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Research paper

Optimization of the loaded contact pattern of spiral bevel and hypoid gears based on a kriging model

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ABSTRACT

In designing spiral bevel and hypoid gears, engineers typically must use trial and error to obtain a satisfactory design. This paper proposes a methodology for optimizing the loaded contact pattern of spiral bevel and hypoid gears. This methodology is divided into two parts: the establishment of an optimization model and a method for solving that model. The optimization model considers the loaded contact pattern, loaded transmission error, contact strength and bending strength. The model is formulated with the parameters of the ease-off surface as the design variables and the indices of loaded tooth contact analysis as the objective function and constraints. To solve the optimization problem with satisfactory computational efficiency and accuracy, a surrogate kriging-based model is introduced. A numerical example addressed by this methodology shows that the loaded contact pattern coincides well with the ideal zone, the loaded transmission error is reduced by 30.3%, and the maximum contact stress and root bending stress also decrease. This methodology is a useful aid for engineers in obtaining favorable designs systematically without trial and error.

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1. Introduction

Spiral bevel and hypoid gears are widely used in the automotive and aeronautical fields because of advantages such as high load-carrying capacity and smooth power transmission. A basic tooth flank design can be obtained by Litvin's local synthesis [1] or by using several commercial software programs. In industrial production, gear designers must use trial and error to obtain an acceptable design. Therefore, the concept of optimized design by modifying the micro-geometry of the tooth surface is proposed.

Stadtfeld [2] proposed a method using ease-off modifications to modify the position of the contact pattern in tooth contact analysis (TCA). Achtmann and Bär [3] established an optimization model using bearing ellipses and a response surface technique. The optimization problem involved varying the bearing ellipses to match the target one. Tian et al. [4–6] studied the effect of parameters associated with local synthesis on the contact path by slightly changing each parameter and optimized the contact path by choosing the appropriate parameters. Stadtfeld and Gaiser [7] proposed the 'ultimate motion graph' to obtain designed high-order transmission error functions using ease-off modifications, and Wang and Fong [8] proposed a sequential local synthesis to obtain a designed fourth-order transmission error function. The common limitation among the abovementioned studies is that they considered only the contact pattern or transmission error of TCA under no load.

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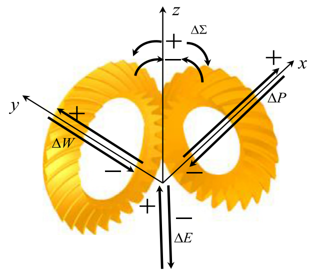

Fig. 1. Coordinate system of misalignments of spiral bevel and hypoid gears.

Based on unloaded optimization and loaded tooth contact analysis (LTCA), Simon [9,10] investigated the effect of machine settings on load distribution and loaded transmission error. The maximum contact pressure and peak-to-peak transmission error were successfully reduced. However, the bending strength of the root and loaded contact pattern were not considered in Simon's study. Artoni [11] introduced an unconstrained optimization model using a parametric surface to establish the ease-off modifications. The goal of the objective function was to make the loaded contact pattern match the target zone with no other constraints. Gabiccini [12] performed research similar to that of Artoni and accounted for misalignment. Based on the unconstrained optimization model, Artoni [13,14] proposed another optimization model for reducing the loaded transmission error (LTE) and contact pressure with no edge contact, but this study also ignored the bending strength.

The common limitation faced by the abovementioned loaded optimization models is that although the loaded contact pattern, LTE and contact strength are considered, the root bending strength is not incorporated. The reason why the root bending strength is not considered is that a fine finite element (FE) model is required to accurately calculate the root bending stress [15]. However, in FE-based semi-analytical LTCA, a coarse FE model is generally used to obtain the load distribution [16] to reduce calculation time. Because using a fine FE model in FE-based semi-analytical LTCA is time-consuming, this approach is not suitable for optimization problems considering the root bending strength, which require multiple LTCA runs.

To obtain a systematically favorable design, this work proposes an optimization methodology involving two steps. First, an optimization model is established to optimize the loaded contact pattern while considering the LTE, maximum contact pressure and maximum root bending stress. The root bending stress is calculated separately using a fine FE model after obtaining the load distribution. The parameters used to control the ease-off surface [17] are taken as the design variables, and the loaded contact pattern is used as the objective function, with separate loaded performance used as constraints. After the optimization model is established, the most important issue is to solve it because FE-based semi-analytical LTCA is time-consuming when accounting for root bending strength. A surrogate kriging-based model is introduced to reduce the high computational cost of the optimization model while ensuring accuracy. This model is established by dynamically adding design points to improve the accuracy of the optimized solution.

The remainder of this paper is organized as follows, Section 2 describes the process used to establish the optimization model and provides a brief introduction of the semi-analytical LTCA method used in this paper. Section 3 illustrates the process used to establish the surrogate model and solve the optimization problem. Section 4 provides a numerical example to verify the effectiveness of the methodology.

2. Establishment of the optimization model

To optimize the loaded performance, the ease-off surface is used to modify the micro-geometry of the pinion tooth surface. The control parameters of the ease-off surface are defined as design variables, and the loaded contact pattern is defined as the objective function, with the LTE, maximum contact pressure and maximum root bending stress acting as constraints.

2.1. Preparations

An initial basic design of a spiral bevel or hypoid gear can be obtained by local synthesis. The wheel machine settings are obtained from this design. The ease-off surface of the pinion is obtained by generating the conjugate pinion surface first as a reference surface, then modifying the reference surface with the control parameters [17]. Because this process is beyond the scope of this paper, it is described in Appendix A. In the actual gear meshing process, misalignments, including those in the direction of the shaft offset (ΔE), pinion axis (ΔP), wheel axis (ΔW) and shaft angle ($\Delta\Sigma$), must be considered. Fig. 1 shows the coordinate system of misalignments used in this paper.

2.2. Design variables

A typical ease-off surface is shown in Fig. 2(a), and (b) shows the contact path on the pinion projection plane. To simplify the description, the range of horizontal and vertical coordinates of the grid points on the projection plane is −1 to 1 in both

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