductor performs reciprocating movement, the flux density of the magnetic field in the conductor changes, and eddy currents are generated. Then, the movement of the conductor is restrained by the action of the electromagnetic force to achieve suppression of machining chatter. When the workpiece is successively close and far from the electromagnet, the eddy current formed in the conductor moves in the opposite direction. An eddy current is generated in the clockwise direction when the workpiece is close to the electromagnet, whereas an eddy current is generated in the counter-clockwise direction when the workpiece is far from the conductor. The formation principle of eddy currents is shown in Figure 2.

Based on the above electromagnetic force generation principle, an electromagnetic eddy current damper was designed as shown in Figure 3. The front end of the damper is an electromagnetic core surrounded by a coil. The coil is connected to the damper shell by a spring. The shell of the damper is a hollow nylon shell that prevents the conduction of electricity and magnetism. When the coil is energized, an electromagnetic field is generated.

As the conductor moves in the magnetic field, the magnetic flux through the conductor changes. This can be expressed using the following Maxwell's equation:

$$\oint_L \mathrm{Edl} = -\frac{d\varnothing_m}{\mathrm{d}t} = -\int_S \frac{\partial B}{\partial t}\mathrm{d}s, \tag{1}$$

where E is the electric field strength, B is the magnetic flux density, and $\varnothing_m$ is the magnetic flux.

The eddy current density J generated by the conductor moving in the magnetic field can be expressed as follows:

$$J = \sigma(v \times B), \tag{2}$$

where v is the speed of movement and σ is the magnetic permeability of the conductor.

When the conductor moves close to the electromagnet in the magnetic field, an eddy current is generated in the conductor, and a magnetic force that hinders the movement

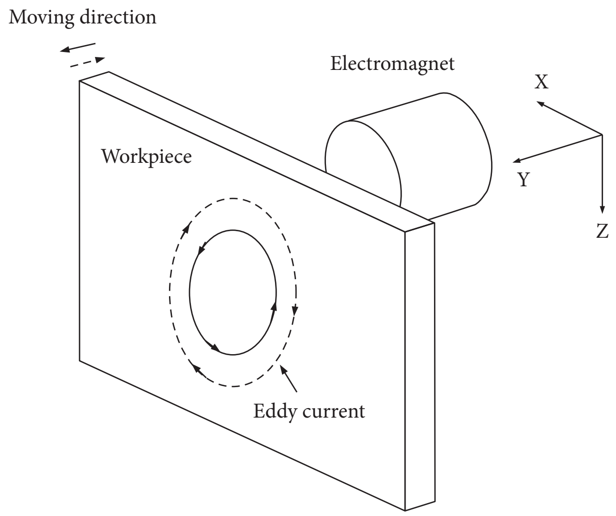

Figure 2: Principle of eddy current formation.

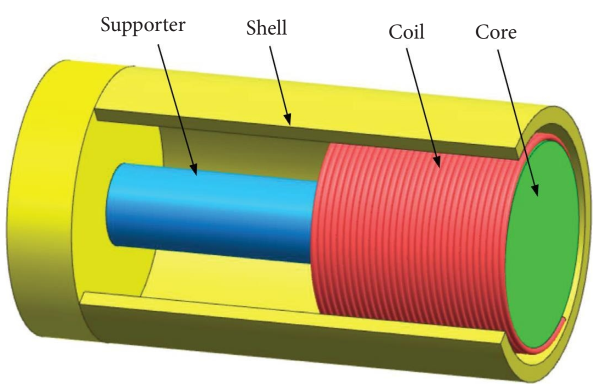

Figure 3: Schematic diagram of the proposed damper structure.

of the conductor is also generated. According to the theory of electromagnetic fields, the magnetic force generated in the magnetic field is mainly related to the change in magnetic flux, which can be expressed as follows [23]:

$$F_D = \frac{B_0^2 S_0}{2\mu_0} \times 10^6, \quad (3)$$

where S_0 is the area of the electromagnet, μ_0 is the permeability, and B_0 is the magnetic flux density.

According to the production principle of the magnetic flux in an electromagnet, the electromagnetic force can also be expressed as follows:

$$F_D = \frac{\mu_0 S_0}{8}\left[\frac{Ud^2}{\rho(D_2 + D_1)\delta}\right] \times 10^6, \quad (4)$$

where δ is the air gap, d is the diameter of the coil, U is the voltage of the electromagnet, ρ is the resistivity of the conductor, and D_2 and D_1 are the outer and inner diameters of the electromagnet.

It can be observed that the maximum displacement during machining is in the normal direction to the surface of the workpiece. Therefore, the focus of modal analysis and machining stability research is on the response and stability in the normal direction of the workpiece. The model has been simplified to a single-degree-of-freedom system model for prediction and analysis. According to the dynamic formula of a single-degree-of-freedom system, the relationship between the exciting force and the displacement, velocity, and acceleration can be expressed as follows:

$$m\ddot{X} + c\dot{X} + \mathrm{k}X = F, \quad (5)$$

where m, c, and k denote the mass, damping, and stiffness of the single-degree system, respectively. When the conductor is machined by a machining tool, it moves close and far from the electromagnet in the axial direction of the electromagnet. An eddy current is generated, and the magnetic force inhibits the reciprocating motion of the machining system. The damping force generated by the eddy current suppresses machining chatter. This effect is related to the magnitude of the electromagnetic force. When the eddy current damper is applied to the machining system, the dynamic model of the system can be expressed as follows:

$$\begin{aligned} m_0\ddot{X} + \left(c_0\dot{X} + F_D\right) + k_0 X &= F, \\ m\ddot{X} + \left(c_0 + c_{\mathrm{eq}}\right)\dot{X} + \mathrm{k}X &= F. \end{aligned} \quad (6)$$

The restraining effect of the magnetic force generated by a single electromagnet on the reciprocating motion of the system can be expressed as the equivalent damping c_{eq}:

$$c_{\mathrm{eq}}\dot{X} = F_D, \quad (7)$$

$$c_{\mathrm{eq}} = \frac{F_D}{\dot{X}} = \frac{\mu_0 S_0}{8v}\left[\frac{Ud^2}{\rho(D_2 + D_1)\delta}\right] \times 10^6, \quad (8)$$

where v is the moving speed of the conductor and δ is the air gap of the magnetic field. It can be concluded from equation (8) that when the structure design of the electromagnetic damper is determined, the equivalent damping of the system in the application is related to the voltage and air gap.

3. Modal Analysis of Workpiece by Finite Element Method

Dampers are usually applied to the zone of the workpiece where the stiffness is low and the dynamic deformation displacement is the largest. To determine the position of the damper, finite element simulation software was used to obtain the results of the modal analysis. The natural frequencies of the workpiece were calculated, and the results are listed in Table 1.

Modal shapes corresponding to the natural frequencies were also obtained. The first-order modal shape of the thin-walled workpiece is shown in Figure 4. This figure indicates that the maximum dynamic deformation displacement is located in the middle and above zones of the thin-walled parts. When the natural frequency is 491.41 Hz, the maximum response displacement is 1 mm. Because the box-shaped component has a close-to-symmetric structure, its low-order results in modal analysis are similar. The four

Table 1: Natural frequencies of the workpiece.

	First order	Second order	Third order	Fourth order	Fifth order	Sixth order
Natural frequency (Hz)	490.41	529.98	530.01	585.08	1015.4	1157.9

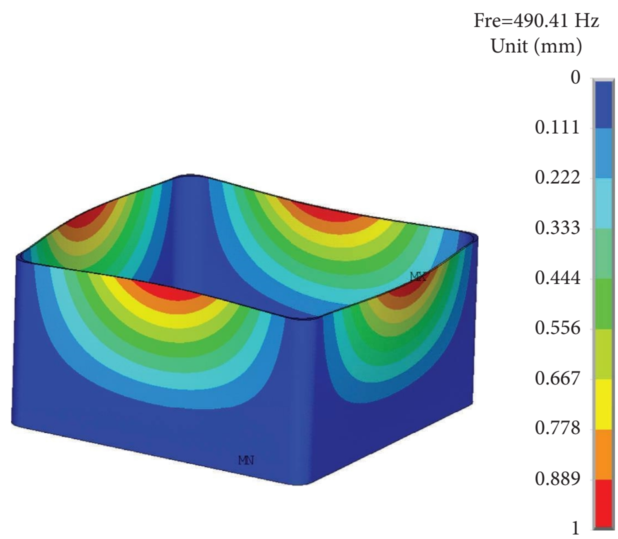

Figure 4: Modal analysis of parts by finite element analysis.

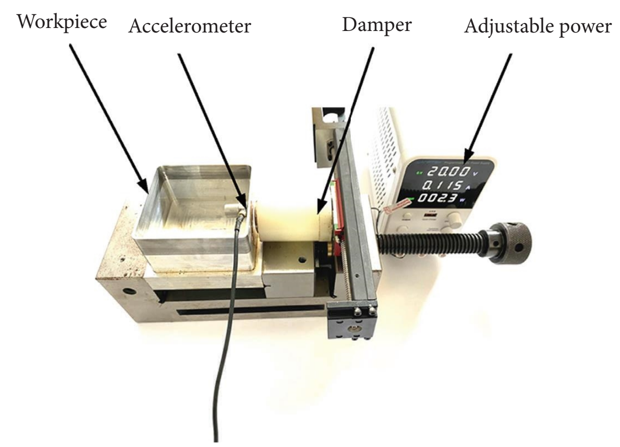

Figure 5: Experimental device for impact test when the damper is applied.

thin-walled edges have similar processing stability, so the analysis of processing stability is only conducted on one edge. Therefore, the damper can be imposed on this zone to suppress machining chatter.

4. Experimental Investigation of Eddy Current Damping

To realize online adjustment of the equivalent damping of the electromagnet, a DC power supply with an adjustable voltage and current was used to control the electromagnet. The equivalent damping of the workpiece can be adjusted online by controlling the voltage and size of the air gap. An electromagnet with an iron core diameter of 14 mm, length of 20 mm, and wire set diameter of 0.5 mm was designed to conduct modal measurement experiments. The influence of the eddy current damper on the system damping was studied experimentally. Thin-walled aluminum-alloy frame parts with a thickness of 2 mm, height of 40 mm, and side length of 100 mm were selected as conductors. The damper was placed in the middle and outer sides of the thin-walled part. Excitation was applied to the inner side of the thin-walled part to measure the response of the system during the impact experiments. The electromagnet was powered by an adjustable DC power supply, and the voltage was adjusted using a voltage adjustment knob. A dynamic signal analyzer (Benstone VP5), hammer, and accelerometer were used for acceleration measurement, and the frequency response function was derived. The experimental device was then set up as shown in Figure 5.

The acceleration response of thin-walled aluminum-alloy parts without damper was obtained by impact tests in the frequency range of 0–2000 Hz. The maximum acceleration was measured to be 586.15 mm/s^2/N at a natural frequency of 700 Hz. Then, the eddy current damper was imposed near the outside of the thin-walled workpiece, and the air gap was set to 3 mm. A voltage of 20 V and current of 0.104 A were applied to the damper. The maximum acceleration still occurred at a natural frequency of 700 Hz, but it was reduced to 403.28 mm/s^2/N for the electromagnetic force caused by the eddy current. The experimental results showed that the response decreased significantly after the damper was applied, decreasing to 68.8% of the maximum value of the original acceleration response. The response curves of the system with and without the eddy current damper are shown in Figure 6.

According to the theoretical analysis defined by equation (9), when the core and coil of the electrode are determined, they cannot be replaced during milling. Therefore, the equivalent damping of the electromagnet can be adjusted online only by adjusting the voltage U of the electromagnet through an adjustable DC power and the air gap δ between the electromagnet and the workpiece. On the basis of the experimental device shown in Figure 5, the voltage and air gap of the electromagnet were adjusted to verify the reliability of the theoretical analysis.

4.1. Influence of Voltage on System Damping. According to milling dynamics theory [25, 26], the amplitude of the frequency response function of a machining system can be expressed as

$$\begin{aligned} |\varnothing(\omega)| &= \left|\frac{X}{F_0}\right| \\ &= \frac{\omega_n^2}{k}\frac{1}{\sqrt{\left(\omega_n^2-\omega^2\right)^2+\left(2\varepsilon\omega\omega_n\right)^2}}, \end{aligned} \tag{9}$$

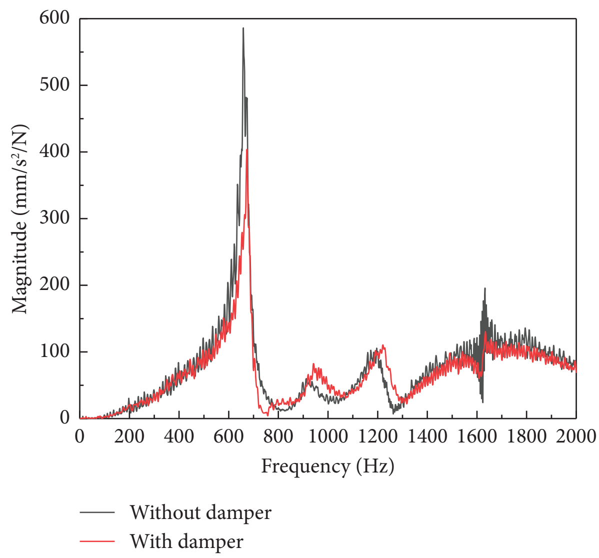

FIGURE 6: Effect of the damper on the system response.

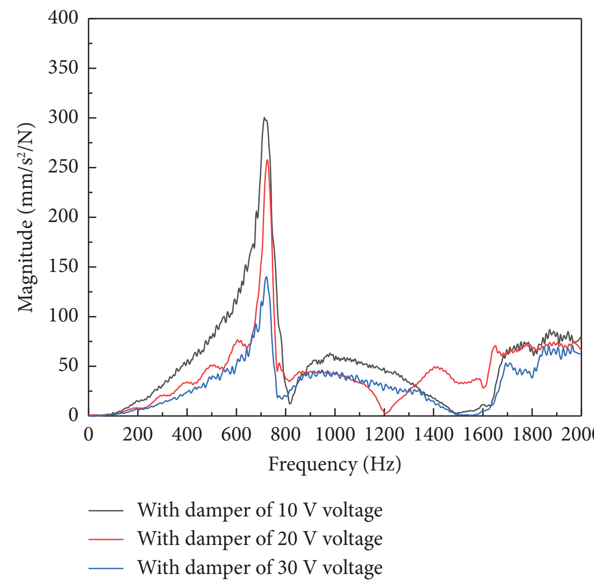

FIGURE 7: The effect of voltage on FRF of parts with eddy current damper.

where ω_n denotes the natural frequency of the system, ε denotes the damping ratio, and k denotes the stiffness of the system.

The frequency response function can be decomposed into the real and imaginary parts as follows:

$$G(\omega) = \frac{\omega_n^2}{k}\frac{\omega_n^2 - \omega^2}{\left(\omega_n^2 - \omega^2\right)^2 + \left(2\varepsilon\omega\omega_n\right)^2},$$
$$H(\omega) = \frac{\omega_n^2}{k}\frac{-2\varepsilon\omega\omega_n}{\left(\omega_n^2 - \omega^2\right)^2 + \left(2\varepsilon\omega\omega_n\right)^2}. \quad (10)$$

Thus, the frequency response function can be expressed as $\varnothing(\omega) = G(\omega) + {}_jH(\omega)$.

When the frequency is equal to the natural frequency $\omega = \omega_n$, the imaginary part of the frequency response function can be expressed as follows:

$$H(\omega) = \frac{\omega_n^2}{k}\frac{-1}{2\varepsilon\omega_n^2} = -\frac{1}{2\varepsilon k}. \quad (11)$$

According to equation (11), when the frequency is equal to the natural frequency, the absolute value of the imaginary part of the frequency response function is inversely proportional to the damping ratio and stiffness. Therefore, with an increase in the input voltage, the equivalent damping of the system will also increase, and the absolute value of the imaginary part of the frequency response function at the natural frequency will be smaller. The voltage applied to the damper was varied by adjusting the DC power, and the voltage values were set to 10 V, 20 V, and 30 V. The image part of the acceleration response of the system was measured during the impact test. The results are shown in Figure 7.

When the natural frequency is constant, the damping ratio increases linearly with increasing damping. It can be observed from the comparison in Figure 7 that the response amplitude of the system decreases with an increase in the electromagnet voltage. When a voltage of 10 V was applied, the first-order natural frequency of the workpiece system was 715 Hz, and the corresponding extreme acceleration value was 299.7 mm/s^2/N. When the applied voltage was increased to 20 V and 30 V, the first-order natural frequency remained unchanged and the extreme value of acceleration increased to 256.7 mm/s^2/N and 139.4 mm/s^2/N, respectively. Thus, it can be concluded that, with an increase in voltage, the eddy current damping generated by the electromagnet increases the equivalent damping of the system and has little effect on the natural frequency of the system. The acceleration response of the system decreases with an increase in voltage, and the absolute value of its acceleration gradually decreases.

When the damper is applied, the damping of the system can be decomposed into two parts: the original damping of the system and the part induced by the damper. The damping ratio of the system at different voltages was obtained by fitting, and the equivalent damping of the system was calculated.

When the damping effect of the electromagnet resulting from the eddy current was applied, the natural frequency of the system remained unchanged. The variation in its equivalent damping is shown in Figure 8. When the voltage increased from 10 V to 30 V, the equivalent damping experimentally achieved increased from 121.92 N/ms^{-1} to 346.6 N/ms^{-1} and the equivalent damping of the predicted increased from 52.05 N/ms^{-1} to 468.4 N/ms^{-1}. When the voltage was less than 20 V, the theoretically predicted results were lower than the experimental results. When the voltage exceeded 20 V, the theoretical prediction results were significantly higher than the experimental results.

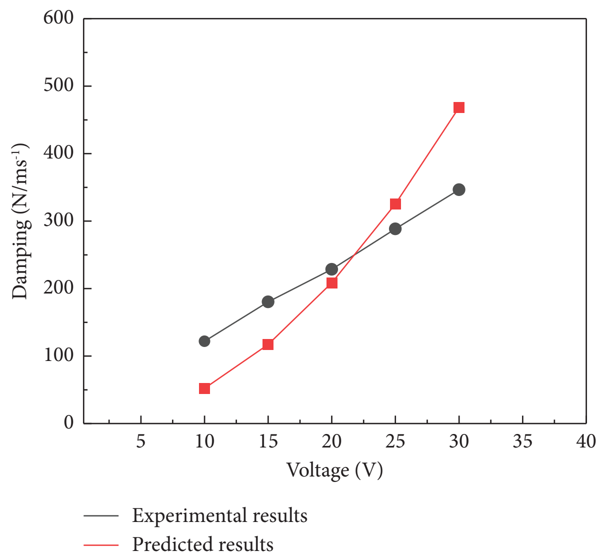

Figure 8: Effect of voltage on equivalent damping.

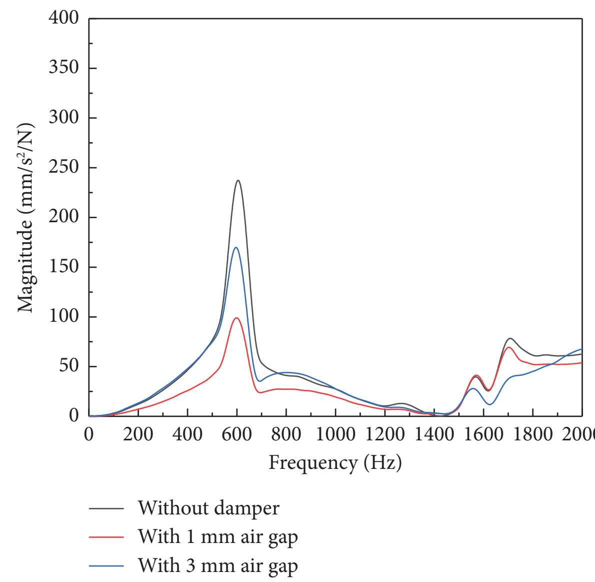

Figure 9: Influence of the air gap on the frequency response function.

4.2. Effect of Air Gap on Equivalent System Damping. According to the theoretical model analysis, there is an inversely proportional relationship between the size of the air gap and equivalent damping of the system. When the electromagnet is close to the conductor, the magnetic flux increases, and when the magnet is far from the conductor, the magnetic flux decreases.

Modal impact experiments were carried out to measure the acceleration results of the frequency response function when the air gaps were set at 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm. The measurement results of the frequency response function are shown in Figure 9.

When the damper was applied to the conductor, the air gap of the electromagnet increased from 1 mm to 3 mm. The amplitude of the response function corresponding to the first natural frequency increased from 98.55 mm/s^2/N to 169.7 mm/s^2/N. The amplitude of the response function without damper was 237.25 mm/s^2/N. With an increase in the air gap, the amplitude of the response function gradually increased on the first-order natural frequency, and the corresponding natural frequency did not change significantly. There is evidence that shows that the magnetic field reduces with an increase in the air gap, and the suppression effect on machining vibration is also reduced.

As can be seen from the comparison of the results shown in Figure 10, an increase in the air gap reduces the equivalent damping of the system in the machining process of thin-walled parts. When the air gap increased from 1 mm to 5 mm, the equivalent damping decreased from 297.36 N/ms^{-1} to 144.84 N/ms^{-1}. The theoretical prediction results show that when the air gap increases from 1 mm to 5 mm, the equivalent damping increases from 433.76 N/ms^{-1} to 33.35 N/ms^{-1}. The variation trend of the theoretical prediction results is clearly greater than that of the experimental results, and the trends of the theoretical and predicted results are consistent.

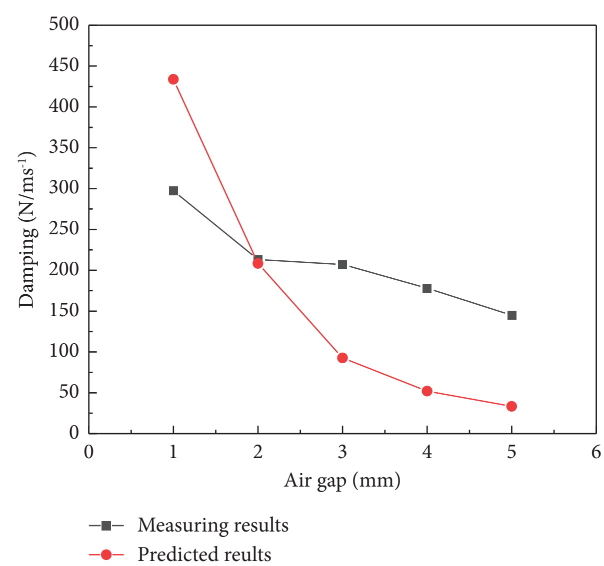

Figure 10: Effect of air gap on equivalent damping.

5. Application of Eddy Current Damping on Thin-Walled Workpiece Milling

The eddy current damper was applied in milling experiments of thin-walled aluminum box parts on a Mikron 500E five-axis machining center. The machining tool was a 10-mm-diameter end-milling cutter. The machining parameters were as follows: spindle speed, 2100 rpm; feed speed, 500 mm/min; axial cutting depth, 4 mm; and radial cutting depth, 4 mm. The settings of the thin-walled aluminum-alloy machining are shown in Figure 11.

To study the suppression effect of the electromagnetic eddy current damper on machining vibration, the surfaces of thin-walled workpieces with and without dampers were

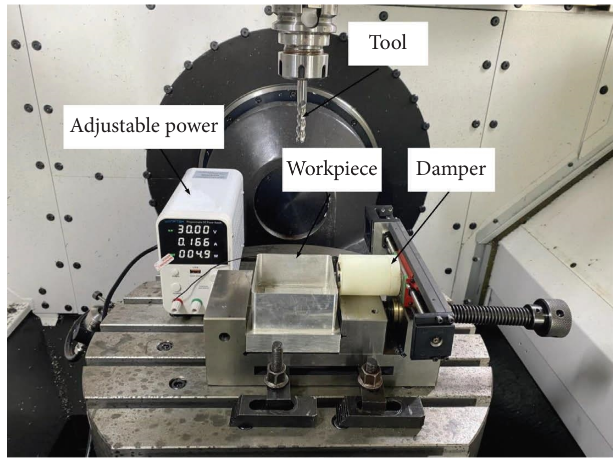

Figure 11: Settings of thin-walled aluminum-alloy machining.

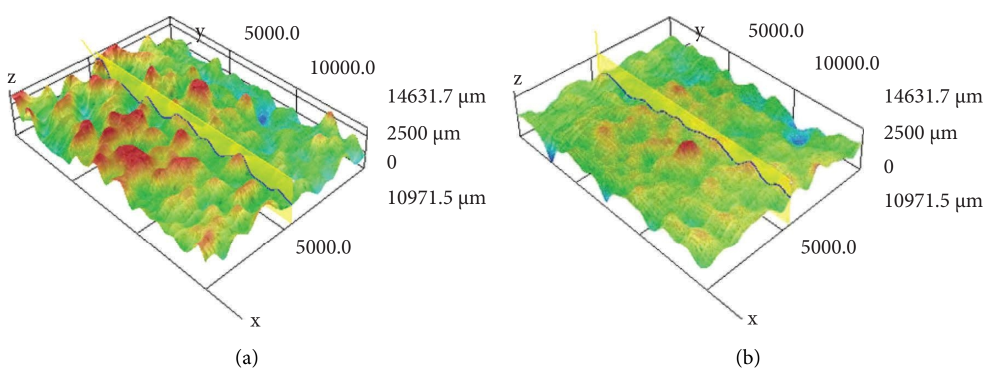

Figure 12: Surface state of workpiece before and after application of damper. (a) Surface state of workpiece without damper. (b) Surface state of workpiece with damper.

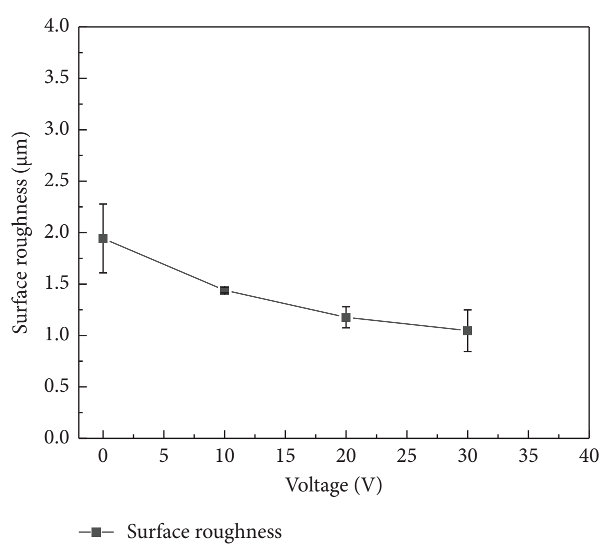

Figure 13: Measured roughness results as a function of the damper voltage.

analyzed. A Hirox RX-100 3D video microscope was used to measure the machined surface of the workpiece and evaluate the surface profiles. The measured surface profile of the workpiece is shown in Figure 12. When the eddy current damper was not applied, there was an evident surface vibration on the workpiece surface. After the damper was applied, the vibration on the workpiece surface was suppressed to a certain extent and the vibration on the workpiece surface disappeared. The peak value of the surface without damper was 2308 μm and the peak value was reduced to 2158 μm.

To quantitatively analyze the suppression effect of the electromagnetic eddy current damper on machining vibration, a sample of aluminum-alloy thin-walled workpiece was characterized: roughness and profile were measured. The measurements were conducted on a Hommel T8000 RC roughness- and profile-measuring instrument. The sampling length was set to 5 mm. The roughness comparison results are shown in Figure 13. The roughness of the surfaces of the workpiece with damper and workpiece without damper were analyzed, and it was found that the surface vibration of the thin-walled aluminum-alloy workpiece mainly appeared in the middle area of the thin-walled part before the damper was applied. Because the rigidity of the middle area was weak, machining vibration was more likely to occur. The two end areas of the workpiece were originally at the corner of the workpiece, the rigidity was significantly enhanced, and the machining surface exhibited no evident vibration. Before the damper was applied, the surface roughness of the middle area of the thin-walled workpiece was 1.94 μm. After the damper was applied, the surface vibration of the workpiece reduced significantly. In addition, the surface roughness was reduced to 1.04 μm. The roughness of the workpiece also reduced to 53.6% of its original value. Therefore, the proposed electromagnetic eddy current damper can significantly increase the system equivalent damping and suppress machining vibration.

6. Conclusions

In this study, an electromagnetic eddy current damper was introduced to suppress the machining chatter of a thin-walled aluminum-alloy workpiece. An electromagnetic eddy current damper is a type of noncontact damper that can suppress machining chatter without destroying the surface of the workpiece. An electromagnetic eddy current damper can change the magnetic flux of the system by controlling the voltage and air gap of the damper. Therefore, the equivalent damping of the system can also be controlled, and the damper can realize online control in this manner. Through theoretical and experimental analyses, the following conclusions were drawn:

(1) A model of the equivalent damping of an electromagnetic eddy current damper was presented resulting from theoretical analysis. The effects of the voltage and gap size on the equivalent damping were analyzed. The position where the damper was applied was also predicted using modal simulation of the finite element analysis method.

(2) Impact experiments on thin-walled aluminum-alloy parts were carried out, and the experimental results were compared with the theoretical prediction results when the voltage and air gap of the damper varied. The equivalent damping of the system increased from 121.92 N/ms^{-1} to 346.6 N/ms^{-1} when the voltage of the damper increased from 10 V to 30 V, and its equivalent damping decreased from 297.36 N/ms^{-1} to 144.84 N/ms^{-1} when the air gap increased from 1 mm to 5 mm. The experimental measurement results were consistent with the theoretical prediction results.

(3) Milling experiments were performed on thin-walled aluminum-alloy parts with and without electromagnetic eddy current dampers. The surface roughness of the workpiece was measured and it was found that the surface roughness of the workpiece was reduced from 1.94 μm to 1.04 μm after the damper was applied. The roughness of the parts decreased to 53.6% when the eddy current damper was used. These results show that the damper has an evident suppression effect on machining chatter, thereby verifying the reliability of the theoretical analysis.

Data Availability

The data that support the findings of this study are available from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this study.

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References

[1] X. B. Dang, M. Wan, W. H. Zhang, and Y. Yang, "Chatter analysis and mitigation of milling of the pocket-shaped thin-walled workpieces with viscous fluid," *International Journal of Mechanical Sciences*, vol. 194, 2021.

[2] G. Quintana and J. Ciurana, "Chatter in machining processes: a review," *International Journal of Machine Tools and Manufacture*, vol. 51, pp. 363–376, 2011.

[3] Y. Nakano, H. Takahara, and E. Kondo, "Countermeasure against chatter in end milling operations using multiple dynamic absorbers," *Journal of Sound and Vibration*, vol. 332, pp. 1626–1638, 2013.

[4] S. Seguy, G. Dessein, and L. Arnaud, "Surface roughness variation of thin wall milling, related to modal interactions," *International Journal of Machine Tools and Manufacture*, vol. 48, pp. 261–274, 2008.

[5] C. Yue, H. Gao, X. Liu, S. Liang, and L. Wang, "A review of chatter vibration research in milling," *Chinese Journal of Aeronautics*, vol. 32, pp. 5–32, 2019.

[6] Y. Mohammadi and K. Ahmadi, "Frequency domain analysis of regenerative chatter in machine tools with linear time periodic dynamics," *Mechanical Systems and Signal Processing*, vol. 120, pp. 378–391, 2019.

[7] R. Yan, X. Tang, F. Peng, Y. Wang, and F. Qiu, "The effect of variable cutting depth and thickness on milling stability for orthogonal turn-milling," *International Journal of Advanced Manufacturing Technology*, vol. 82, pp. 765–777, 2016.

[8] O. Ozkirimli, L. T. Tunc, and E. Budak, "Generalized model for dynamics and stability of multi-Axis milling with complex tool geometries," *Journal of Materials Processing Technology*, vol. 238, pp. 446–458, 2016.

[9] D. Li, H. Cao, X. Zhang, X. Chen, and R. Yan, "Model predictive control based active chatter control in milling process," *Mechanical Systems and Signal Processing*, vol. 128, pp. 266–281, 2019.

[10] X. Zhao, L. Zheng, Y. Wang, and Y. Zhang, "Services-oriented intelligent milling for thin-walled parts based on time-varying information model of machining system," *International Journal of Mechanical Sciences*, p. 219, 2022.

[11] J. Munoa, X. Beudaert, Z. Dombovari et al., "Chatter suppression techniques in metal cutting," *CIRP Annals-Manufacturing Technology*, vol. 65, pp. 785–808, 2016.

[12] K. Kolluru, D. Axinte, and A. Becker, "A solution for minimising vibrations in milling of thin walled casings by applying dampers to workpiece surface," *CIRP Annals-Manufacturing Technology*, vol. 62, pp. 415–418, 2013.

[13] C. Brecher, S. Schmidt, and M. Fey, "Analytic tuning of robust multi-mass dampers," *CIRP Annals-Manufacturing Technology*, vol. 65, pp. 365–368, 2016.

[14] Y. Yang, W. Dai, and Q. Liu, "Design and machining application of a two-DOF magnetic tuned mass damper," *International Journal of Advanced Manufacturing Technology*, vol. 89, pp. 1–9, 2017.

[15] B. Ebrahimi, M. B. Khamesee, and M. F. Golnaraghi, "Design and modeling of a magnetic shock absorber based on eddy current damping effect," *Journal of Sound and Vibration*, vol. 315, pp. 875–889, 2008.

[16] W. Ma, Y. Yang, and X. Jin, "Chatter suppression in micromilling using shank-mounted two-DOF tuned mass damper," *Precision Engineering*, vol. 72, pp. 144–157, 2021.

[17] G. S. Duncan, M. F. Tummond, and T. L. Schmitz, "An investigation of the dynamic absorber effect in high-speed machining," *International Journal of Machine Tools and Manufacture*, vol. 45, pp. 497–507, 2005.

[18] J. Munoa, A. Iglesias, A. Olarra, Z. Dombovari, M. Zatarain, and G. Stepan, "Design of self-tuneable mass damper for modular fixturing systems," *CIRP Annals-Manufacturing Technology*, vol. 65, pp. 389–392, 2016.

[19] G. Habib, T. Detroux, R. Viguie, and G. Kerschen, "Nonlinear generalization of Den Hartog's equal-peak method," *Mechanical Systems and Signal Processing*, vol. 52, no. 53, pp. 17–28, 2015.

[20] M. Wan, X. Y. Liang, Y. Yang, and W. H. Zhang, "Suppressing vibrations in milling-trimming process of the plate-like workpiece by optimizing the location of vibration absorber," *Journal of Materials Processing Technology*, vol. 278, pp. 1–28, 2020.

[21] S. Li, Y. Li, J. Wang, and Z. Chen, "Theoretical investigations on the linear and nonlinear damping force for an eddy current damper combining with rack and gear," *Journal of Vibration and Control*, vol. 28, pp. 1035–1044, 2022.

[22] M. A. Butt, Y. Yang, X. Pei, and Q. Liu, "Five-axis milling vibration attenuation of freeform thin-walled part by eddy current damping," *Precision Engineering*, vol. 51, pp. 682–690, 2018.

[23] H. A. Sodano, J. S. Bae, D. J. Inman, and W. K. Belvin, "Concept and model of eddy current damper for vibration suppression of a beam," *Journal of Sound and Vibration*, vol. 288, pp. 1177–1196, 2005.

[24] B. Ebrahimi, M. B. Khamesee, and F. Golnaraghi, "Eddy current damper feasibility in automobile suspension: modeling, simulation and testing," *Smart Materials and Structures*, vol. 18, no. 1, 2008.

[25] Y. Altintas, *Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design*, Cambridge University Press, Cambridge, UK, 2000.

[26] Y. Altintaş and E. Budak, "Analytical prediction of stability lobes in milling," *CIRP Annals-Manufacturing Technology*, vol. 44, pp. 357–362, 1995.