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An output amplitude model of a giant magnetostrictive rotary ultrasonic machining system considering load effect

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ABSTRACT

The load effect is a key factor influencing the amplitude stability of an ultrasonic machining system during processing. To explore the influence of the load, a giant magnetostrictive rotary ultrasonic machining system was designed and fabricated by utilizing giant magnetostrictive materials. Based on the single-degree-of-freedom vibration characteristics of the ultrasonic oscillator, an output amplitude model that considers the load effect was proposed for the system. In order to validate the model, a rotary ultrasonic drilling experiment of quartz glass was performed. A critical cutting ability parameter on the basis of cutting depth for a single abrasive grain was put forward to differentiate between acceptable and unacceptable ultrasonic performance. The actual ultrasonic amplitude in the machining process obtained from the model was explored. The experimental results indicate that the load has a significant effect on the resonant frequency, resulting in a decrease in the actual ultrasonic amplitude. Moreover, the amplitude characteristics can be considerably improved by tuning. The process parameters of the giant magnetostrictive rotary ultrasonic machining system can be optimized by using the proposed model. The results of this study provide reference data for research and development of rotary ultrasonic machining equipment.

1. Introduction

In rotary ultrasonic machining (RUM), tools coated with abrasives such as diamonds or cubic boron nitride (CBN) rotate at high spindle speed superimposing ultrasonic vibration in the axial or circumferential direction. A large number of experiments have proved that RUM is an effective method to process hard and brittle materials [1–3]. In order to achieve better processing efficiency and surface quality of hard and brittle material workpieces, giant magnetostrictive materials (GMMS), which have the advantages of a large magnetostrictive coefficient, high power capacity, and fast response speed [4,5], were developed to build a giant magnetostrictive rotary ultrasonic machining system (GMRUMS). However, during the machining process, the impact of the load on the ultrasonic machining system is very significant, including the resonant frequency drift of the GMRUMS, resulting in a reduction in the output amplitude and even the failure of the ultrasonic action.

Research has shown that the impact of high-frequency vibration cutting tools on the workpiece has a significant impact on the processing stability due to the complexity of the nonlinear behavior of the machine when variable loads are processed; this makes it difficult to establish excitation and stabilization of the resonant oscillation [6]. Zhang et al. have shown that the spindle speed, feed rate, cutting depth, ultrasonic vibration amplitude, and abrasive size in ultrasonic machining will affect the cutting force, resulting in instability in ultrasonic machining [7]. However, the processing parameters are very complex. The measurement of the ultrasonic amplitude is affected by factors such as the high-speed rotary motion of the spindle, the cutting fluid, and the ultrasonic cavitation [8]. Therefore, it is of great significance to study the vibration characteristics of the GMRUMS while considering the load effect to ensure good processing quality of hard and brittle materials.

To date, many kinds of loads, such as force, liquid, and solid have been used in the ultrasonic vibration system to investigate the impedance, output displacement, etc. Lin et al. used the tool bar as the load part of the transducer and studied the influence of the tool length on the resonant frequency of the transducer [9]. In addition, some scholars have examined the influence of a force load on the performance parameters of GMMS. Zheng et al. [10] analyzed the influence of different stress conditions on the saturation magnetostriction coefficient, hysteresis operator, and coercive field distribution function of GMMS. A quadratic transition model and homogeneous energy field

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hysteresis model, which considered the effect of variable stress, were obtained. Huang et al. [11] compared the dynamic strain under different bias magnetic field and AC magnetic field amplitude and frequency to optimize the design of the structure. However, in RUM, it is difficult to measure the impedance and output amplitude of the ultrasonic machining system under high-speed rotary conditions. Therefore, there are few reports on the variation of the vibration performance of the rotary ultrasonic machining system while considering the load effect.

In this study, a GMRUMS was designed and developed as an accessory of machine tools. An experimental study of rotary ultrasonic drilling (RUD) of quartz glass was conducted and an output amplitude model that considers the load effect was proposed to determine the actual ultrasonic amplitude of the ultrasonic system during processing. The machining performance of the GMRUMS was evaluated based on the proposed parameter of the critical cutting ability, the acceptable and unacceptable ultrasonic performances were determined, and the validity of the model was verified.

2. Output amplitude model and critical cutting ability of GMRUMS

2.1. Structure of GMRUMS

Figure 1 shows the GMRUMS that considers the load effect, where k_L and c_L represent the load stiffness and load damping, respectively. The ultrasonic power supply outputs an electrical signal, which is transmitted through the structure; this causes the excitation coil to generate a high-frequency alternating magnetic field in the magnetic circuit. GMMS are utilized to produce ultrasonic vibration in the alternating magnetic field and the ultrasonic vibration is transmitted and amplified by the horn. The preload acting on the GMMS is produced by the rear cover and the output cover, which are connected by bolts. The compensation circuit ensures the optimal state of the GMRUMS so that the system exhibits pure resistance in the resonant state. The diamond abrasive grains attached to the horn rotate during ultrasonic machining. The specific structural parameters of the GMRUMS are shown in Table 1.

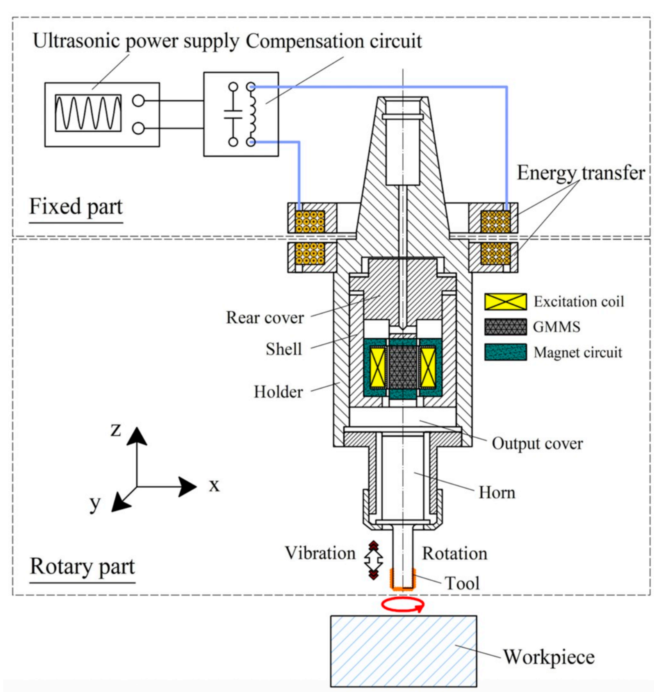

Fig. 1. The structure of the GMRUMS.

Table 1
Parameters of the GMRUMS.

Item	Property (Unit)	Value
Ultrasonic power supply	Frequency (kHz)	0–30
	Power (W)	0–300
Compensation circuit	Capacitance (nF)	0–999
Excitation circuit	Diameter (mm)	0.6
	Turns	180
GMMS (Terfenol-D)	Material	Tb0.3Dy0.7Fe1.92
Rear cover	Material	Stainless steel
Output cover	Material	Aluminum
Horn	Material	45#
Tool	Material	Diamond abrasives

2.2. Output amplitude model

In RUM, a discontinuous contact behavior of "impact-separation-impact" occurs between the acoustic tool and the workpiece. The ultrasonic machining system bears a high-frequency non-linear impact load from the workpiece. Based on the theory of non-linear dynamics, the harmonic linearization method can be utilized to ascertain the high-frequency impact load on the system. Based on the single-degree-of-freedom vibration characteristics of the ultrasonic oscillator, the front-end vibration part of the Terfenol-D rod (including the output cover of the transducer shell and the horn) is equivalent to a single-degree-of-freedom spring-mass-damper system. The equivalent dynamic model of the GMRUMS that considers the interaction force between the structure and the load effect was established, as shown in Fig. 2 (a). Due to the single-degree-of-freedom (*Z*-direction) vibration characteristics of the ultrasonic system, we focus on the cutting force and load stiffness in the *Z*-direction for theoretical modeling and in the experiment and ignore the influence of the forces in the *X*- and *Y*-directions. The displacements of x_1 and x_2 are the displacements of the output ends of the Terfenol-D rod and tool, respectively. The magnetostrictive strain output by the Terfenol-D rod is amplified and transferred to the tool output by the horn. Therefore,

$$x_2 = Mx_1 \tag{1}$$

where M is the amplitude amplification factor.

In a single vibration period, the load stiffness k_L and the load damping c_L can be expressed as functions of the cutting force and actual ultrasonic amplitude, as shown in equation (2) [12,13].

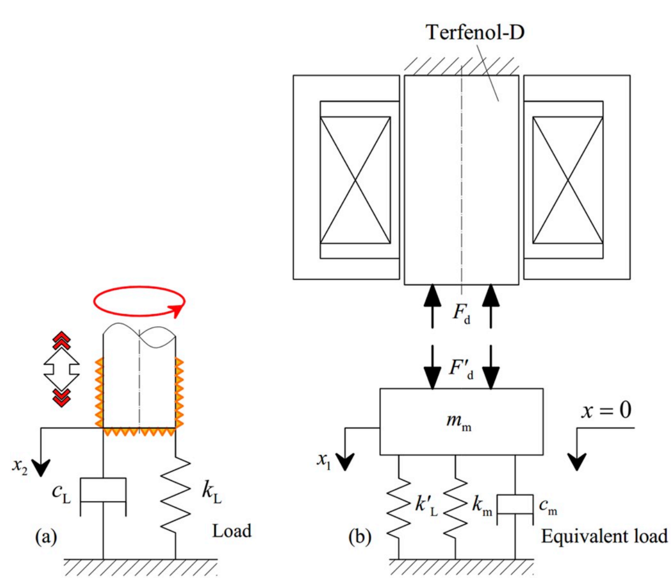

Fig. 2. Kinetic analysis of the GMRUMS during machining: (a) load acting on the tool end and (b) equivalent dynamic model considering the load effect.

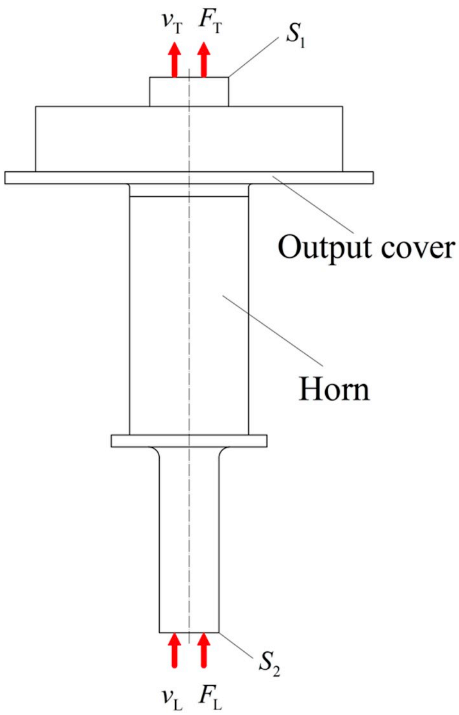

Fig. 3. Transmission characteristics of the load force in the output cover and the horn.

$$\begin{cases} k_L \approx \frac{2F_z}{A'} \\ c_L = 0 \end{cases} \tag{2}$$

where F_z is the average cutting force in a single vibration period and A' is the actual ultrasonic amplitude considering the load effect.

Therefore, the load force F_L of the workpiece acting on the GMRUMS is:

$$F_L = k_L x_2 \tag{3}$$

The load force F_L will drive the GMRUMS to produce reverse vibration. Figure 3 shows the transmission of the reverse vibration in the output cover and the horn. If the mechanical structural damping is neglected, the input and output power should be conserved. Therefore,

$$F_L v_L = F_T v_T \tag{4}$$

where F_T is the force acting on the Terfenol-D rod caused by the load force F_L and the vibration velocities of v_T and v_L are respectively the output speed of the Terfenol-D rod and the output speed of the tool attached to the end of the horn.

According to the vibration amplification characteristics of the mechanical structures, the vibration velocities of the input and output ends should satisfy the following equation:

$$v_T = \frac{v_L}{M} \tag{5}$$

then

$$F_T = MF_L = M^2 k_L x_1 \tag{6}$$

Equation (6) indicates that F_T can be expressed as the equivalent effect of the load force F_L at the output end of the Terfenol-D rod. Since the displacement of the output end of the Terfenol-D rod is x_1, the load stiffness k_L is equivalent to the k_L', which is called the equivalent load stiffness. The equivalent mechanical model shown in Fig. 2 (b) is established; k_L' is defined in equation (7).

$$k_L' = M^2 k_L \tag{7}$$

The output amplitude model of the GMRUMS in an idling condition was obtained from a previous study [14] and is defined in equation (8).

$$\begin{cases} A_I(I_s, f) = \dfrac{\alpha_1 I_s + \alpha_2 I_s^3}{\sqrt{\left(1 - \frac{f^2}{f_n^2}\right)^2 + \left(\frac{2\varsigma f}{f_n}\right)^2}} \\ \alpha_1 = \dfrac{4\chi_1 E_T S_T L_T}{k_m L_T + E_T S_T} \\ \alpha_2 = \dfrac{4\chi_2 E_T S_T L_T}{k_m L_T + E_T S_T} \end{cases} \tag{8}$$

where A_I denotes the idling amplitude, I_s denotes the amplitude of the excitation current, f denotes the frequency of the excitation signal, f_n denotes the idling resonant frequency, and ς denotes the damping ratio of the GMRUMS. The unknown parameters α_1, α_2 consists of E_T S_T L_T, and k_m, which represent Young's modulus and the area, length, and equivalent stiffness of the Terfenol-D rod respectively; χ_1, χ_2 are determined by experiments. Therefore, the output amplitude model that considers the load effect (Fig. 2 (b)) is obtained by combining equations (7) and (8) as follows:

$$\begin{cases} A'(I_s, f) = \dfrac{\alpha_1' I_s + \alpha_2' I_s^3}{\sqrt{\left(1 - \frac{f^2}{f_n'^2}\right)^2 + \left(\frac{2\varsigma f}{f_n'}\right)^2}} \\ \alpha_1' = \alpha_1 \dfrac{k_m L_T + E_T S_T}{k_m L_T + k_L' L_T + E_T S_T} \\ \alpha_2' = \alpha_2 \dfrac{k_m L_T + E_T S_T}{k_m L_T + k_L' L_T + E_T S_T} \\ f_n' = f_n \sqrt{1 + \dfrac{k_L' L_T}{k_m L_T + E_T S_T}} \end{cases} \tag{9}$$

where A' indicates the actual ultrasonic amplitude of the GMRUMS considering the load effect and f_n' is the actual resonant frequency. The coefficients α_1' and α_2' are expressed as functions of the resonant frequencies:

$$\begin{cases} \alpha_1' = \dfrac{\alpha_1 f_n^2}{f_n'^2} \\ \alpha_2' = \dfrac{\alpha_2 f_n^2}{f_n'^2} \end{cases} \tag{10}$$

Equation (9) and equation (10) indicate the following. 1) With the increase in the equivalent load stiffness, the actual resonant frequency of the GMRUMS increases and the coefficients α_1' and α_2' decrease, resulting in a decrease in the ultrasonic amplitude under certain excitation conditions. 2) According to the resonant frequency of the GMRUMS during processing, the ultrasonic amplitude considering the load effect can be calculated.

2.3. Critical cutting ability

During the material removal in RUM, the intermittent contact between the tool and workpiece shortens the effective contact time between the diamond abrasive grains and the workpiece, thus reducing the cutting force and the damage to hard and brittle materials. Figure 4 shows the trajectory of a single abrasive grain [15], where δ represents

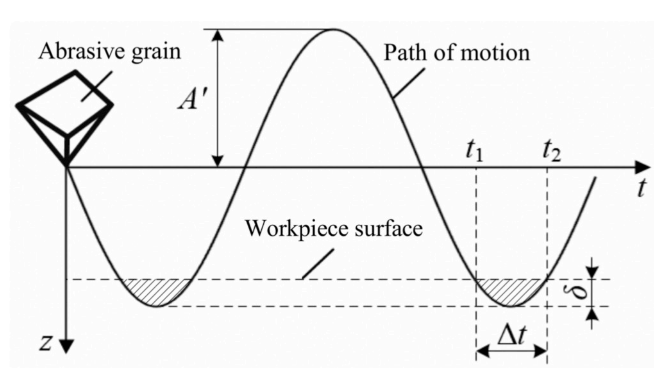

Fig. 4. The trajectory of a single abrasive grain.

the depth of the abrasive penetration into the material (referred to as penetration depth), Δt is the contact time between the abrasive grain and the workpiece, the top dotted line represents the workpiece surface, and the height of the shadowed part represents the penetration depth δ. Due to the very small feed rate relative to the ultrasonic vibration speed, the effect of the axial feed rate on the penetration depth δ can be neglected when a single abrasive particle is observed in a single vibration cycle.

During material processing, every abrasive particle at the tool end removes material from the workpiece. Each abrasive particle can be regarded as a point and the trajectory of each point changes synchronously over time in three-dimensional space. Due to the rotation motion, it can be considered that the workpiece surface processed by a single abrasive particle is different in each vibration period and the penetration depth represents the depth of the abrasive particles entering the material during machining. The maximum displacement of the abrasive particles occurring in a single vibration period is $2A'$, where A' represents the amplitude of the abrasive particles. If the penetration depth is greater than $2A'$, the end face of the horn (the non-abrasive part) enters the material's interior. Because the non-abrasive part cannot remove much material from the workpiece, the penetration depth cannot be greater than $2A'$. Thus, the critical value of the penetration depth is $2A'$. Therefore, when the penetration depth is equal to $2A'$, the intermittent contact between the tool and the workpiece will change into continuous contact, the advantage of RUM will be weakened, and the cutting force will increase rapidly [16]. In addition, increasing the penetration depth will increase the cutting force and the load stiffness in the machining process. Equation (9) shows that the ultrasonic amplitude will decrease with an increase in the load stiffness under certain excitation conditions. Therefore, it is proposed that the critical penetration depth of RUM is $\delta_{\lim}$. The relationship between the vibration amplitude and the critical penetration depth is defined in equation (11).

$$\delta_{\lim} = 2A' \tag{11}$$

In order to ensure good performance of RUM, suitable processing parameters and ultrasonic parameters should be selected so that the actual penetration depth is less than the critical value. In order to guide the selection of the process parameters for actual machining, the relationship between the process parameters and the penetration depth in RUD was analyzed.

Figure 5 (a) is a schematic diagram of RUD, where d_5 is the diameter of the tool and β is the helix angle. In the process of RUD, the abrasive

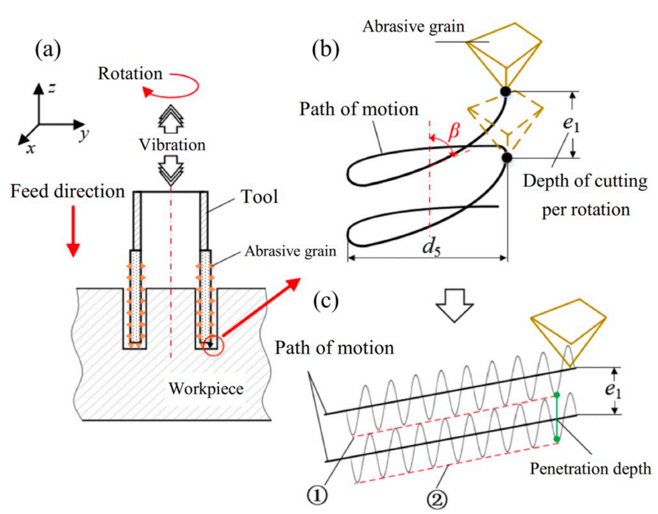

Fig. 5. Diagram of the cutting depth of a single abrasive grain: (a) diagram of RUD, (b) the three-dimensional trajectory, and (c) the equivalent two-dimensional trajectory.

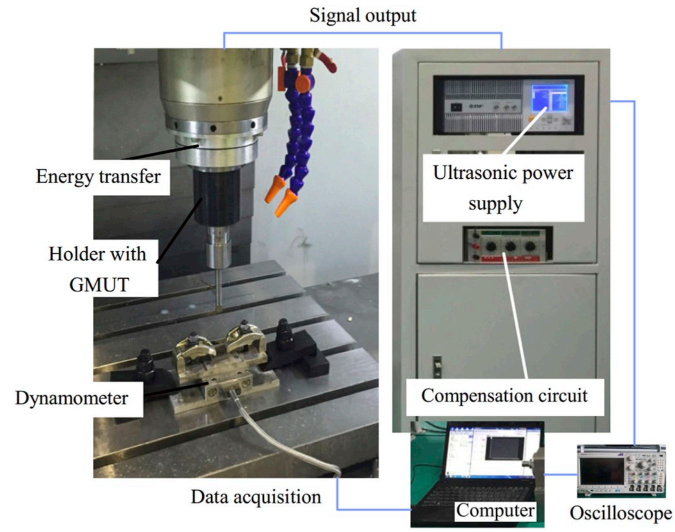

Fig. 6. Experimental apparatus.

grains on the end face of the tool rotate, superimposing ultrasonic vibration on the feed motion in the axial direction; this phenomenon plays a major role in material removal. The analysis of a single abrasive grain on the end face of the tool indicates that the movement path of the abrasive grain is the superposition of three kinds of motion, including ultrasonic vibration, rotary motion, and feed motion. Considering both the rotary motion and feed motion, the abrasive grains will cut into the workpiece by following a helix pattern, as shown in Fig. 5 (b). The three-dimensional trajectory of the abrasive grains is expanded into a two-dimensional trajectory, as shown in Fig. 5 (c). The trajectory of the abrasive grains represents the trajectory of the balanced position of the abrasive vibration. Lines ① and ② are the trajectories left by a single abrasive grain on the workpiece after two revolutions of the tool. Therefore, the depth of the abrasive grains entering the material in the single vibration process should be equal to the distance between lines ① and ②.

It can be seen that the penetration depth in the RUD is equal to the depth of cutting per rotation e_1. According to the relationship between the critical penetration depth and the actual ultrasonic amplitude, the critical feed rate is defined as follows.

$$v_f' = 2A'n \tag{12}$$

where v_f' is the critical feed rate, n is the spindle speed.

In this study, the critical cutting ability depends on the critical feed rate. For a given ultrasonic amplitude, the relationship between the critical feed rate and the spindle speed can be determined to avoid ultrasonic failure. As shown in this study, it can be predicted that when the actual feed rate reaches or exceeds the critical feed rate, which indicates that the GMRUMS has reached the critical cutting state, the RUM performance will decrease, the abrasive particles will no longer have an intermittent impact on the workpiece, and the resonant frequency and cutting force of the ultrasonic machine tool will increase, which negatively affect the quality and efficiency of the workpiece processing.

Equation (12) indicates the following: 1) An increase in the ultrasonic amplitude and spindle speed increases the critical feed rate in RUD. 2) The range of the effective process parameters in RUD can be calculated based on the ultrasonic amplitude that considers the load effect; 3) During the drilling process, the ultrasonic amplitude of the GMRUMS cannot be measured directly and it is difficult to measure the ultrasonic amplitude based on the dimension of the machined workpiece. In order to verify the output amplitude model of the GMRUMS considering the load effect, the actual ultrasonic amplitude during the drilling process can be calculated using equation (12). In addition, it

Table 2
Experimental parameters of RUD.

Group	Idling amplitude A_I (μm)	Spindle speed n (r/min)	Feed rate v_f (mm/min)
1	18	1000	1、2、3、4、5
2		2000	1、2、3、4、5、6、8
3		3000	1、2、3、4、5、6、8

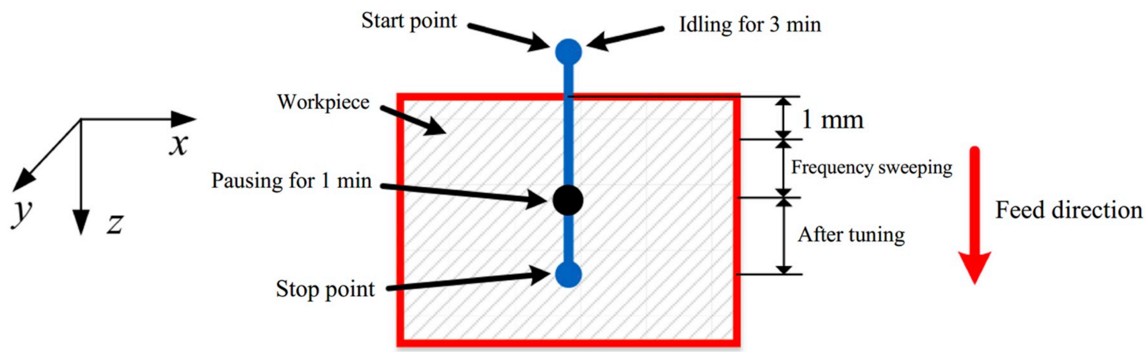

Fig. 7. Tool path in the experimental verification test.

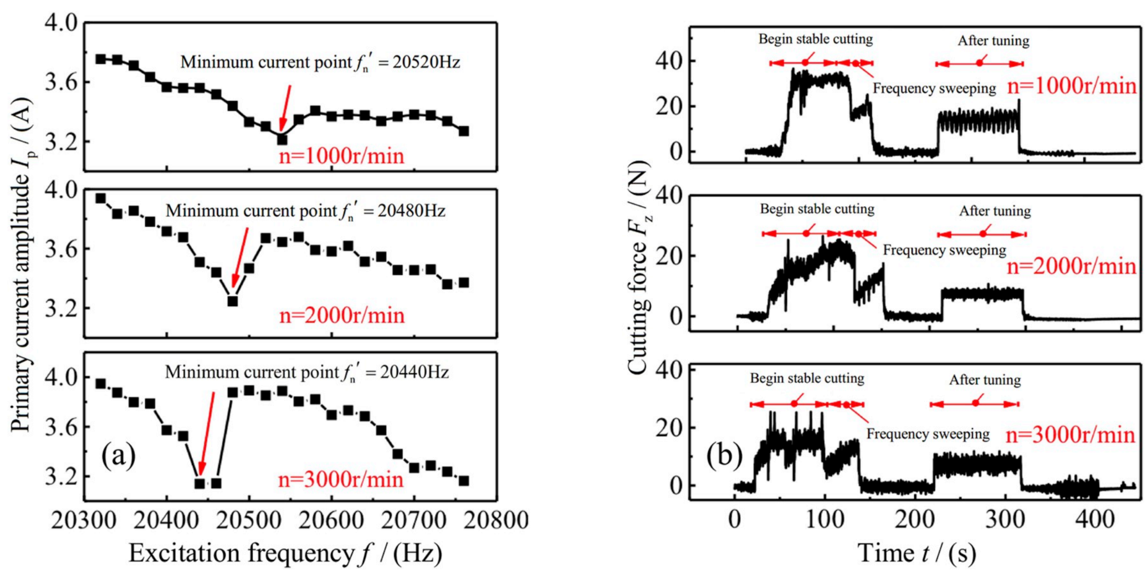

Fig. 8. Sweep frequency signals and cutting forces for different process parameters ($v_f = 2$ mm/min): (a) primary current amplitude and (b) cutting force.

can be determined that the ultrasonic system has reached the critical cutting ability if the cutting force rises sharply when the feed rate is changed; this is indicated by the abrupt increase in the slope of the cutting force curve corresponding to the feed rate during drilling. This phenomenon can be used to verify the output amplitude model that considers the load effect.

3. Experimental verification

3.1. Experiment apparatus and experimental scheme

The experiments were carried out on the independent-developed GMRUMS, as shown in Fig. 6. The ultrasonic power supply was used to generate primary excitation signals with different frequencies and voltage amplitudes, converting the primary excitation signal into the secondary excitation signal through energy transfer; the signal was monitored by an oscilloscope (MDO3041). The compensation circuit ensured that the GMRUMS exhibited pure resistance in the resonant state. The sampling frequency of the oscilloscope was 200 kHz. A Kistler 9256C2 dynamometer was used to measure the cutting force during the machining process. The computer was utilized for data acquisition and signal output. The actual resonant frequency was identified by acquiring current signals and the actual ultrasonic amplitude was calculated using the proposed model.

The experimental parameters are shown in Table 2. In the experimental verification test, quartz glass was used as the workpiece material. The size of the workpiece was 40 mm × 40 mm × 6 mm, the amplitude of the primary excitation voltage was constant at 35 V, and the idling amplitude was 18 μm.

The tool path in the experiment is shown in Fig. 7. Before the experiment, the GMRUMS was run for 3 min under an idle condition to reach the thermal equilibrium state. At this time, the resonant frequency of the GMRUMS was 20360 Hz. The excitation frequency was set to the resonant frequency of the GMRUMS under an idle condition. When the system entered the stable cutting condition (the cutting depth was 1 mm), the sweep frequency signal was used to excite the ultrasonic system. The sweep frequency step distance was analyzed according to the electrical characteristics of the GMRUMS. If the step distance is too

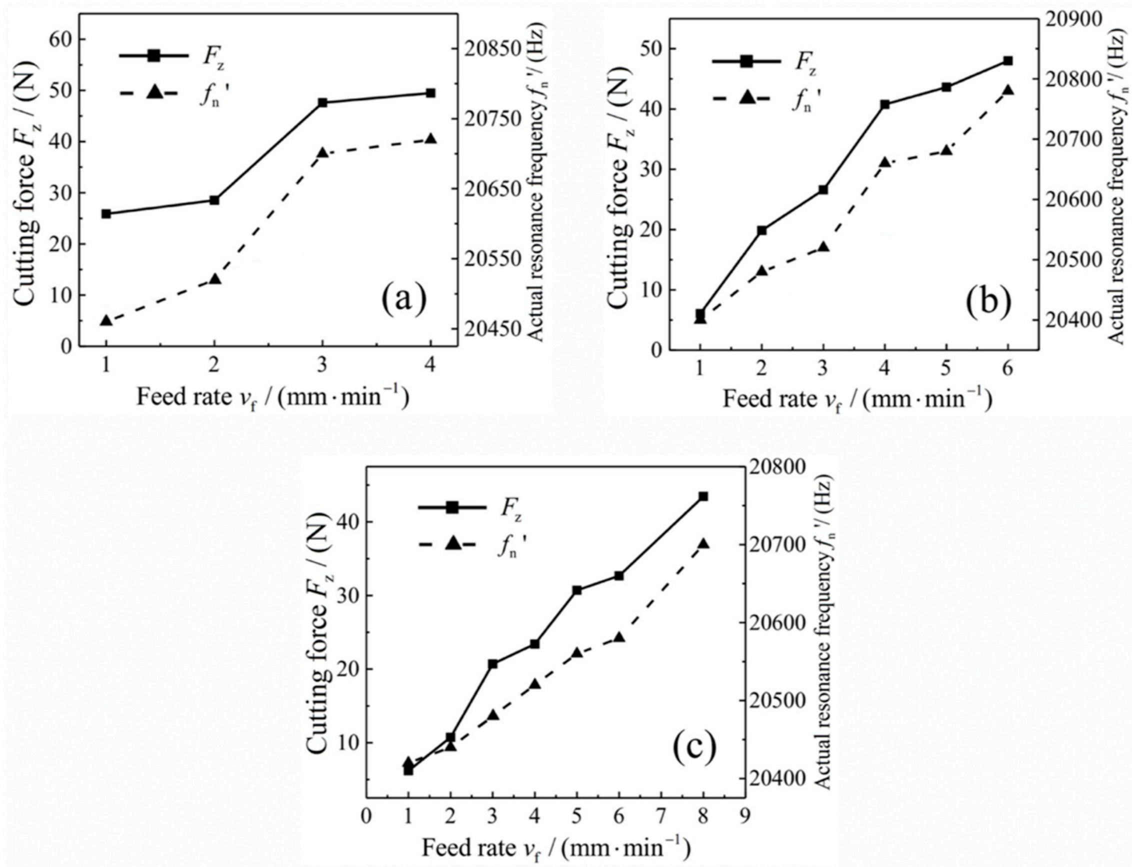

Fig. 9. Cutting force and actual resonant frequency versus the feed rate: (a) 1000 r/min, (b) 2000 r/min, and (c) 3000 r/min.

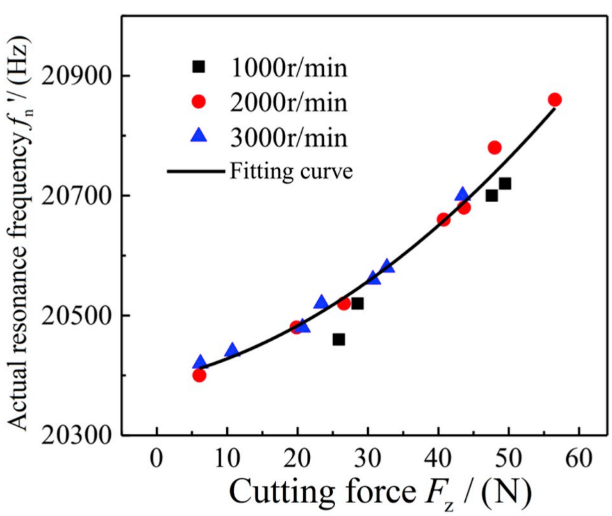

Fig. 10. The relationship between the actual resonant frequency and the cutting force of the GMRUMS.

large, the characteristic points of the collected data cannot be obtained, which results in an experimental error and inaccurate frequency values corresponding to the minimum current. If the step distance is too small, there are disturbances in the environment, increasing the difficulty of data processing and prolonging the time of signal action, which leads to further errors in the experiment caused by the eddy current effect. Considering the various influences, the sweep frequency range was 20240 Hz to 21220 Hz, with a 20 Hz step distance in this experiment. The primary current amplitude at the excitation frequency was measured.

3.2. Actual resonant frequency

In order to obtain the actual resonant frequency during machining, the experiments were conducted according to the selected experimental scheme; the results are shown in Fig. 8. Figure 8 (a) shows the primary current amplitude versus the excitation frequency and Fig. 8 (b) shows the cutting force data during the cutting process.

As shown in previous research [17], when the system reaches the optimal compensation state, the primary current amplitude under a certain excitation voltage is minimized in the resonant state of the GMRUMS. Therefore, the actual resonant frequency corresponding to the minimum current for different cutting forces can be determined by conducting a short-time sweep experiment of during machining. The actual resonant frequency of the GMRUMS during the process was determined (Fig. 8 (a)), and the system was tuned. During machining, the cutting force was considered during the stable drilling process.

The results shown in Fig. 8 indicate that 1) the actual resonant frequency of the GMRUMS is higher during the machining process than in the idle condition, which verifies the influence of the load on the resonant frequency of the GMRUMS. 2) For the different process parameters, the cutting force is significantly lower after tuning, which indicates that the actual resonant frequency obtained by searching the current minimum is accurate. By tuning, the ultrasonic amplitude is increased and the cutting force is reduced, which shows that resonant frequency tracking is of great significance to ensure the RUM performance.

3.3. Actual ultrasonic amplitude

In order to validate the output amplitude model that considers the load effect, the ultrasonic amplitude of the GMRUMS was further investigated. The actual resonant frequencies corresponding to different

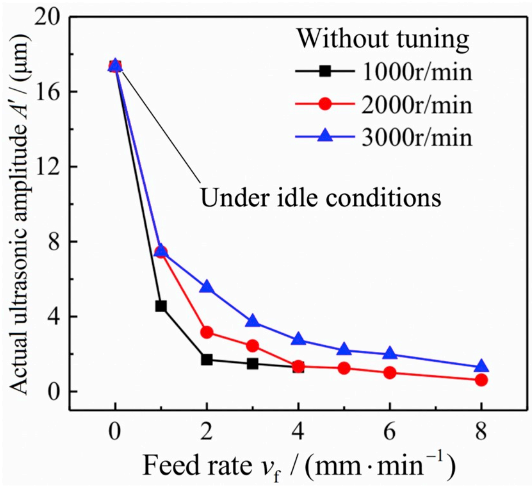

Fig. 11. The actual ultrasonic amplitude of the GMRUMS for different process parameters.

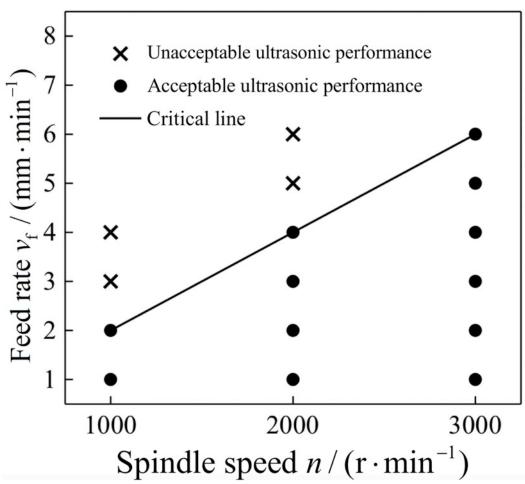

Fig. 12. The range of the processing parameters at different spindle speeds (excitation voltage amplitude: 35 V).

cutting forces were obtained at different spindle speeds; the relationships between the different process parameters, actual resonant frequencies, and cutting forces are shown in Fig. 9. The results indicate that when the load effect is considered, the actual resonant frequency and cutting force increase with the increase in the feed rate and the parameters have a similar trend at different spindle speeds. Therefore, the relationship between the actual resonant frequency and the cutting force was established, as shown in Fig. 10.

As shown in Fig. 10, the actual resonant frequency of the GMRUMS during the machining process is positively correlated with the cutting force and the fitting curve is the same, regardless of the process parameters. Therefore, the actual resonant frequency of the GMRUMS can be determined based on the cutting force.

The actual ultrasonic amplitude A', as shown in Fig. 11, can be calculated by combining equation (9) and equation (10).

Figure 11 shows that the actual ultrasonic amplitude of the GMRUMS decreases with the increase in the feed rate for a constant excitation signal. Due to the high mechanical quality factor of the GMRUMS, the actual resonant frequency drift caused by the processing load results in a reduction in the actual ultrasonic amplitude. At the same feed rate, the larger the spindle speed, the smaller the rate of decrease in the actual ultrasonic amplitude is. In addition, the ultrasonic amplitude remains at about 18 μm when the feed rate is zero (i.e., under idle conditions) but at the feed rate of 1 mm/min, the ultrasonic amplitude decreases rapidly by less than 50% for all three spindle speeds. With the increase in the feed rate, the ultrasonic amplitude continues to decrease significantly, which negatively affects the RUM performance decreases significantly, resulting in an increase in the cutting force and a decrease in the processing efficiency. Therefore, the GMRUMS cannot be operated without tuning. This shows that automatic tracking of the resonant is a key factor in high-power ultrasonic vibration processing.

3.4. Critical feed rate and model verification

Due to the difficulty of measuring the actual ultrasonic amplitude during RUD, it is impossible to verify the correctness of the theoretical calculation results directly. As shown in Fig. 11, the critical feed rate, which is obtained using equation (12), is used to determine whether the ultrasonic performance is acceptable for the different processing parameters. Figure 12 shows the range of effective processing parameters for ultrasonic machining under certain excitation conditions (excitation voltage amplitude: 35 V). It is evident that the critical feed rate of the GMRUMS can be increased by increasing the spindle speed.

By validating the effective cutting range, the actual ultrasonic amplitude of the GMRUMS can be indirectly verified. Therefore, the relationship between the feed rate and the actual resonant frequency and the cutting force for different process parameters was determined, as shown in Fig. 13.

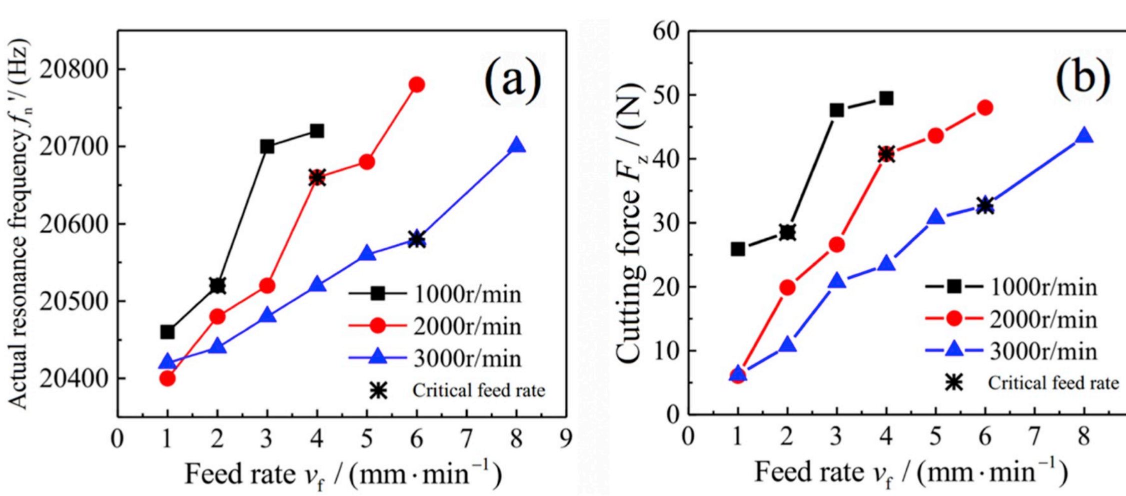

Fig. 13. Actual resonant frequency and cutting force versus the feed rate: (a) actual resonant frequency and (b) cutting force.

Considering the experimental error, when the feed rate approaches the value of the theoretical critical feed rate, it can be seen from the theoretical prediction that the actual resonant frequency and the cutting force both sharply increase simultaneously. The experimental results obtained for the y-values corresponding to the x-values of 2 and 3 for 1000 r/min, for the y-values corresponding to the x-values of 3 and 4 for 2000 r/min, and for the y-values corresponding to the x-values of 6 and 8 for 3000 r/min (Fig. 13 (a) and (b)) verify the conclusion obtained from the model. The reason for these results is that when the feed rate reaches or exceeds the critical value, the contact type between the abrasive grains and the workpiece changes from intermittent contact to continuous contact, which results in an increase in the cutting force, indicating that the theoretical critical feed rate is correct. However, the number of experimental groups needs to be higher to minimize the experimental error. It can be inferred that the theoretically calculated ultrasonic amplitude is correct, and the output amplitude model that considers the load effect is verified.

4. Conclusion

In this study, we investigated the load effect on the vibration performance of the GMRUMS and established an output amplitude model of the GMRUMS that considers the load effect. The model was verified by evaluating the proposed critical cutting ability parameter. The following conclusions are drawn:

1. The load had a significant effect on the actual resonant frequency of the GMRUMS during machining. Due to the load, the actual resonant frequency of the GMRUMS increased and deviated from the excitation frequency of the ultrasonic power supply, resulting in a decrease in the actual ultrasonic amplitude of the GMRUMS.
2. The actual ultrasonic amplitude can be increased by tuning, thereby reducing the cutting force. Automatic tracking of the resonant frequency is important to ensure stable machining performance of the GMRUMS.
3. At a given feed rate, an increase in the spindle speed reduced the penetration depth per rotation, reducing the cutting force and the resonant frequency drift and improving the actual ultrasonic amplitude. As a result, the critical cutting ability of the GMRUMS was improved, thereby improving the performance.

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