

Prediction and Analysis of Milling Stability Under Multi-Effect Synergy

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Abstract: In the milling process is often accompanied by a lot of vibration, these vibrations will lead to the instability of the processing process resulting in the occurrence of chatter, chatter in the process will seriously affect the processing efficiency, reduce the quality of processing, so the mechanism of chatter and influencing factors to study, and through the analysis of stable milling processing parameters, to achieve efficient precision machining is very important. In this paper, based on the traditional milling model, the regeneration effect, process damping effect and modal coupling effect are taken into account, and the friction effect of the front cutter face is also taken into account for frictional chatter to make the prediction range of the model more accurate. Then, a milling dynamic model was established combining various effects, and the stability lobe diagram was solved by the fully discrete method. The influence of each effect on milling stability was analyzed and the influence of friction effect was emphatically discussed. Finally, the accuracy of the model was verified by the milling stability experiment.

Keywords: Regenerative flutter, Frictional flutter, Multi-effect coupling, Stability analysis.

1. Introduction

With the rapid development of aerospace and other industries, flutter has become an urgent problem in the field of efficient milling. At present, it is one of the important methods to solve milling stability by constructing system dynamics equation and drawing stability lobe diagram. Compared with traditional empirical method, this method can realize milling without chatter more efficiently and accurately from the theoretical perspective, which has important engineering guiding significance..

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In recent years, many scholars have conducted a lot of research on the prediction of milling chatter stability. Eynian and Altintas[1] established a milling system dynamics model taking into account process damping changes. Iturraspe et al. [2] analyzed orthogonal cutting using the state-space theory and pointed out that the cross action of stiffness, damping and natural vibration modes of the system determined the modal coupling effect. Ahmadi[3] et al. will use multi-frequency analytic method and semi-discrete method to analyze the equivalent viscous model in process damping and draw the stability lobe diagram, compare the two methods and illustrate the influence of process damping on the milling stability in low speed zone. Lu[4] et al. adopted robust discrete vector method to identify the joint surface (CWE) between the cutter and the workpiece of the flat end milling cutter of the five-axis machine tool, and analyzed and predicted the milling stability of the five-axis machine tool by combining regeneration effect and modal coupling effect. Li et al. [5] established a dynamic model considering both modal coupling and regeneration effects, and adopted second-order semi-discrete method to solve milling stability. Based on the semi-discrete analytic method, Ding[6] et al. proposed a fully discrete analytic method that discretized both the state term

and the delay term in the delay differential equation, which improved the efficiency of solving. Ji et al. [7] established a dynamic model considering regeneration effect, modal coupling effect and process damping effect at the same time, studied the influence of multi-factor coupling on the stability, and used the fully discrete method to predict the stability of the system more efficiently and accurately. With the continuous development of the manufacturing industry, the precision and efficiency of parts processing requirements are increasingly high, it is necessary to establish a more refined dynamic model to predict the milling stability more accurately, so the milling model only consider regeneration chatter is difficult to achieve high precision requirements. Therefore, some scholars began to study other types of chatter, among which friction chatter is the focus of current research. Friction chatter refers to the friction between the front or back tool face and the chip due to the relative motion in the cutting process, and the friction coefficient between the two decreases with the increase of the relative speed between the tool and the chip. The vibration caused by the friction between the chip and the workpiece is called frictional vibration. Slim[8] et al., in order to describe the thermodynamic relationship between cutting tools and cutting, modeled chip formation in the cutting process and studied the friction phenomenon of secondary shear zone. Yan[9] et al. studied the influence of frictional flutter by establishing stribeck friction model of friction coefficient and relative velocity between cutter and chip, and proved through experiments that the dynamic model considering frictional flutter could better predict milling stability in low speed region. In order to build a more complete model and predict milling stability more efficiently and accurately, a dynamic model combining regeneration effect, process damping effect, modal coupling effect and friction effect was established, and a more efficient fully discrete analytical method was used to predict the stability of the system, and the stability blade diagram was drawn to analyze the influence of each effect on the stability. Finally, combined with the stability lobe diagram, the stability verification experiment was carried out in a vertical machining center to verify the accuracy of the model.

2. Establishment of Dynamic Model

2.1. Section Headings

For the milling dynamic model, only the vibration of the tool and the workpiece in the X-Y plane was considered, and the two-degree-of-freedom milling dynamic model was constructed, as shown in Figure 1.

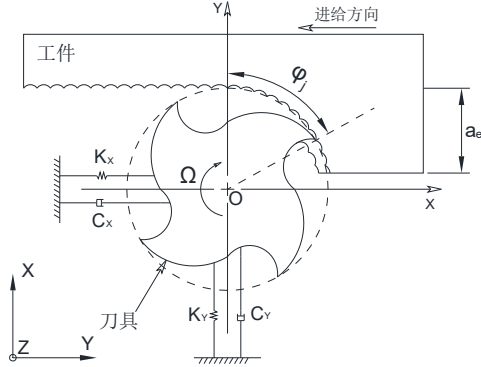


Figure 1. Dynamic model of milling with two degrees of freedom

After the dynamic model is established, the milling force needs to be modeled and the cutter is discretized into M micro-elements along the axial direction. For each element we can approximate the helix Angle to 0° ,

Then, the relationship between the instantaneous instantaneous immersion Angle of the l ($l=1 \dots M$) element on the J -th ($j=1 \dots N$) cutting edge and the spindle speed and time can be expressed as

$$\phi_{j,l}(t) = \phi(t) + (j-1)\phi_p + \Psi_j(z) \quad (1)$$

$\phi(t) = 2\pi\Omega t/60$ is the rotation Angle of the spindle, that is, the angular position of the reference cutting edge when it passes t , Ω [rad s^{-1}] is spindle speed, $\phi_p = 2\pi/N$ is the Angle between teeth, Namely, the Angle between the J -th cutting edge and the reference cutting edge, N is the number of teeth. $\Psi_j(z)$ is the lag Angle of the cutting edge element.

The shear force is modeled by mechanical model, that is, it is assumed that the shear force is proportional to the cross-sectional area, and the proportional coefficient is determined by the geometric parameters of the tool and the characteristics of the material, then the shear force is expressed as

$$F_{t,j,l} = K_t \Delta a h_{j,l}(t) \quad (2)$$

In the process of cutting the workpiece, the tool moves to the workpiece with the feed speed v . When the workpiece is deformed in the main cutting area, the front tool surface extruded the workpiece to produce extrusion pressure between the chip and the tool, and the chip produces relative motion between the chip and the tool in the process of cutting, which makes the friction between the tool and the chip, then

$$F_f = \mu F_t \quad (3)$$

The cutting force of the front cutter face can be regarded as the resultant force of the friction between the chip and the tool and the crushing pressure between the chip and the tool. Refer

to [11], as shown in FIG. 1-4. For the equivalent friction coefficient μ , due to the low relative sliding velocity, the stribek friction model was established by referring to [10]

$$\mu = \text{sign}(V_r) \left(\mu_d + (\mu_s - \mu_d) \exp\left(-\frac{|V_r|}{V_s}\right) \right) \quad (4)$$

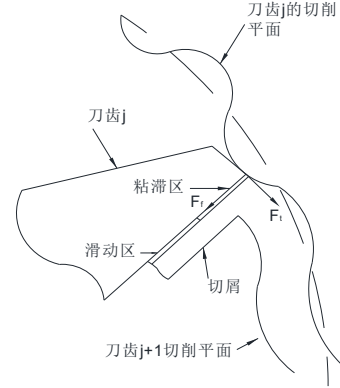


Figure 2. The geometric relationship between cutting tools and chips

The friction force and shear force of the front cutter face were decomposed into X and Y directions, and the efforts of all cutter teeth were obtained

$$\begin{aligned} F_x(t) &= \sum_{j=1}^N g(\phi_{j,l}(t)) [-\sin \phi_{j,l}(t) \quad -\cos \phi_{j,l}(t)] [F_f \quad F_t]^T \\ F_y(t) &= \sum_{j=1}^N g(\phi_{j,l}(t)) [\sin \phi_{j,l}(t) \quad -\cos \phi_{j,l}(t)] [F_t \quad F_f]^T \end{aligned} \quad (5)$$

$g(\phi_{j,l}(t))$ is the unit step function, whose function is to determine whether the cutter teeth participate in cutting within a cycle. Where, is the cutting Angle when the cutter teeth start to cut into the workpiece, and is the cutting Angle when the cutter teeth leave the workpiece. Down milling time

$$\phi_{st} = \arccos(2a_D - 1), \quad \phi_{ex} = \pi$$

Reverse milling time

$$\phi_{st} = 0, \quad \phi_{ex} = \arccos(1 - 2a_D)$$

Where is the radial invasion ratio.

For the rear cutter face, extrusion will occur between the rear cutter face and the workpiece in the cutting process, resulting in process damping force, which can be expressed as

$$F_{tp} = \mu F_{rp} \quad (6)$$

$$F_{rp} = g(\phi_{j,l}(t)) C_{eq} \dot{q} \quad (7)$$

where C_{eq} is equivalent damping coefficient, K_{sp} is compression coefficient, a_p is axial cutting depth, μ is coulomb force coefficient, W_j is the width of tool wear zone.

In summary, the dynamic model of the system combining the front and back cutter surfaces can be expressed as

$$M\ddot{q} + C\dot{q} + Kq = a_p H(q(t) - q(t-T)) + C_{eq} G \dot{q}(t) \quad (8)$$

M is the mass matrix of the system, C is the damping matrix of the system, K is the stiffness matrix of the system, and

$$M = \begin{bmatrix} m_{xx} & m_{xy} \\ m_{yx} & m_{yy} \end{bmatrix} \quad C = \begin{bmatrix} c_{xx} & c_{xy} \\ c_{yx} & c_{yy} \end{bmatrix} \quad K = \begin{bmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{bmatrix}$$

Gyroscopic effect [8] is an effect that cannot be ignored in the process of high-speed milling. Precession will occur in the

process of high-speed rotary machining, which changes the natural frequency of the system. Moreover, positive precession is considered for the cutting tool in milling, that is, the change of natural frequency increases with the increase of rotational speed. The tool is equivalent to a cantilever beam to solve the natural frequency under the influence of gyro effect, i.e. [12]

$$\omega_n = \left[r^2 \omega^2 \frac{A_n}{l^2} + \omega_0^2 \right]^{1/2} \quad (9)$$

Where r is the turning radius of the tool bar with respect to the diameter of the unit length; l is the overhanging length of the tool bar; A_n is the mode shape coefficient; ω_0 is the natural frequency of the cantilever tool bar without considering the gyroscope effect; ω is the rotational speed of the tool bar.

3. Prediction of Milling Stability with Multi-effect Collaboration

The kinetic equation is transformed into delay differential state space equation

$$\dot{X}(t) = A_0 X(t) + A(t)X(t) + B(t)X(t-T) \quad (10)$$

Among them

$$A_0 = \begin{bmatrix} -\frac{M^{-1}C}{2} & M^{-1} \\ \frac{CM^{-1}C}{4} - K & -\frac{CM^{-1}}{2} \end{bmatrix} \quad (11)$$

$$A(t) = \begin{bmatrix} 0 & 0 \\ -\frac{GM^{-1}C}{2} + a_p H & GM^{-1} \end{bmatrix} \quad (12)$$

$$B(t) = \begin{bmatrix} 0 & 0 \\ a_p & 0 \end{bmatrix} \quad (13)$$

By solving the state-space equation, the stability lobe diagram with spindle speed as the horizontal coordinate and axial cutting depth as the vertical coordinate was drawn to predict the milling stability. The full discrete analytic method [6] is adopted to solve the problem. The stability of the system is judged according to Floquet theory. When the modulus of all eigenvalues of the state transition matrix is less than 1, the system is in a stable state. Otherwise, it is in an unstable state.

4. Multieffect Milling Stability Prediction

According to the modal parameters and the tool, the system dynamics equation was solved by the fully discrete method, and the stability lobe diagram was drawn to verify the stability of the model and analyze the influence of each effect on the stability.

For the study of the influence of various effects on the stability, the first order full discrete method is used to analyze and solve the model of different effects coupling. Milling cutter diameter $D=20\text{mm}$, number of teeth $N=2$, milling force coefficient, discrete number of 50, radial invasion ratio $aD=0.5$, milling mode is down milling.

Each single effect is removed through the stability lobe diagram and then compared with the multi-effect synergy

curve to analyze the influence of a single effect on the system

For the process damping effect, it can be seen that the stability region of the system without considering the process damping effect decreases to a certain extent in the whole speed range and gradually decreases with the increase of the speed. In the speed range of (0-6000rpm), the stability region decreases significantly. It can be seen that due to the introduction of various effects, The speed region of the system under the influence of process damping effect has changed. However, due to the generation mechanism of process damping, the thrust volume of the rear cutter face is directly related to the influence of process damping, so it mainly affects the stability of the low speed region. See Figure 5 for stability lobes.

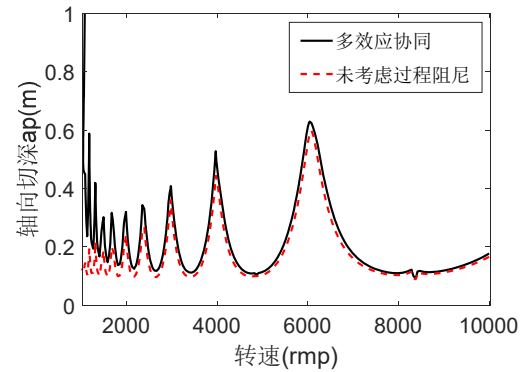


Figure 3. Analysis of process damping effect on the lobe diagram

The modal coupling effect is caused by many factors, not only from the cross terms of tool structure, but also from the workpiece or machine tool. Combined with the stability lobe figure 6, it can be seen that the modal coupling effect can improve the stability region of the system, and its influence on the stability of the system is mainly reflected in the influence on the trough of the lobe diagram and is reflected in the whole speed range. Therefore, the influence of modal coupling effect on stability domain cannot be ignored.

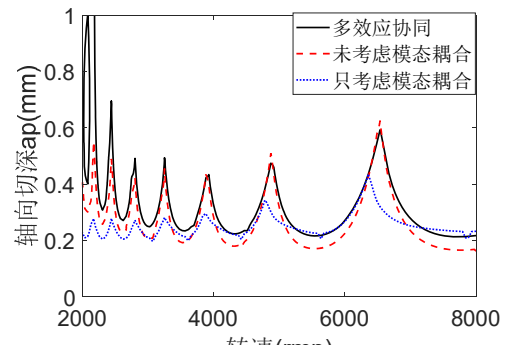


Figure 4. Modal coupling affects the lobe pattern

As can be seen from FIG. 7 of the stability lobe diagram, the influence of friction effect on the system is mainly reflected in the low speed zone, because with the increase of the tool speed, the viscous zone of the front tool face gradually decreases, and the front tool face will enter the sliding zone faster. Therefore, the influence of friction effect will gradually decrease with the increase of the speed. Combined with the stability lobe diagram, it can be seen that the friction effect will reduce the stability of the low speed

region, mainly because at low speed, the viscous zone between the tool and the workpiece is large, so that the friction between the chip and the tool is larger, thus affecting the stability of cutting. Only considering the friction effect has little effect on the stability of the system, but considering the synergistic effect of multiple effects, the effect of friction effect cannot be ignored.

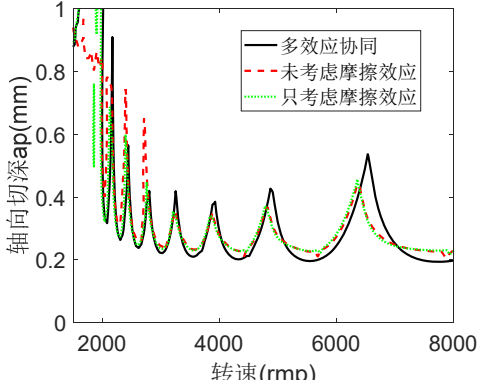


Figure 5. Comparison of friction effects

Considering the gyroscopic effect, due to the increase of the tool's natural frequency, the stiffness of the tool in the process of cutting at high speed will increase, and its stability will also be improved. According to the comparison of the stability lobe diagram in FIG. 8, the blade diagram without considering the gyroscopic effect and the blade diagram with the synergistic effect of multiple effects, it can be seen that the gyroscopic effect is the main factor affecting the stability of the tool in high-speed milling. Moreover, compared with the system that only considers gyro effect, the system considering multiple effects still has some differences in the high-speed region. It can be seen that if the stability needs to be predicted more accurately in the high-speed region, it is still necessary to establish a prediction model under the synergistic effect of multiple effects.

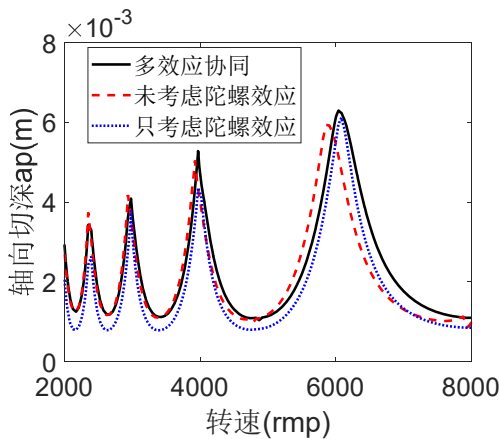


Figure 6. Comparison of gyroscopic effects

Combined with the above analysis, it can be seen that the speed is the main reason affecting the effect of process damping effect, friction effect and gyroscope effect. In the low speed region, the main effect includes process damping effect and friction effect. The mechanism of process damping effect is the interference between the rear cutter surface and the workpiece corrugated surface, and its influence on the stability of the low speed region cannot be ignored. Considering process damping effect, the stability of low

speed region can be greatly improved. For the friction effect, a single consideration of the friction effect on the stability of the system is not outstanding, but combined with the effects of multiple effects, friction effect is another important factor affecting the low speed zone, considering the friction effect can achieve a more precise prediction and analysis of milling stability, improve the efficiency of teaching. In the process of high speed milling, the damping effect and friction effect have little influence. Gyro effect is the main factor affecting the stability of the system in high speed milling. When the efficiency of stability prediction of high speed system is emphasized, the gyro effect alone can get higher results. However, the improvement of the stability region of the system can not be ignored by the stability system under the multi-effect synergy. If more precise stability prediction is needed, the stability model considering the multi-effect synergy will be a better choice.

In order to verify the accuracy of the model under the synergistic effect of multiple effects, the stability verification experiment was carried out on the numerical control machine tool, and the Kistler milling force test system was used to verify the experiment. The experimental tool material is hard alloy, the tool parameters are the same as the above parameters, the workpiece material is aluminum alloy, the size is 50×60×100mm, the workpiece adopts different spindle speed and axial cutting depth combination for the experiment, the milling method adopts downmilling. Due to the influence of multiple effects on the whole speed region, different axial cutting depths were selected for experiments at different speed ranges. The measured milling forces at point A (4800rpm,0.007m) and B(4800rpm,0.008m) were taken for Fourier transform to obtain their spectral maps

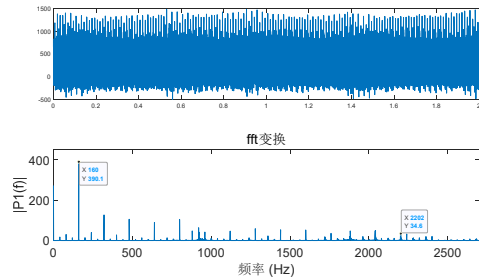


Figure 7. The spectrum diagram of milling force measured at point A

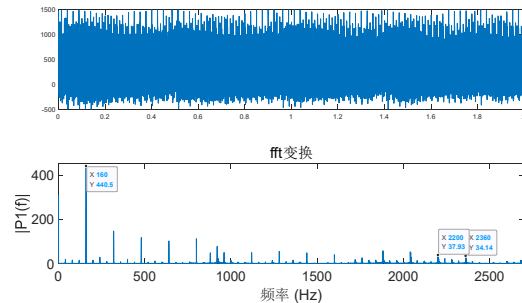


Figure 8. The spectrum diagram of milling force measured at point B

Combined with the time-frequency diagram and workpiece surface morphology, it can be seen that there is no flutter frequency at point A and the workpiece surface is relatively flat, it can be known that it is stable milling. In the spectrum diagram at point B, there is flutter frequency near the natural frequency of the tool and vibration marks on the workpiece

surface, it can be known that there is flutter at point B during machining. The processing conditions of each parameter combination obtained by the experiment are compared with the stability lobe diagram, as shown in the figure. X indicates the tested flutter points, Δ indicates the tested steady milling points, and \triangle indicates the boundary points, as shown in Figure 9.

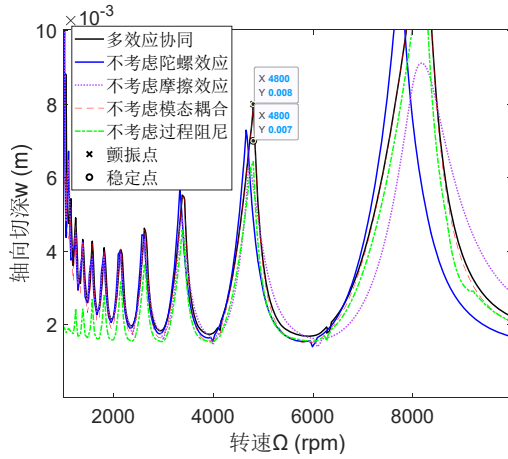


Figure 9. Stability verification diagram

It can be seen that the experimental results are basically consistent with the stability prediction vane diagram, so the milling stability prediction model considering the multi-factor coupling of the milling model is accurate.

5. Summary

(1) Considering the multi-factor collaborative milling model, and considering the regeneration effect, process damping effect, modal coupling effect, gyroscopic effect and friction effect, the fully discrete analytical method is used to predict the stability. The stability flap diagram is drawn to realize the non-flutter machining, improve the machining efficiency and optimize the process parameters, which provides the theoretical basis and data support.

(2) By analyzing the stability lobe diagram, it can be seen that the influencing factors of the modal coupling effect are tool structure and machine tool, so the stability domain will be affected in the who

le speed range. The process damping effect improves the stability domain in the low speed region due to its action mechanism, and the gyro effect is the main factor affecting the stability in the high speed milling process. Considering the gyroscopic effect, the stability region has a certain rise at high speed. The single friction effect has little influence on the stability of the system, but considering the system under the synergistic action of multiple effects, the friction effect reduces the stability region in the low speed region, which indicates that considering the friction effect in the low speed region will make the prediction more precise.

(3) A variety of effects in milling process exist at the same time, in the study of its stability should be considered

comprehensively, but in the actual processing process, efficiency and accuracy should be taken into account. By comparing the blade graphs of low speed stability with gyroscopic effect and without gyroscopic effect, it can be seen that ignoring gyroscopic effect can improve the prediction efficiency and has no significant influence on the accuracy when predicting the stability of low speed machining. Similarly, the damping effect and friction effect can be ignored for the stability prediction of high-speed machining. The modal coupling effect is not negligible in all speed ranges.

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