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Optimization of face-hobbed hypoid gears

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ABSTRACT

In this study, an optimization methodology is presented to systematically define head-cutter geometry and machine tool settings to introduce optimal tooth modifications in face-hobbed hypoid gears. The goal of the optimization is to simultaneously minimize tooth contact pressures and angular displacement error of the driven gear (the transmission error), while concurrently confining the loaded tooth contact pattern within the tooth boundaries and avoiding any edge- or corner-contact conditions. The proposed optimization procedure relies heavily on the loaded tooth contact analysis for the prediction of tooth contact pressure distribution and transmission errors developed by the author of this paper. The targeted optimization problem is a nonlinear constrained optimization problem, belonging to the framework of nonlinear programming. In addition, the objective function and the constraints are not available analytically, but they are computable, i.e., they exist numerically through the loaded tooth contact analysis. For these reasons, a nonderivative method is selected to solve this particular optimization problem. The effectiveness of this optimization was demonstrated by using a face-hobbed hypoid gear example. Considerable reductions in the maximum tooth contact pressure and in the transmission errors were obtained.

1. Introduction

1.1. Literature review

Two major cutting systems exist for the manufacturing of spiral bevel and hypoid gears: The face-milling method, which is a single-indexing method, and the face-hobbing method, a continuous cutting process. Since many decades, numerous authors have carried out many studies about the representation and design of spiral bevel and hypoid gears cut by the face-milling method. On the contrary, about gear cut by continuous indexing process, much less works are available. Litvin described the generality of the face-hobbing cutting process and applied it to spiral bevel gears [1]. By Litvin et al. [2] a method is proposed for the direct determination of relations between the pitch cone angles and spiral angles in hypoid gears with face-hobbed teeth of uniform depth. The geometry of the tooth surface of spiral bevel gears in a Klingelnberg cyclo-palloid system is described and a method for the inspection of this type of spiral bevel gears is proposed in Ref. [3]. The paper published by Kawasaki et al. [4] contains the design method, tooth contact analysis, and the investigation of the influence of assembly errors on the paths of contact and transmission errors in the case of Klingelnberg spiral bevel gears with small spiral angles. The manufacturing of large-sized spiral bevel gears in a Klingelnberg cyclo-palloid system using multi-axis control and a multi-tasking machine tool is presented by Kawasaki [5]. Kato and Kubo [6] developed a calculation procedure to determine the tooth bearing and transmission errors of the gears obtained from cutters with different diameters and to clarify the quantitative effects of the cutter diameter on the gear performance. The procedure to obtain the correction values of machine settings for tooth surface modification in the case

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of face hobbing and the construction of the corresponding prototype gear cutting machine is presented in Ref. [7]. The basis of the new face-hobbing method, presented by Stadtfeld [8], is a cutter system that uses an outside and an inside blade per blade group only and has an equal spacing between all blades. Lelkes et al. [9] proposed a flexible parameter variation method for tooth-surface and contact simulation of the cyclo-palloid spiral bevel gear and discussed the influences of cutting parameters on the result of tooth contact analysis. Fan [10] presented the theory of the Gleason face-hobbing process, who later presented a generic model of tooth surface generation for spiral bevel and hypoid gears produced by face milling and face hobbing processes conducted on freeform CNC hypoid gear generators [11]. The same author in Ref. [12] presented a polynomial representation of the universal motions of machine tool settings on CNC machines. A mathematical model for the universal hypoid generator that can simulate all primary face-hobbing and face-milling processes for spiral bevel and hypoid gears is presented by Shih et al. [13]. Shih and Fong [14] proposed a flank modification methodology for face hobbing spiral bevel gears and hypoid gears, based on the ease-off topography of the gear drive. A flank-correction methodology derived directly from the six-axis Cartesian-type CNC hypoid generator is proposed in Ref. [15]. Shih [16] developed a novel ease-off methodology for flank modification of face-milled and face-hobbed hypoid gears based on a Cartesian-type hypoid gear generator. Vimercati [17] presented a mathematical model able to represent the tooth surfaces of a complex gear drive: hypoid gears cut by a face-hobbing method. Zhang and Wu [18] presented a systematic approach for the determination of complete tooth geometry of hypoid and spiral bevel gears that are generated by the face-hobbing process.

Methods for load and stress distribution calculations in face-milled spiral bevel and hypoid gears were presented in References [19–35]. Wilcox [19] in his paper outlines the general theory for calculating stresses in bevel and hypoid gears using a flexibility matrix method in combination with the finite element method. Bibel et al. [20] applied the FEM to establish the model of tooth contact of spiral bevel gears by using gap elements. The loaded tooth contact analysis predicting the motion error of spiral bevel gear sets, by applying influence matrices, is presented by Gosselin et al. [21]. Handschuh and Bibel [22] analytically and experimentally rolled through the mesh of a spiral bevel gearset to investigate the tooth bending stress by the finite element method. The research reported in paper [23] presents a concept of flexibility tensor by which the flexibility factor in arbitrary directions can be obtained, used to solve the contact problem with friction. In the simulation of the manufacturing process of bevel gears, Linke et al. [24] presented a method that takes into account any additional motions mapped in the process-independent mathematical model of the generating process. This study demonstrated how such additional motions influence the meshing and stress conditions. Vogel et al. [25] proposed a new methodology for TCA by using sensitivities of tooth contact properties regarding arbitrary machine settings. By Fuentes et al. [26] the FEM was used for stress analysis in spiral bevel gears. Fang et al. [27] consider the edge contact in loaded tooth contact analysis. De Vaujany et al. [28] presented a numerical tool that simulates the loaded meshing of spiral gears and experimental tests carried out on a real helicopter gear box. Tooth surface contact stress, maximum tensile bending stress and maximum compressive bending stress are investigated by using loaded tooth contact analysis and the finite element method in Ref. [29]. Artoni et al. [30] proposed a fully automatic procedure to optimize the loaded tooth contact pattern. Ref. [31] presents an automatic procedure to optimize the loaded tooth contact pattern of face-milled hypoid gears with misalignments varying within prescribed ranges. An approach is proposed by Schlecht et al. [32] for determining the local load capacity in the early development of spiral bevel and hypoid gears under the action of load spectra. In Refs. [33–35] a new approach for the computerized simulation of load distribution in mismatched spiral bevel and hypoid gears is presented.

Only a few references can be found on load and stress distribution calculations in face-hobbed spiral bevel and hypoid gears. An advanced contact solver that, using a hybrid method combining finite element technique with semianalytical solutions is applied by Piazza and Vimercati [36] to carry out both contact analysis under light or heavy loads and stress tensile calculation in aerospace face-hobbed spiral bevel gears. Saiki et al. [37] proposed an innovative loaded tooth contact analysis method directly using the measured tooth flanks at each manufacturing step including milling and hobbing process. Ref. [38] presents the numerical procedure to simulate the loaded behavior of the hypoid gear manufactured by the face-hobbing cutting process. The loaded contact patterns and transmission error of both face-milled and face-hobbed spiral bevel and hypoid gears are computed by enforcing the compatibility and equilibrium conditions of the gear mesh in Ref. [39] published by Kolivand and Kahraman. Through the formulation of an appropriate nonlinear optimization problem, study [40] proposes a novel methodology to systematically define optimal ease-off topography to simultaneously minimize loaded transmission error and contact pressures, while concurrently confining the loaded contact patterns within prescribed allowable region on the tooth surface to avoid any edge- or corner-contact condition. An algorithmic framework was proposed by Artoni et al. [41] to accurately solve the problem of multi-objective ease-off optimization for spiral bevel and hypoid gears. Artoni et al. [42] present a novel methodology to restore the designed functional properties of hypoid gear sets whose teeth deviate from their theoretical models due to inevitable imperfections in the machining process. Kolivand and Kahraman [43] proposed a practical methodology based on easy-off topography for loaded tooth contact analysis of face-milled and face-hobbed hypoid gears having both local and global deviations. Kawasaki and Tsuji [44] investigated the tooth contact patterns of large-sized cyclo-palloid spiral bevel gears both analytically and experimentally. Hotait et al. [45] investigated experimentally and theoretically the impact of misalignments on root stresses of hypoid gear sets.

1.2. The goal of the optimization

To achieve maximum life in a hypoid gear set, an appropriate bearing pattern location with low tooth contact pressure and low vibration levels must coexist. Loaded transmission error is the primary source of noise and vibration. The conditions of meshing,