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A novel tooth surface modification method for spiral bevel gears with higher-order transmission error

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ABSTRACT

To reduce the running noise and vibration of spiral bevel gears, we present a novel method for designing high-contact-ratio spiral bevel gears with the higher-order transmission error (HTE) based on the function-oriented design. According to the design HTE curve and contact path, the pinion target tooth surface can be acquired by correcting the conjugated tooth surface derived from the mating gear. We establish a mathematical model for the computerized numerically controlled cradle-style pinion generator with the following design parameters: tool parameters, initial machine settings, and polynomial coefficients of the auxiliary tooth surface correction motion. An optimal model was developed to solve for the polynomial coefficients. TCA and LTCA results show that the HTE spiral bevel gears designed with the auxiliary tooth surface correction motion meets the design requirements. The meshing quality of the HTE spiral bevel gears is also better than that of gears designed using the parabolic transmission error (PTE). The tooth surface correction method proposed in this paper can serve as a basis for modifying high-contact-ratio (HCR) spiral bevel gears.

1. Introduction

As a key component in the aviation industry, spiral bevel gears need to meet many requirements in terms of noise, strength and reliability. However, because the contact path of traditional low-contact-ratio gears is nearly perpendicular to the root cone, they produce significant amounts of running vibration when working under high-speed, heavy-load conditions [1,2]. Determining the best way to use the relationship between the transverse-contact-ratio and the face-contact-ratio of spur gears to increase the contact-ratio of spiral bevel gears and then to improve their strength and dynamic performance has been a great concern to scholars worldwide [3]. Engineers have expended much effort to solve this problem. Fang and Deng proposed the use of high-contact-ratio (HCR) spiral bevel gears, which were developed by adjusting the direction of the contact pattern and extending the contact path [4,5].

Transmission error (TE) has a significant impact on gear vibration and noise. To reduce this vibration and noise of spiral bevel gears, the TE is usually designed as a parabola. Artoni proposed an optimization methodology to minimize the loaded transmission error of hypoid gears based on ease-off [6]. Simon analyzed the influences of machine settings on tooth contact pressure and loaded transmission error, and then presented a method to improve gear meshing performance by reducing the loaded transmission error and the maximum tooth contact pressure of hypoid gears [7–11]. However, as shown in Fig. 1(a), there are three meshing areas in one engagement period involving low-contact-ratio spiral bevel gears, and the PTE can

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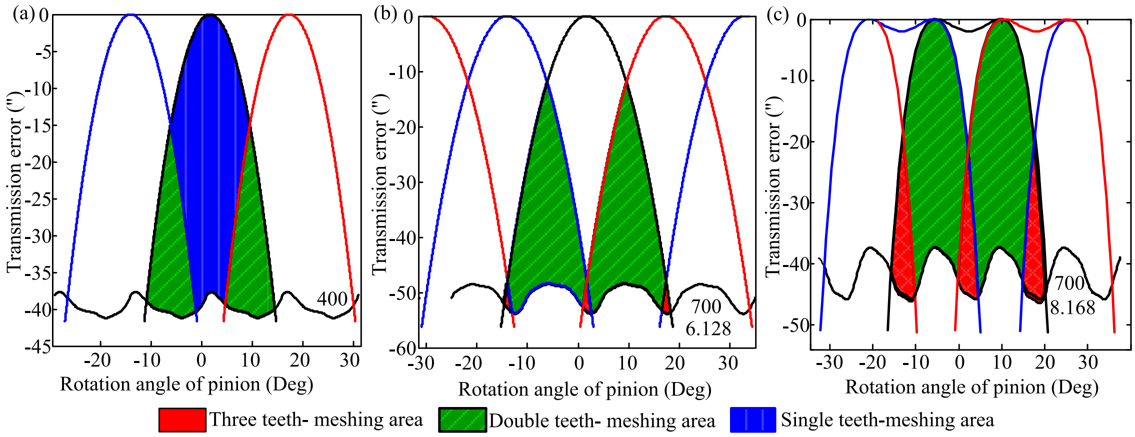

Fig. 1. LTCA results for low-contact-ratio spiral bevel gears with second-order TE (a), high-contact-ratio spiral bevel gears with second-order TE (b), and high-contact-ratio spiral bevel gears with seventh-order TE (c).

effectively reduce the amplitude of the loaded transmission error (ALTE). There are five meshing zones in one engagement period involving HCR spiral bevel gears, as shown in Fig. 1(b). The loaded transmission error (LTE) curve is a higher-order curve, and the PTE cannot meet the demands of reducing the ALTE. To reduce vibration, Stadtfeld [2] and Su [12] proposed the seventh-order TE for spiral bevel gears. Notably, the ALTE of spiral bevel gears with seventh-order TE is much larger than that of the PTE when the actual contact-ratio is greater than 2, as shown in Fig. 1(c). Therefore, seventh-order TE cannot reduce the ALTE of HCR spiral bevel gears, and it is necessary to design a novel transmission error curve.

Calculating the machine settings for gears is based on the local synthesis method [13], which was applied to spiral bevel gears by Litvin [14–16]. Tooth surface correction is important for reducing the noise and vibration of spiral bevel gears. In recent years, a new concept for spiral bevel gears was proposed with the application of a CNC gear generator developed by Gleason Works. Fong built a mathematical model for hypoid generator with higher-order tooth surface correction motion [17]. Stadtfeld proposed a higher-order tooth surface correction method with ease-off [18]. Shih proposed an ease-off flank correction method for spiral bevel gears based the auxiliary tooth surface correction motion [19,20]. Fan proposed a higher-order tooth surface error correction for face-milled spiral bevel and hypoid gears to reduce noise [21,22]. With the widespread application of CNC technology in spiral bevel gear machine tools, the generative theory of spiral bevel gears is no longer limited by cradle machines. It is possible to perform nonlinear corrective motions during gear processing. Fong proposed the MRM method for spiral bevel gears without causing an increase to the Hertzian contact stress [23,24]. Mu and Fang proposed the modified curvature motion method for spiral bevel gears with seventh-order TE [25].

In this paper, we proposed the tooth surface correction method for HCR spiral bevel gears with the novel HTE to improve the meshing quality. We also present comparisons of the HTE and PTE based on a combination of the TCA and LTCA [26,27]. Furthermore, the comparisons show that the HTE can effectively reduce the ALTE of HCR spiral bevel gears. The HTE also presents advantages in terms of the load distribution factor, bending stress, tensile stress and contact stresses.

2. Function-oriented design

The goal of function-oriented design is to generate the pinion target surface meeting the desired function requirements. We obtained the target surface of HCR spiral bevel gears with seventh-order TE based on function-oriented design in our previous work [25]. The principal is that the pinion target tooth surface is acquired by correcting the conjugated tooth surface derived from the mating gear with the design HTE and contact path.

To obtain a gear set meeting the design requirements, we designed the HTE curve (Fig. 2). The equation for this curve is:

$$\delta(\varphi_1) = c_0 + c_1\varphi_1 + c_2{\varphi_1}^2 + c_3{\varphi_1}^3 + \ldots + c_{10}{\varphi_1}^{10} + c_{11}{\varphi_1}^{11} \quad (1)$$

where $c_i (i = 0, 1, 2, \ldots, 10, 11)$ are polynomial coefficients and φ_1 is the pinion meshing angle.

3. Mathematical model

The locus of the tool surface is given by the following equations:

$$\mathbf{r}_p(s_p, \theta_p) = \begin{bmatrix} (R_p + s_p \sin\alpha_1)\cos\theta_p \\ (R_p + s_p \sin\alpha_1)\sin\theta_p \\ -s_p\cos\alpha_1 \\ 1 \end{bmatrix} \quad (2)$$