Construction of Milling Force Model of Cycloid Gear

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Abstract. The change of the milling force during the milling process will directly affect the machining accuracy of the cycloid gear. In this article, the milling force prediction model of the cycloidal gear is used to predict the milling force of the cycloid gear. The results show that when the spindle speed increases, the milling force gradually decreases; the milling force is also closely related to the feed speed, axis milling depth and radial milling width. With the increase of axial milling depth and radial milling width, the milling force gradually increases, but the magnitude of the increase is different.

1. Introduction

In the milling process, the cutting force is an important factor affecting the tool wear and service life, machining accuracy and surface quality, tool vibration and work piece deformation. Especially in the process of low-rigidity thin-walled parts, because the cutting force is too large so that the parts have serious deformation. The machining accuracy and surface quality are reduced. Cycloid gear is one of the typical low-rigidity thin-walled parts. Due to its insufficient stiffness, the surface of the cycloid gear is elastically deformed. The deformation error of the cycloid gear surface greatly affects its machining accuracy. And the cycloid gear has the characteristics of high hardness and complicated processing contour. Therefore, the milling force variation is complicated in the milling process, which causes the uneven deformation of the cycloid gear is obvious. It will directly affect the machining accuracy of the cycloid gear, so it is necessary to analyze the variation of milling force of milling cycloid gear.

Zhao Kai et al. [1] reviewed the current main mathematical models for predicting milling force. Jiang Min et al. [2] proposed a new milling force model to predict the milling force of machining turbine blade surface. Dong Xinfeng et al. [3] proposed milling force coefficient models for different cutter radii. Yang Yiqing et al. [4] studied the prediction accuracy and dynamic characteristics of five cutting force models in detail. Luo Zhiwen et al. [5] proposed a milling force prediction method considering the instantaneous feed direction for flat curve end milling. Zhao Qing et al. [6] proposed a prediction model of axial cutting force for spiral milling of carbon fiber reinforced composites using the second-order response surface method. Han Shengchao et al. [7] used the instantaneous rigid force prediction model to model and simulate the milling force of the multi-tooth milling cutter side milling process of multi-layer CFRP materials. Bian Rong et al. [8] analyzed the micro-precision machining mechanism of hard zirconia ceramics. Wu Hong et al. [9] studied the changing law of milling force and deduced the empirical formula of milling force. Jia Xinjie et al. [10] proposed a dynamic milling force model for forming spiral bevel gears.
From the above analysis, we can see that the current prediction methods of milling force can be divided into multiple regression analysis prediction model, micro-element prediction model of milling force, finite element model and artificial neural network prediction model. A lot of practice has proved that the prediction model of micro-element milling force has very high prediction accuracy. In this work, the prediction model of milling force is used to predict the milling force of cycloid gear.

2. Dynamic Cutting Force Model of Face Mill

Based on the instantaneous rigid force calculation model, the tangential \((dF_{t,j})\), radial \((dF_{r,j})\) and axial \((dF_{a,j})\) forces acting on the micro-elements of the cutting-edge \(j\) with height \(d_z\) are expressed as:

\[
\begin{align*}
  dF_{t,j}(\phi_j, k) &= k_t h(\phi_j, k) db + k_a dS \\
  dF_{r,j}(\phi_j, k) &= k_r h(\phi_j, k) db + k_r dS \\
  dF_{a,j}(\phi_j, k) &= k_a h(\phi_j, k) db + k_a dS
\end{align*}
\]  

(1)

Where \(h(\phi_j, k)\) is the cutting thickness measured in the normal direction of the cutting edge, the value is \(f_j \sin \phi_j \sin k; \) \(db\) is the cutting width, its value is \(dz / \sin k; \) \(dS\) is the cutting edge length, its value is \(dz \sqrt{\left(r(z)\right)^2 + \left(r'(z)\right)^2} + 1\). Therefore,

\[
\begin{align*}
  dF_{t,j}(\phi_j, z) &= K_t f_j \sin \phi_j d_z + K_a dS(z) \\
  dF_{r,j}(\phi_j, z) &= K_r f_j \sin \phi_j d_z + K_r dS(z) \\
  dF_{a,j}(\phi_j, z) &= K_a f_j \sin \phi_j d_z + K_a dS(z)
\end{align*}
\]  

(2)

Through coordinate transformation and axial integration, the resulting cutting forces on the cutting edge can be expressed as follows.

\[
\begin{bmatrix}
  F_{t,j}(\phi_j) \\
  F_{r,j}(\phi_j) \\
  F_{z,j}(\phi_j)
\end{bmatrix} =
\begin{bmatrix}
  \int_{z_1}^{z_2} dF_{t,j}(\phi_j, z) \\
  \int_{z_1}^{z_2} dF_{r,j}(\phi_j, z) \\
  \int_{z_1}^{z_2} dF_{z,j}(\phi_j, z)
\end{bmatrix}
\]  

(3)

By adding the cutting forces on each cutting tooth, the cutting force can be obtained in three directions.

\[
\begin{bmatrix}
  F_{t,\phi_j} \sum_{j=1}^{n_j} F_{t,j}(\phi_j) \\
  F_{r,\phi_j} \sum_{j=1}^{n_j} F_{r,j}(\phi_j) \\
  F_{z,\phi_j} \sum_{j=1}^{n_j} F_{z,j}(\phi_j)
\end{bmatrix}
\]  

(4)
3. Analysis of Milling Force of Face-milling Cycloid Gear

In order to study the effect of the radial milling width of the Face-milling cycloid gear on the milling force, the parameters in Table 1 were used for numerical simulation. The simulation results of the dynamic cutting force of the face milling cycloid gears (I) are shown in Fig.1.

Table 1. The parameters were used for numerical simulation (I)

| Tool parameters | Work piece | Cutting parameters |
|-----------------|------------|--------------------|
| Tool type       | Tool material | diameter r /mm | Helix angle (°) | Number of teeth | Work piece material | Axial milling depth /mm | Feed rate mm/min | Spindle speed n /(r/min) |
| Face mill       | WC-based cemented carbide | 6 | 30 | 2 | 20CrMnTi | 1 | 1000 | 5000 |

(a) The radial milling width is 0.8 mm       (b) The radial milling width is 1.2 mm

Figure 1. The simulation results of the dynamic cutting force of face milling cycloid gear (I)

As can be seen from the figure that the milling force peak and the milling force shape of the two teeth in a cycle alternating are the same. Because the influence of milling cutter rotation eccentricity, cutter beating and processing system vibration on the milling force is not considered in the milling force model. because there is an interdental angle for a period of time, no milling edge is involved in the cutting. This will result in the figure where the milling force value is zero. It can be seen in the end milling conditions, the end milling cutter is in the single-tooth cutting, the two teeth are alternately cutting. In the milling process, the cutting forces in the three directions are different. The order of the cutting forces is: main cutting force, radial milling force, axial milling force. The tangential milling force and the radial milling force are more intense with the milling cutter rotation. The corresponding curve of milling force is jagged, and the axial milling force changes smoothly with the milling cutter angle. Figure 2 shows the effect of radial milling width on the maximum cutting force. As the radial milling width increases, both the maximum tangential milling force and the radial milling force increase, while the tangential milling force increases at a greater rate.
Figure 2. The effect of radial milling width on the maximum cutting force.

In order to study the effect of axial milling depth on the milling force, the parameters in Table 2 are used to simulate the milling force of face milling cycloid gear (II), which are shown in Figure 3. As can be seen from the figure that when the axial milling depth increases from 0.9 mm to 1.2 mm, the maximum tangential force increases from 8.2 N to 40 N. Figure 4 shows the relationship between axial milling depth and maximum cutting force. As the depth of axial milling increases, the milling force increases in three directions, and the maximum tangential milling force and the radial milling force increase at a high rate. As the axial milling depth increases, the cutting area also increases, the total friction and elastic-plastic deformation force increase, so the cutting force will increase.

Table 2. The parameters were used for numerical simulation (II)

| Tool parameters | Work piece | Cutting parameters |
|-----------------|------------|--------------------|
| Tool type       | Tool material | diameter /mm | Helix angle (°) | Number of teeth | Work piece material | radial milling width /mm | Feed rate mm/min | Spindle speed n/(r/min) |
| Face mill       | WC-based cemented carbide | 6 | 30 | 2 | 20CrMnTi | 1 | 1000 | 5000 |

Figure 3. The simulation results of the dynamic cutting force of face milling cycloid gear (II)
In order to study the influence of spindle speed on the milling force of face milling cycloid gear, the parameters in Table 3 are used for numerical simulation. The dynamic cutting force results obtained from the simulation of face milling cycloid gear are shown in Fig.5. Figure 6 shows the relationship between the spindle speed and the maximum cutting force. With the increase of the spindle speed, the maximum tangential milling force and the radial milling force become smaller gradually, the change trend of which is basically the same. As the axial milling force increases, the axial milling force remains basically unchanged.

**Table 3.** The parameters were used for numerical simulation (III)

| Tool parameters | Work piece | Cutting parameters |
|-----------------|------------|--------------------|
| Tool type       | Tool material | diameter /mm | Helix angle (°) | Number of teeth | Work piece material | axial milling width /mm | Feed rate mm/min | radial milling width /mm |
| Face mill       | WC-based cemented carbide | 6 | 30 | 2 | 20CrMnTi | 1 | 1000 | 1 |

(a) Spindle speed is 14000 r / min  
(b) Spindle speed is 17000 r / min

**Figure 5.** The simulation results of the dynamic cutting force of face milling cycloid gear (III)

**Figure 6.** The relationship between the spindle speed and the maximum cutting force
In order to study the influence of feed rate on the milling force, the parameters in Table 4 are used to simulate the dynamic cutting force of face milling cycloid gear (Fig. 7). Figure 8 shows the relationship between the feed rate and the maximum cutting force. With the increase of feed rate, the maximum tangential milling force and the radial milling force increase sharply, and the change trend of both is basically the same. It is shown that the feed rate has great influence on the tangential milling force and the radial milling force.

Table 4. The parameters were used for numerical simulation (IV)

| Tool parameters | Work piece | Cutting parameters |
|-----------------|------------|--------------------|
| Tool type       | Tool material | diameter /mm | Helix angle (°) | Number of teeth | Work piece material | axial milling width /mm | Spindle speed \(n\) (r/min) | radial milling width/mm |
| Face mill       | WC-based cemented carbide | 6 | 30 | 2 | 20CrMnTi | 1 | 5000 | 1 |

Figure 7. The simulation results of the dynamic cutting force of face milling cycloid gear (IV)

Figure 8. Influence of feed rate on maximum cutting force

Influence of spindle speed on the tangential force and radial force is relatively large, the impact on the axial force is relatively small. Tangential and radial forces decrease with the increase of spindle speed, but tangential and radial forces do not change when the spindle speed is greater than 15,000 rpm. The milling forces in three directions increase with the increase of feed rate, and they have linear correlation. Because as the feed rate increases, the corresponding cutting area also increases proportionally, resulting in an increase in milling force. The conclusion is basically consistent with the basic theory of metal cutting. It can be seen from the above analysis that increasing the spindle speed, reducing the feed rate, axial depth of cut and radial depth of cut can get a smaller milling force and high machining accuracy.
4. Conclusion
Based on the instant rigid milling force equation, a dynamic milling force model of the end mill was established, and the finishing milling force simulation was carried out based on the model. The research results show that each milling parameter has a different degree of influence on the milling component forces in the three directions. Each milling parameter has the greatest influence on the tangential force, followed by the radial force, and the axial force has the least influence. And each milling component force is arranged in order of tangential force, radial force and axial force. The milling force in the three directions is greatly affected by the spindle speed. As the spindle speed increases, the milling force gradually decreases; the milling force is also closely related to the feed speed, axis milling depth and radial milling width. With the feed speed, With the increase of axial milling depth and radial milling width, the milling force gradually increases, but the magnitude of the increase is different. Therefore, increasing the spindle speed, reducing the feed speed, axial depth of cut and radial depth of cut can obtain smaller milling force and higher machining accuracy.

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References
[1] Zhao K, LIU Z Q. An Overview on Milling Force Prediction Methods and Influencing Factors [J]. Mechanical Science and Technology for Aerospace Engineering, 2015, 34(8):1190~1200.
[2] Jiang M, Zhan Y X. The Research of Milling Force Prediction Model Suitable for Turbine Blade Surface Machining[J]. Modular Machine Tool & Automatic Manufacturing Technique | Modul Mach Tool Autom Manuf Techn, 2015, 000(003):129-133,137.
[3] Dong X F, Zhang W M, Sun J B, et al. Reconstruction of Milling Force Coefficients in Asymmetrical Teeth Milling Thin-walled Part [J]. Journal of Mechanical Engineering, 2015, 51(19): 197~205.
[4] Yang Y Q, Zhang B, Liu Q. Analysis and comparison of various cutting force models in the milling process simulation[J]. Zhendong Gongcheng Xuebao/Journal of Vibration Engineering, 2015, 28(1):82-90.
[5] Luo Z W, Zhao W X, Jiao L, et al Modeling and prediction of milling force in flat curve end milling process [J]. Acta Armamentarri, 2015, 36(9): 1727~1735.
[6] Zhao Q, Qin X D, Zhang X P, et al. Axial Cutting Force Prediction during Helical Milling of Carbon Fiber Reinforced Polymers Based on Response Surface Methodology [J]. Materials and Testing, 2015, 39(7): 108~112.
[7] Han S C, Chen Y, Xu J H, et al. Modeling and simulation of milling forces in side milling multilayer CFRP with multitooth cutter [J]. Acta Materiae Compositae Sinica, 2014, 31(5):1375~1381.
[8] Bian R, He N, Liu L, et al. Analysis on Characteristics of Milling Force in Micro-milling of ZrO_2 Ceramics [J]. China Mechanical Engineering, 2014, 25(23): 3200~3205.
[9] Wu H, Chen Y, Han S C. Study on milling force of carbide tool milling carbon fiber composite materials [J]. Mechanical Science and Technology for Aerospace Engineering, 2014, 33(8):1255~1258.
[10] Jia X J, Deng X Z, Su J X. Forming method to machine the spiral cone gear milling force model [J]. Transactions of the Chinese Society for Agricultural Machinery, 2012, 43(12): 268~272.