

Prediction of Hobbing Cutting Force based on Finite Element Simulation

Yanhui Liu

Baotou Light Industry Vocational Technical College of Energy Engineering, Baotou, China

lxfimu@163.com

Keywords: Hobbing; cutting force prediction; cutting area; finite element simulation

Abstract: The performance requirements of mechanical equipment for gears are also constantly increasing. Hobbing is a gear machining method that meets the needs of the product. The hobbing process is an extremely complex multi-edge interrupted cutting process. It is important to predict and analyze the cutting force of the tool to understand the effect of tool wear on the hobbing parameters. Therefore, this paper studies the cutting force prediction problem of hobbing. Firstly, using the mathematical model of the hobbing motion relationship, the mathematical models of the two-dimensional hobbing state and the three-dimensional hobbing state are established respectively, and the cutting area of the hob teeth is analyzed. Then, based on the finite element simulation, the cutting force of the hobbing teeth is calculated and compared with the analytical results. The experimental results verify the effectiveness of finite element simulation on the prediction of hobbing cutting force. The research results can provide a theoretical basis for the selection of cutting parameters.

1. Introduction

In recent years, China's manufacturing industry has maintained a good development trend. Gear is a basic part that is widely used in industrial equipment and is used in a large number [1-2]. The machining accuracy of the gear directly affects its transmission accuracy. Therefore, the key to gear manufacturing is to ensure that its machining accuracy meets the requirements. Hobbing, gear shaping and milling are very common gear machining methods [3-4]. Among these gear processing methods, the precision and efficiency of hobbing processing is high, which is the main way of gear production. The hobbing process is a multi-blade interrupted cutting process that forms the gear involute. With the use of new tool materials, the hobbing machine structure is optimized and the gear machining accuracy is getting better and better.

During hobbing, the selection of hobbing cutting parameters often needs to be determined by worker experience. This does not meet the requirements of efficient and low cost processing. Currently, conventional wet hobbing is the main method of hobbing [5]. Research institutes at home and abroad are committed to researching the mechanism of hobbing machining, and hope to achieve high-speed machining requirements by optimizing the machine structure. The new hob tool material achieves high performance cutting requirements. Therefore, it is necessary to find an effective method to predict the cutting state of the hobbing process [6]. The cutting parameters of the hobbing are determined by factors such as tool material, work-piece material, and cutting conditions. The result of the selection of the cutting parameters of the hobbing directly affects the machining quality of the gear, the power consumption of the machine tool, and the efficiency of gear machining. For the prediction problem of hobbing cutting parameters, the main problem currently exists is the imperfect cutting database.

The problem of hobbing cutting force prediction is studied in this paper. Firstly, the cutting state of each hob tooth during the hobbing process is analyzed, and the cutting area of each hob tooth under simplified conditions is calculated. Then, based on the finite element method, the dynamic cutting force of the hobbing is calculated, and the model of the cutting power of the hobbing process is established. Finally, the prediction results of the hobbing cutting force are verified by the hobbing cutting experiment. The research results provide a theoretical basis for the selection of

hobbing cutting parameters in engineering.

2. Modeling analysis of hobbing process

During the hobbing process, the hob teeth on the basic spiral surface of the hob enter the cutting area in sequence. An in-depth analysis of the development process between the tool and the gear can provide effective theoretical support for hobbing research. The modeling analysis of the hobbing process can obtain the chip shape during the machining process of the work-piece, which lays a foundation for the subsequent analysis of the hobbing using the finite element model.

2.1 Hobbing motion curve analysis

When the hob is cut, multiple hob teeth are often involved in the cutting at the same time, and the cutting conditions of each tooth are different [7]. Therefore, it is very difficult to study all the hob teeth at the same time, and it is necessary to study the single hob teeth. Hobs can be divided into two types: integral hobs and insert hobs. The material of the insert hob cutter body and the cutter teeth can save the use of valuable materials on the cutter body and reduce the cost. The machining of a gear is equivalent to the process in which one tooth groove is machined multiple times at different locations. The process of cutting each of the slots is the same. Therefore, any one of the slots can be selected for analysis. Based on the Boolean operation, the cutting area of all the teeth involved in one cogging cutting can be obtained.

The equation of motion of the hobbing is

$$\theta = \arccos \left[\left(\frac{z_1}{z_1 + 2} \right) \cos 20^\circ \right] - \frac{\pi}{9} + \frac{\pi(p_i - s_i)}{z_1 p_1} + \frac{2L_0}{m_0 z} \quad (1)$$

$$L_0 = \sqrt{r_f^2 - r_a^2} - \frac{m_0 \pi}{4} - 1.25 m_0 \tan 20^\circ \quad (2)$$

$$\frac{n_1}{n_2} = \frac{z_2}{z_1} \quad (3)$$

where L_0 is the distance between the starting point of the rack and the intersection of the rack and the gear axis, θ is the angle at which the rack cuts in and out, z_1 is the number of teeth of the machined gear, z_2 is the number of hobs, and m_0 is the normal of the hob mold.

2.2 Cutting area analysis

According to the motion relationship between the false rack and the gear, the cutting area per tooth on the hob can be solved. In the case where the hob and gear size parameters are constant, the cutting area per tooth of the tooth does not change. In order to calculate the cutting area per tooth, a tooth groove is selected for cutting, and then the machining number of the tooth on the hob is indicated. Therefore, we will start cutting the hob tooth of the selected tooth groove to No. 1, and the number of the cutting teeth to be followed is 2, 3, and 4.

We use MATLAB programming to calculate the cutting area of each tooth. Since the area of the micro-element is small, the arc can be simplified to a straight line for calculation. As can be seen from the shape of the chip, the cut chip portion is composed of a plurality of triangles, the line E is the range that can be processed by the cutting tooth being processed, and the line F is the processed shape of the gear that has been formed before the tooth is machined. . In order to calculate the enclosed area enclosed by the two lines, the coordinates of the four vertices of the closed area are first determined, and then the straight line equation of the top edge of the blade and the two side edges is determined according to the coordinates of the four points. The chip area is actually formed by the intersection of the three straight lines and the gear tip circle.

Knowing the equation of the line, the intersection of the line, and the formula of the area of the triangle, the chip area can be solved. The cutting area consists of 6 triangles. The area of the triangle

is calculated by the Helen formula.

$$S = \sqrt{p(p-a)(p-b)(p-c)} \quad (4)$$

$$p = \frac{1}{2}(a+b+c) \quad (5)$$

where S is the area of the triangle, a , b , and c are the three sides of the triangle, respectively, and p is the semi-perimeter of the triangle. The calculation results are shown in Figure 1.

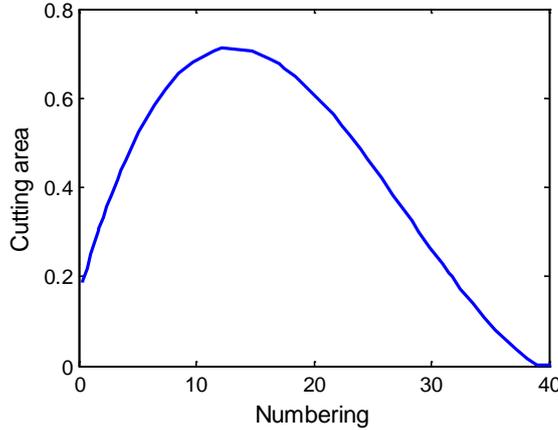


Figure 1 Cutting area calculation result

3. Cutting force calculation model

The hobbing cutting force varies with the angle of rotation of the hob. When the corner of the cutter is constant, the cutting section of the cutter can be obtained by dividing the chip along the axial section of the cutter. The cutting cross-sectional area is then micronized. The main cutting force of the micro-element is calculated according to the Kienzle-Victor formula. The area of the microelement in the Kienzle-Victor formula is derived using the Helen formula. The Kienzle-Victor formula and the Helen formula equation are

$$dF = Kh^{-u} dA \quad (6)$$

$$dA = \sqrt{p(p-a)(p-b)(p-c)} \quad (7)$$

where K is the ratio of the cutting force to the nominal cross-sectional area of the cutting layer, dA is the area of the micro-element, h is the chip thickness, a , b , and c are respectively three sides long, P is a half circumference.

The tooth path surface is a continuous surface. According to the shape of the chip, the thickness h is related to the axis coordinate and the angle of rotation of the blade. The distance between the normal of any point on the chip and the intersection of the tooth-forming surface is the chip thickness h at that point, which is calculated as

$$h = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (8)$$

Calculate the change of the main cutting force on the 10th tooth with the rotation angle of the cutter.

4. Finite element prediction of cutting force

4.1 Simulation condition

If the correct finite element model can be established, the finite element method can be used instead of the actual cutting process. Moreover, finite element simulation analysis can also study some variables that are not easy to observe and acquire during the experiment. The complexity of

the hobbing process has made it difficult to implement single-tooth machining experiments. Therefore, the machining process of the hobbing can be analyzed by the single-tooth finite element simulation, and the prediction of the hobbing cutting force can be realized.

In order to verify the correctness of the cutting force prediction method, two cutting simulation models were used to verify. We simulated the cutting of the 10th and 22nd hob teeth. The geometric simulation of the hobbing motion based on the hobbing motion relationship is obtained to obtain the shape of the work-piece formed by any cutter cutting. In order to obtain the cutting force generated when the No. 10 and No. 22 cutters cut the work-piece, it is necessary to introduce the work-piece model formed after the No. 9 and No. 21 cutters into the simulation software. Set the tool to a rigid body and the tool moves according to the tool path.

4.2 Results and analysis

The cutting force generated by the cutting process comes from the running results of the finite element simulation software. The cutting force obtained from the No. 10 tooth simulation was fitted. The fitting equation is

$$y = A_1 \exp(-x/t_1) + y_0 \quad (9)$$

where $A_1 = -28.82998$, $t_1 = -4.97211$, $y_0 = 1056.3$. The cutting force prediction results and fitting results of the finite element simulation software are shown in Figure 2.

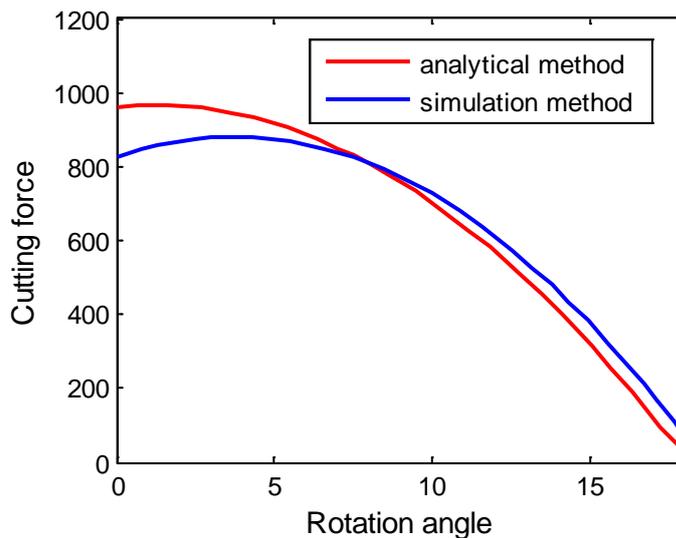


Figure 2 Tool cutting force comparison result of No. 10 tooth

According to the comparison chart of the cutting force curve, it can be seen that when the rotation angle is less than 9 degrees, the cutting force obtained by the simulation method is slightly larger than that obtained by the analytical method. This is caused by an instantaneous increase in cutting force when cutting into the work-piece. As the teeth are gradually cut into the work-piece, the simulation error is gradually reduced. When the rotation angle is greater than 9 degrees, the cutting force obtained by the simulation method is slightly smaller than the cutting force obtained by the analytical method. [8] This is because the change in cutting temperature is taken into account in the simulation. As the temperature increases, the cutting force decreases. The experimental results show that the cutting force calculated by the analytical method and the finite element simulation method are similar in cutting force from the cutting of the cutter to the end cutting, and the change trend is the same.

The cutting force obtained from the No. 22 cutter tooth simulation was fitted. The fitting equation is

$$y = A_1 + B_1x + B_2x^2 + B_3x^4 + B_4x^4 + B_5x^5 \quad (10)$$

where $A_1 = 570.65$, $B_1 = 65.2$, $B_2 = -39.7$, $B_3 = 7.41$, $B_4 = -0.582$, $B_5 = 0.021$. The cutting force

prediction results and fitting results of the finite element simulation software are shown in Figure 3.

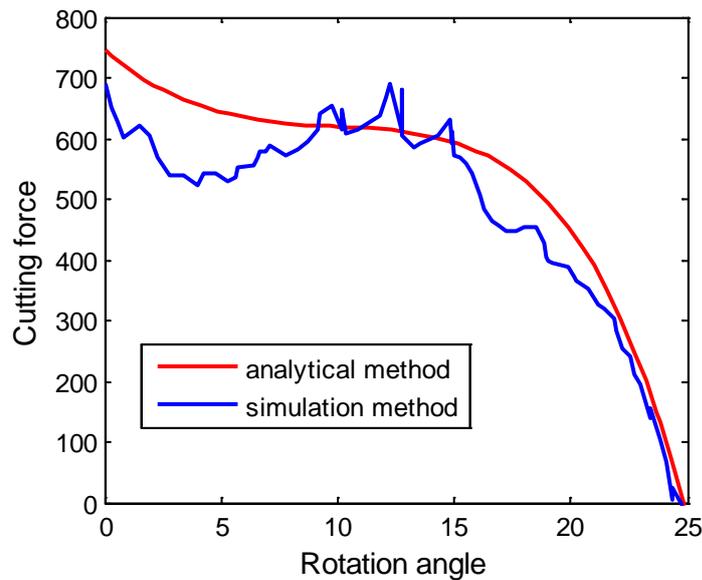


Figure 3 Tool cutting force comparison result of No. 22 tooth

The results show that the cutting force obtained by the simulation method is larger than the cutting force obtained by the analytical method at the beginning of cutting. As the angle of rotation changes, the error between the cutting force obtained by the simulation method and the cutting force obtained by the analytical method gradually decreases. The cutting force obtained by the two methods has the same tendency.

5. Conclusion

Gears are one of the basic transmission parts in the manufacturing industry. Its demand is increasing. Combined with the development trend of hobbing cutting and the demand of enterprise production, a geometric simulation method which can accurately study the hobbing process is proposed, and the change of cutting force during hobbing process is analyzed. The research results lay a foundation for the research of high-speed dry hobbing, and also provide new ideas for designing gears and improving the structure of the hob.

References

- [1] Slimane A, Kebdani S, Bouchouicha B, et al. An interactive method for predicting industrial equipment defects [J]. *International Journal of Advanced Manufacturing Technology*, 2018, 95(21):1-11.
- [2] Adebogun A, Hudson R, Breakspear A, et al. Industrial Gear Oils: Tribological Performance and Subsurface Changes [J]. *Tribology Letters*, 2018, 66(2):65.
- [3] Jin C, Guo C, Gao Y. Research on cutting vibration characteristics of face-milling involute gear [J]. *Defence Technology*, 2017, 13(5).
- [4] Dong X, Liao C, Shin Y C, et al. Machinability improvement of gear hobbing via process simulation and tool wear predictions [J]. *International Journal of Advanced Manufacturing Technology*, 2016, 86(9-12):2771-2779.
- [5] Cao W D, Yan C P, Ding L, et al. A continuous optimization decision making of process parameters in high-speed gear hobbing using IBPNN/DE algorithm [J]. *International Journal of Advanced Manufacturing Technology*, 2016, 85(12):2657-2667.
- [6] Sabkhi N, Pelaingre C, Barlier C, et al. Characterization of the Cutting Forces Generated During

the Gear Hobbing Process: Spur Gear [J]. *Procedia Cirp*, 2015, 31:411-416.

[7] Hu L, Tang L, Wen P, et al. Research on Fault Location Algorithm with Traveling Wave Based on Determinant of Matrix A[J]. *Journal of Applied Science and Engineering Innovation*, 2018, 5(3): 73-79.

[8] P. Xu, Research and application of near-infrared spectroscopy in rapid detection of water pollution, *Desalination and Water Treatment*, 122(2018)1-4.