Dual Closed-loop Error Compensation Systems Applied in Manufacturing the Spiral Bevel Gears

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Abstract. To improve machining accuracy of CNC spiral bevel gear grinder, there were two main ways: spatial error compensation of CNC spiral bevel gear grinder and tooth profile error compensation of the spiral bevel gears. Based on spatial error detection and compensation principle, laser doppler displacement measurement, computer and CNC spiral bevel gear grinder constructed the closed-loop system, which improved the accuracy of the spatial motion effectively. Based on tooth profile error detection principle of the spiral bevel gears, gear measuring center, CNC spiral bevel gear grinder, the software for designing and analyzing the gears formed the closed-loop system, which reduced the tooth profile error of the spiral bevel gears validly. Experiments have been done on the spiral bevel gear grinder by the dual closed-loop systems, and the results show they can improve machining accuracy of the grinder to a certain extent.

Introduction

Spiral bevel gear is a kind of key component in the field of mechanical transmission for transmitting power between the Intersecting axis. The structures of the machine tools for cutting spiral bevel gears are the most complex. At present, the final machining process for the spiral bevel gear is grinding the teeth in the CNC spiral bevel gear grinder. There are three linear motion axis of X,Y,Z, and four rotation axis, such as the workpiece axis, friction wheel axis, grinding wheel and dresser rotation axis in the grinder. Only when five axis of them move simultaneously, the surfaces of spiral bevel gears form. In the process of spiral bevel gears, the errors of the machine adjustment, the axis motion, workpiece and tool fixtures and so on, cause a certain profile error between the theoretical and actual tooth surfaces, which is the machining error [1]. The smaller the error is, the higher the precision of gears is.

Spiral bevel gears have many advantages such as big overlapping coefficient, high load capacity, smooth meshing, low noise and so on, which are widely used in kinds of mechanical equipments with high-speed and heavy-load, especially in aviation, automobiles, engineering machines, textile machinery, precise machine tools. If the spiral bevel gear could improve machining accuracy for one higher level, the load capacity may be increased two times, the transmission performance can be raised two to three times, determining how to increase the machining precision of spiral bevel gears becomes a central issue [2]. At present, the main CNC spiral bevel gear grinder manufacturers are Gleason in America, Klingelnberg in Germany, Zhongdachuangyuan and Haliangkaishuai companies in China. The first two almost occupied the NC machining equipment market for cutting spiral bevel gear worldwide, and represent the advanced technology, which is confidential. However, every company is spending lots of time and energy to improve the machining accuracy of spiral bevel gears further.

The movement precision of the machine tool and adjustment data card for gear machining that influence the accuracy of spiral bevel gears would be discussed in the paper. Firstly the importance of improving the accuracy of spiral bevel gears is going to be introduced. Secondly based on the principle of Laser Doppler Displacement Measurement (LDDM), closed-loop system for the spatial error compensation of the grinder would be built. Thirdly closed-loop system for the tooth profile error compensation of spiral bevel gear is to be established after researching on detecting principle of Gear Measuring Center(GMC). Next experiments would be done on the CNC spiral bevel gear grinder with and without the dual closed-loop systems, and the results would be analyzed in detail. Finally the work of all the parts would be concluded.

Building Closed-loop System for the Spatial Error Compensation

The errors tested in body diagonal method are used to evaluate the spatial accuracy by International Organization Standardization [3]. However, the traditional body diagonal errors can not be used to compensate the spatial error of the machine tool because it only allows three linear axis to move simultaneously. While in the latest segmented body diagonal method three axis moves sequentially so that the deviations detected in the direction of body diagonals include the errors in the linear axis. Theoretical method cannot exist without the measuring instruments. The laser interferometer is always utilized to detect the spatial error [4], but the measuring principle does not apply to the segmented body diagonal method. Laser Doppler Displacement Measurement (LDDM) provides hardware support for the method [1]. The laser principium, doppler effect, optical heterodyne principle are applied in LDDM. When it works, the processor would compute the error along the direction of body diagonal caused by the movement of a single axis based on the doppler frequency shift. Every linear error can be got through processing the data by the way of mathematical statistics, which lays the foundation for error compensation.

If all the linear errors are input into the numerical control system of the grinder with the compensation function, then measuring the spatial error again, it would be found that after error compensation the spatial error reduced evidently. For the purpose of ensuring the higher spatial movement accuracy in grinder, Closed-loop system for spatial error compensation of the grinder is built so as to monitor the spatial movement accuracy in real time by laser doppler displacement measurement, computer and CNC spiral bevel gear grinding machine, shown in Fig.1.

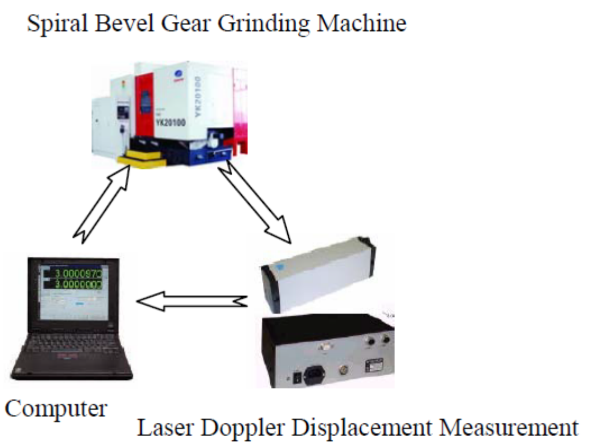


Fig.1. Spatial error compensation system of grinder

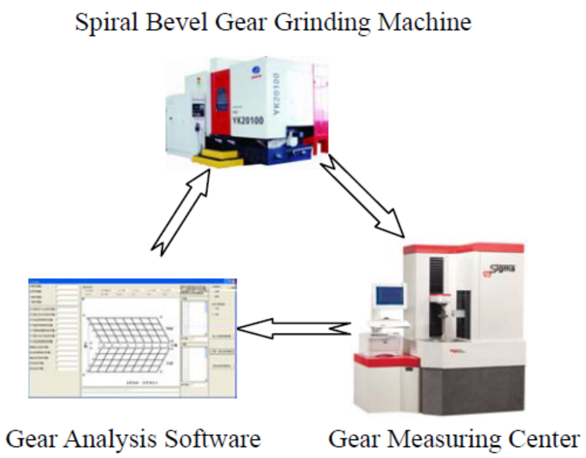


Fig.2. Error compensation system of the gear

Establishing Closed-loop System for the Tooth Profile Error Compensation

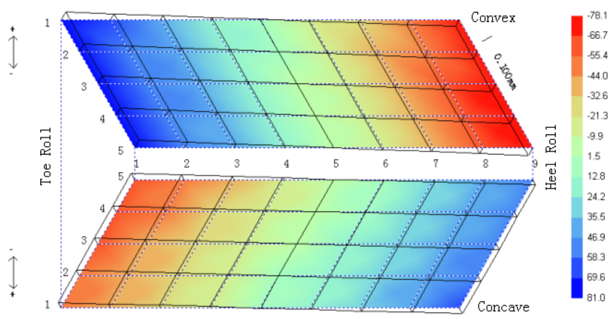
The main parameters of spiral bevel gears are: number of teeth, module, face width, pinion offset, pressure angle, shaft angle, limit pressure angle, transverse contact ratio, face contact ratio, modified contact ratio, outer cone distance, mean cone distance, pitch diameter, addendum, dedendum, working depth, whole depth, outside diameter, pitch apex to cross point and so on. These are input into the software system for gear design and analysis to compute the adjustment data card before processing the gear. The primary data are: wheel diameter, outside wheel angle, inside wheel angle, point width, wheel edge radius, teeth number of gear, mean radius, hand of spiral, vertical, horizontal, machine root angle, index position, index interval, wheel grinding depth, normal chordal addendum, normal chordal thickness, mean whole depth [5]. The accuracy of data would influence the precision of the gear directly.

The traditional method for detecting spiral bevel gears is that observing the size and location of the contact zone when a pair of gears are meshing. The accuracy is somewhat dependent on the subjective judgment of the inspector, so it is possible to misjudge [6]. Gear measuring center (GMC) can test the errors without manual intervention. The principle is as follows: dividing the surface by the length and width to get 45 grid nodes, then measuring the spatial coordinates of the grid nodes with three-dimensional probe and compared with the theoretical coordinates, finally getting the tooth profile errors of every node through the mathematical and statistical analysis.

When the tooth profile errors are got, the adjustment data for the grinder can be computed according to the profile errors using the gear design and analysis software again. Then the gear is ground again and detected, the errors are reduced to a certain extent. In order to compensate the tooth profile error in real time, the closed-loop system is established by GMC, CNC spiral bevel gear grinding machine, the software for designing and analyzing the gears, seen in Fig.2.

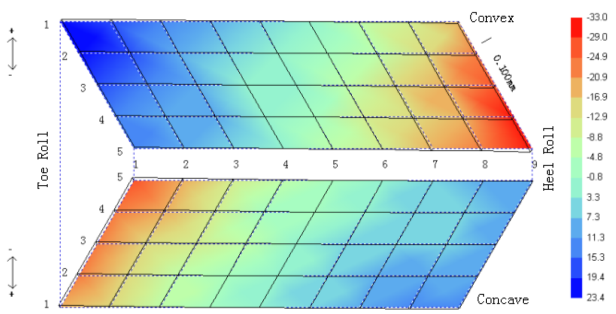
Experiment and Verification

Experiments are done in order to verify the effectiveness of the dual closed-loop systems. The basic parameters of the spiral bevel gear are as follows: number of teeth 40, module 11.43, helix angle 33.38, pressure angle of convex 31, pressure angle of concave 14, width of teeth 70, pitch cone angle 73.03, addendum 3.28, dedendum 17.46, outside diameter 459.11. First the gear is ground without the dual closed-loop systems, the tooth profile errors are shown in Fig.3. As can be seen, the node errors are larger generally, the biggest data of all is 81μm. Then a gear with the same parameters is ground with the dual closed-loop systems, the results is in Fig.4. The errors are reduced, and the largest one is 33μm. Comparison indicates that the precision of spiral bevel gears could be improved through the dual closed-loop systems.



1	81.0	59.3	41.1	23.3	3.9	-13.9	-29.7	-49.6	-66.9
2	77.9	57.6	39.0	21.7	2.5	-16.3	-33.8	-54.8	-68.9
3	77.9	56.1	38.2	19.9	0.3	-17.5	-36.0	-57.6	-75.2
4	77.8	56.0	37.5	19.1	-0.5	-19.2	-37.5	-59.9	-76.5
5	78.5	56.1	37.0	19.7	-0.1	-18.7	-37.0	-59.5	-78.1
	1	2	3	4	5	6	7	8	9
5	-62.1	-47.1	-34.7	-18.5	-2.7	9.1	24.2	36.2	51.7
4	-59.7	-46.4	-31.4	-17.3	-2.9	9.0	24.5	37.4	50.9
3	-58.5	-43.1	-28.9	-14.6	-1.2	13.1	27.5	41.4	55.2
2	-55.1	-41.5	-26.8	-12.6	2.4	14.1	28.1	42.3	57.7
1	-52.0	-39.0	-25.7	-11.1	4.3	17.8	32.3	44.6	58.8

Fig.3. Tooth deviation of gear before compensation



1	23.4	19.0	13.9	8.9	4.7	0.4	-5.2	-10.9	-19.2
2	19.8	16.1	10.3	6.4	2.3	-2.0	-8.1	-14.3	-23.1
3	17.4	12.2	7.5	3.2	-0.2	-5.8	-14.2	-20.2	-27.6
4	14.8	10.9	7.6	0.5	-3.1	-9.3	-16.0	-20.8	-31.2
5	14.2	9.1	4.2	1.4	-5.2	-10.1	-18.2	-23.8	-33.0
	1	2	3	4	5	6	7	8	9
5	-26.1	-19.7	-11.6	-6.2	-1.4	1.8	6.2	7.7	7.5
4	-24.4	-18.1	-12.0	-4.8	-0.9	1.8	4.7	6.6	9.6
3	-23.1	-16.7	-9.9	-4.9	-0.1	4.9	6.3	6.6	8.6
2	-21.9	-13.7	-8.1	-3.0	2.1	4.5	8.0	9.5	9.1
1	-20.7	-13.4	-7.2	-1.0	3.1	6.4	9.3	12.8	12.0

Fig.4. Tooth deviation of gear after compensation

Tooth surface structure of the spiral bevel gear is very complex, its precision is affected by the rotating accuracies of the workpiece axis, friction wheel axis, grinding wheel and dresser rotation axis in the grinder besides the spatial movement error of CNC spiral bevel gear grinder [7]. If these rotating errors could be detected and compensated, the machining precision would be improved further. When computing adjustment card data according to the profile error using the software for gear designing and analyzing, the modeling error of gears would affect the precision of spiral bevel gears. In addition, the installation error of grinding wheel also affects the tooth profile [8]. It is worth researching on these aspects in the future to improve the precision better.

Conclusion

In the paper, the dual closed-loop error compensation systems were put forward to improve the precision of spiral bevel gears. The spatial error detection methods of CNC spiral bevel gear grinder, the work principles of LDDM and GMC were researched, dual closed-loop systems for spatial error compensation of the grinder and tooth profile error compensation of spiral bevel gears were built to monitor the precision. Finally, the spiral bevel gear with 40 teeth was ground on CNC spiral bevel gear grinder respectively with and without the dual closed-loop systems. Results show that the systems can improve the precision of spiral bevel gears effectively. At the same time the methods and ideas that could improve the precision further were proposed.

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