Analysis of Hobbing Tooth Surface Polygonal Error

H. ITAYA S. OBATA S. NAKAGAWA

Hob gear cutting is widely used as an inexpensive and highly accurate processing method. Even in the rack and pinion type used in electric power steering, the pinion is machined by hob gear cutting, which has a major impact on performance. Hob processing is an extremely complicated processing in which a large number of cutting edges process the tooth surface, so analysis and evaluation are commensurately difficult.

The authors clarified the mechanism of tooth surface creation for hob gear cutting and developed analysis software. We also proposed a new evaluation method. Finally, we prototyped and evaluated gears using this method, actually mounted them on an electric power steering system, and confirmed the usefulness of this method.

Key Words*: hob, polygonal error, electric power steering, rack and pinion gear, friction force, tooth surface*

1. Introduction

Among steering systems, the rack and pinion (hereinafter, “R&P”) type is most commonly used, and the properties of meshing tooth surfaces in R&P steering systems exert a major impact on steering noise and vibration. Especially in recent years, highly quiet vehicles such as hybrids and EVs have come to account for a larger share of vehicles due to heightened environmental awareness. As R&P steering systems are also used for electric power steering (EPS), demands for increased R&P steering system quietness will continue as electrification progresses in the future.

Figure 1 shows an overview of R&P steering systems. Due to vehicle mounting conditions, most R&P steering systems have rack and pinion gears that are not perpendicular to each other, but which cross at an angle. Although it is common knowledge that gears with an involute tooth profile will slip in the tooth profile direction as meshing progresses, such slippage simultaneously occurs in tooth trace direction in the case of R&P steering systems with a cross angle. Slipping noise caused by such slippage in the tooth profile and tooth trace directions, as well as due to the tooth surface shape, has become a significant problem in recent years, making it necessary to discuss the tooth profile direction and tooth trace direction simultaneously for the properties of meshing tooth surfaces in R&P steering systems.

The processing of the pinion component of R&P steering systems is often done using hobbing in order to enhance productivity while keeping costs low. Although hobbing is suitable for mass production because it enables processing to be performed at high speeds while keeping production costs low, it results in a unique convex shape called “polygonal error” that is caused by intermittent cutting during the machining process. **Figure 2** shows an image of polygonal error on the tooth surface. Polygonal error is a machining error that always occurs during hobbing, in which a convex shape forms on the sliding surface, causing sliding noise to occur.

As a result, R&P steering systems are characterized as having slippage in the tooth profile and tooth trace directions, and as having polygonal error on the pinion tooth surface, which makes it necessary for comprehensive polygonal error analysis to be conducted on the entire tooth surface. Moreover, because polygonal error also impacts manufacturing costs, it is unrealistic to unnecessarily pursue manufacturing conditions that reduce polygonal error upon providing high-quality, low-priced products.

For this reason, we have developed an analysis tool by obtaining a theoretical formula for deriving polygonal error across the entire tooth surface. Furthermore, we have succeeded in establishing a more realistic evaluation method by first establishing a measurement method focused on polygonal error and linking it with the above-mentioned analysis tool. Finally, we used this method to conduct trials for optimal polygonal error conditions and prototype gears whose performance we evaluated by actually mounting them on a steering system. This paper provides an account of these case studies.

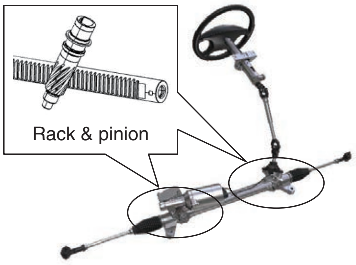

Fig. 1 Dual-pinion type electric power steering

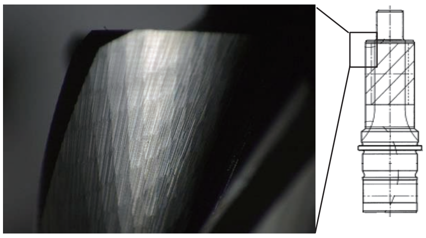

Fig. 2 Photo of tooth surface

2. Tooth Surface Analysis Method

2. 1 Polygonal Error in Tooth Profile Direction

Hobbing is a processing method in which the gear being machined is rotated in synchronization with a cutting tool with many cutting edges called a "hob." **Figure 3** shows an overview of hobbing. Hobbing utilizes a machining process in which the tooth profile shapes of the cutting tool and the gear being machined do not match, and is performed using an intermittent machining process in which cutting edges machine tooth surfaces one after another. For these reasons, the difference between the ideal tooth profile curve and the cutting edges of the hob results in a portion remaining uncut, as shown in **Fig. 4**. This uncut portion appears on the tooth surface as polygonal error in the tooth profile direction.

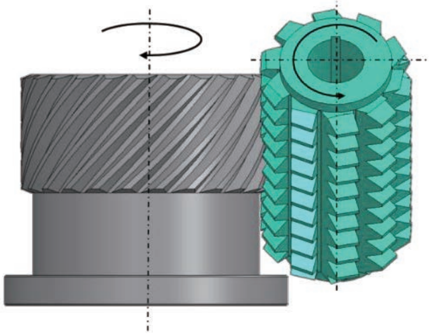

Fig. 3 Cutting teeth by hobbing

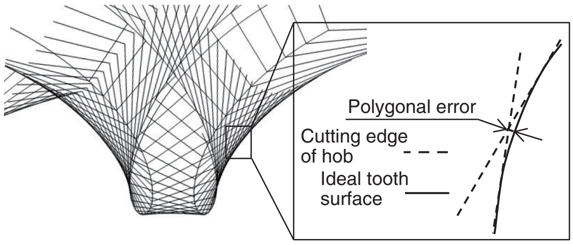

Fig. 4 Polygon error, tooth profile

2. 2 Polygonal Error in Tooth Trace Direction

Hobbing is performed by machining while the hob moves in the tooth trace direction. During machining, a portion remains uncut due to the cylindrical shape of the hob and the feed rate, as shown in **Fig. 5**. This uncut portion is transferred to the surface of the meshed tooth, resulting in polygonal error in the tooth trace direction. That reducing the hob feed rate will reduce polygonal error is self-evident. However, such reductions are disadvantageous due to the fact that machining times will be longer and machining efficiency will be decreased.

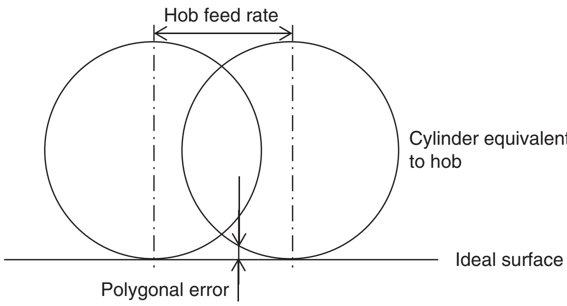

Fig. 5 Polygon error, tooth lead

2. 3 Polygonal Error That Appears on the Tooth Surface

Combinations of the above-mentioned polygonal error in the tooth profile and tooth trace directions will appear on tooth surfaces that have been machined using actual hobbing. Hobs have a large number of cutting edges and the machining trajectory of the cutting edges that actually machine the tooth surface will change depending on the trajectory and specifications of the hob itself. These conditions must be considered when obtaining polygonal error that appears on the tooth surface.

We therefore considered these conditions when developing a tool for calculating the shape of polygonal error across the entire tooth surface. **Figure 6** shows an example of polygonal error analysis using the developed tool. Although actual tooth surfaces will have an involute or other tooth profile curve in the tooth profile direction and a spiral shape in the tooth trace direction in the case of a helical gear, this tool expresses errors on the tooth surface by using a plane in place of an ideal tooth surface with no errors. This enables the amount of polygonal error at any position on the tooth surface to be confirmed, while also enabling polygonal error to be graphically expressed in an intuitive, easy-to-understand form.

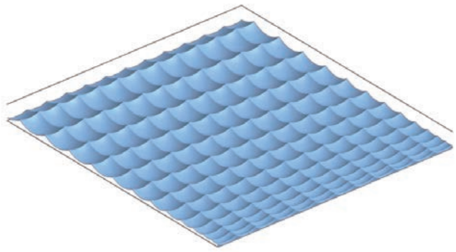

Fig. 6 Polygon error analysis on tooth surface

3. Tooth Surface Measurement & Analysis Methods

The actual shape of the tooth surface is measured using a gear tester. **Figure 7** shows an example of a comparison between the analysis results and the measurement results for the tooth profile direction taken from a gear tester. Measurement results from the gear tester plot the amount of error with the ideal tooth surface expressed as a straight line. Actual measurement results from the gear tester show minor errors and undulations that occur on the tooth surface shape due to equipment runout and vibration or the condition of the cutting tool. While these are important indicators for judging performance, if the goal is to evaluate only polygonal error, these will only serve as noise and are one factor in why judging the success of an assumed process is so difficult. We therefore performed frequency analysis on the tooth surface shape by focusing on the cyclic nature of polygonal error. When doing so, the above-mentioned analysis tool was linked with the measurement results from the gear tester to ensure that the ranges being evaluated were identical. As seen in **Fig. 8**, actual measurements match the frequency analysis results obtained using the analysis tool with a high degree of accuracy. This means that, by using this method, we were able to correctly evaluate the polygonal error of the actual gear, as well as confirm the reliability of the analysis tool.

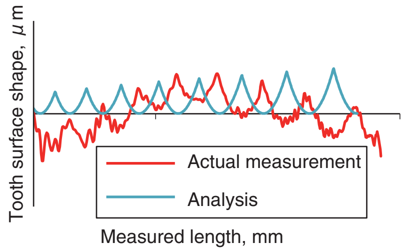

Fig. 7 Comparison of tooth surface profile

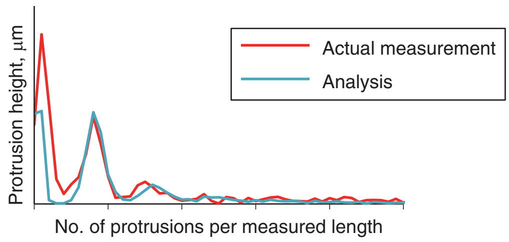

Fig. 8 Frequency analysis comparison of tooth surface profile

4. Tests to Improve Polygonal Error

We attempted to improve polygonal error using this analysis method. For the purpose of comparison, amounts such as gear specifications, cutting tool specifications, hob circumferential speed, and feed rate were assumed to be the same, and parameters such as the hob locus, which has little effect on production, were used to conduct analysis using the developed tool and obtain the optimal machining conditions. Moreover, an actual gear was prototyped based on the obtained optimal machining conditions. **Figure 9** shows a comparison between the current product and the prototype manufactured based on optimal machining conditions. It is possible to see that the prototype has a smoother tooth surface and is machined to a higher quality than the current product.

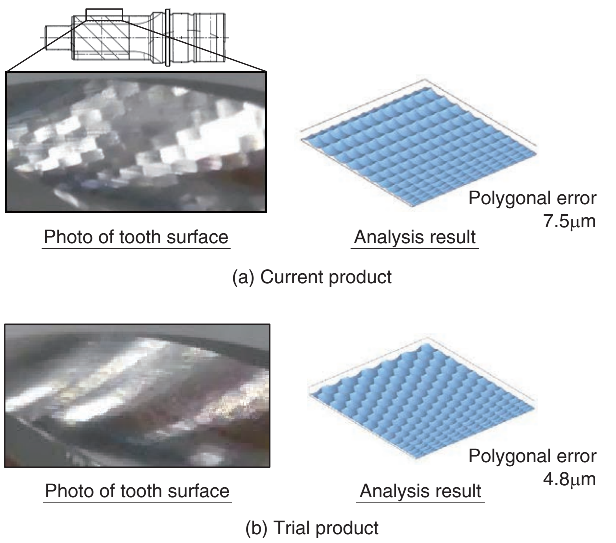

Fig. 9 Comparison of tooth surface

Furthermore, both the current product and prototype were actually mounted on the steering system, enabling the impact exerted on the product by polygonal error to be confirmed. **Figure 10** shows an overview of the test method. For this test, we used a DP-EPS system, which are known for their noise problems. With the steering system affixed to a jig and the rack on the drive side and the pinion on the driven side, a load cell was used to measure the load applied to the rack at a constant speed. To minimize the impact of heat treatment strain, alignment errors, and lubrication to the greatest extent possible, we tested the same steering system by replacing the pinions of the current product and the trial product. We also subjected the pinions to a hobbing finish after the heat treatment. **Figure 11** shows the result of rack load measurement. As can be seen, the rack load is smaller when using the trial pinion with improved polygonal error. **Figure 12** shows the comparison results. The horizontal axis represents the current product and trial product with improved polygonal error, while the vertical axis represents the normalized result when the current product is at 100%. Compared to the current product, the trial product yielded a 10% reduction in maximum rack load and 14% reduction in fluctuation width. Noise improvements were recognized by listening within the actual vehicle, proving that improvements in polygonal error result in improved steering system performance.

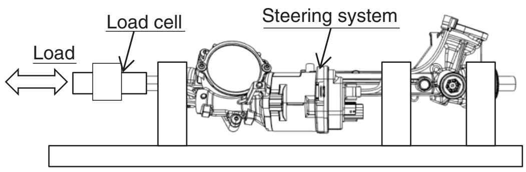

Fig. 10 Outline of examination procedure

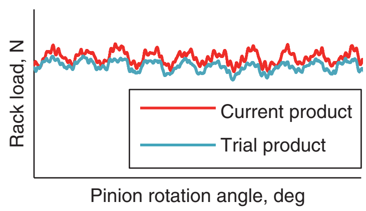

Fig. 11 Result of rack load measurement

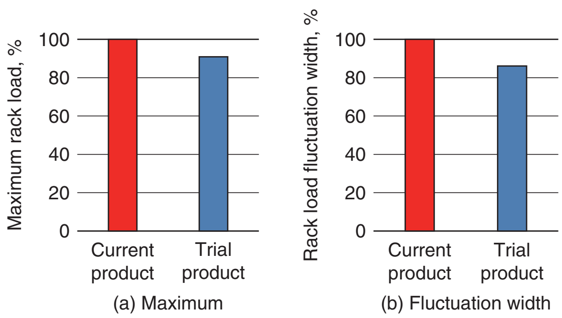

Fig. 12 Results of trial product and current product

5. Conclusion

This paper introduced our efforts to analyze and evaluate polygonal error caused by hobbing. The results we obtained are as follows.

(1) We succeeded in deriving a theory of polygonal error for the entire tooth surface, and in developing an analysis tool capable of easily calculating polygonal error.

(2) We are now capable of conducting tooth surface evaluations that focus on polygonal error by linking the analysis tool we developed through frequency analysis conducted on the tooth surface shape.

(3) We were able to obtain a high-quality tooth surface by manufacturing a trial product based on processing conditions aimed at improving polygonal error derived using the analysis tool we developed. Moreover, by incorporating the trial product into the steering system, we were able to improve the maximum rack load and rack load fluctuation width, enabling us to confirm the effectiveness of this method.

By using the method in this report, we are now able to analyze hobbing conditions instead of relying upon experimental methods as we had done previously. Furthermore, by linking the analysis results with actual measurement results, we are now capable of performing evaluations that focus on polygonal error. As this method can be applied to all forms of hobbing, it is expected to contribute to future development.

References

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