Journal of Manufacturing Systems 41 (2016) 228–238

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

A hybrid modification approach of machine-tool setting considering high tooth contact performance in spiral bevel and hypoid gears

Han Ding, Jinyuan Tang*, Jue Zhong, Zhenyu Zhou

State Key Laboratory of High-performance Complex Manufacturing, School of Mechanical and Electrical Engineering, Central South University, Changsha, PR China

ARTICLE INFO

Article history:
Received 18 August 2016
Received in revised form
12 September 2016
Accepted 13 September 2016

Keywords:
Machine-tool setting modification
Spiral bevel and hypoid gears
Ease-off
High tooth contact performances
Hybrid modification
Proportional modification

ABSTRACT

Machine-tool setting modification for spiral bevel and hypoid gears has been continually demanding more strength and less noise in terms of tooth contact performance. However, it only considers ease-off, but ignores tooth contact performance items. In the present paper, a novel hybrid systematic method is proposed to obtain high tooth contact performance by modifying machine-tool settings. In addition to the traditional item, namely residual ease-off, other three items: (i) the maximum contact pressure, (ii) the maximum loaded transmission error, and (iii) the contact ratio are applied to comprehensively evaluate the gear tooth contact performance. The universal machine-tool setting modification only considering the residual ease-off is first applied to identify initial machine-tool settings. Then, the relationships of high tooth contact performance items and machine-tool settings are established based on the loaded tooth contact analysis (LTCA). Finally, after selecting a few machine-tool settings as the optimal variables based on the sensitivity analysis method, a proportional modification is performed by designing different modification schemes about the optimal settings with different proportions and synthetically evaluating their results on multi-objective high tooth contact performance. The numerical instance and test are employed to verify the validity of the proposed hybrid modification.

1. Introduction

The sophisticated flank optimization has increasingly become an essential stage due to the continuous demand for more strength and less noise in terms of tooth contact performance in design and manufacturing of spiral bevel and hypoid gears [1,2]. Recently, machine-tool modification by compensating the tooth flank form error, namely, the so-called ease-off, is one of main solutions. This method usually proceeds as follows: (i) the tooth flank model is established based on basic design parameters including the tooth blank and machine-tool settings; (ii) the modification objective function is determined after the ease-off is prescribed; (iii) new machine-tool settings with modification variation are calculated and directly provided for the actual process. It is worth noting that the target is to modify the machine settings to obtain a design flank approximating the target flank with prescribed ease-off as far as possible.

In the past decades, all kinds of modifications based on a full range of machine tools such as Gleason or Klingelnberg series have emerged in endlessly. Accordingly, there have been some modeling problems with regard to low efficiency and poor accuracy, due to a plenty of machine-tool setting categories, complex generation motions and redundancy of design parameters [3,4]. More recently, machine-tool setting modification technique has been being continually developed. Firstly, the universal motion concept (UMC) which was dramatically enhanced and developed by Stadtfeld and Gaiser [5] has been implemented on most computer numerically controlled (CNC) hypoid generators, where more freedoms are provided to generate tooth surfaces with modified complex geometries [6] of face-milling and face-hobbing processes, as well as to correct the ease-off. Consequently, some advanced mathematical algorithms have been developed to improve tooth flank optimization design. Fan [7] obtained a universal generation model (UGM) to calculate tooth surface coordinates for any type of processes based on a free-form CNC hypoid generator [8], in which the basic machine tool settings are represented by a series of higher-order polynomials. Astoul et al. [9] provided a foundation for gear tooth contact analysis (TCA) based on a mathematical model by utilizing universal machine-tool settings and presented a simple and robust method to simulate the generating and meshing processes. Secondly, the ease-off micro-geometry optimization by modifying machine-tool settings is gaining more popularity. Shih

* Corresponding author.
E-mail address: jytangcsu_312@163.com (J. Tang).

http://dx.doi.org/10.1016/j.jmsy.2016.09.003
0278-6125/

and Chen [10,11] carried out a novel ease-off flank modification for face-milling based on the Cartesian-type CNC hypoid generator after simulating all primary processes for spiral bevel and hypoid gears. Artoni et al. [12,13] proposed an ease-off flank modification to achieve high gear transmission performance and improvement in other requirements by means of the actual machine-tool settings. Simon [14,15] provided an optimized tooth surface geometry to execute generating motions on the cradle-type machine tool, and then some optimizations for significant reduction in maximum tooth contact pressure and transmission error as well as for other superior properties. Thirdly, distinguished from the conventional first or second order flank form error correction, the higher-order modification has been proposed to achieve a higher level of accuracy and efficiency. Wang and Fong [16] got an access to a modified radial motion (MRM) correction presenting fourth-order motion curves in the machine plane of a CNC hypoid generator with an arbitrary predetermined contact path on the pinion tooth surface. Fan et al. [17] described a new approach for face-milling spiral bevel and hypoid gears. The higher-order components of the ease-off flank may be corrected by using higher-order universal generating motions. An optimization process for minimizing ease-off is applied to determine the corrective universal motion coefficients. In some developed modifications, the established modification model with application of the universal machine settings based UMC has a more extensive versatility [5–8] and the obtained numerical solution about the unknown design parameters has a stronger robustness [12,13], as well as the residual ease-off as a major item to evaluate the geometric shape of tooth flank has a higher accuracy [12,13,17].

As can be seen from the above described modifications, most recent researches only pursue the minimization of the tooth form error without comprehensive consideration of the enhancement of tooth contact performances. Even if there is some awareness of this issue, it is only a separate consideration. Ref. [18] only considers the systematic optimization of the tooth contact pattern by automatic ease-off topography modification. In the paper [19], loaded transmission error (LTE), as one of the primary sources of gear noise and vibration, is investigated by modifying ease-off. In Ref. [13], Artoni et al. described a multi-objective ease-off optimization methodology considering the efficiency, noise and durability performances, but it is somewhat regrettable that the selected design variables, i.e., tooth flank ease-off coefficients, are too complex to affect the calculation efficiency, in addition to the application of the hypoid analysis program (HAP) [20] and deterministic DIRECT algorithm [21] for the whole system. Moreover, the functional relationships between high tooth contact performance items and relevant machine-tool settings have not yet been established to introduce the actual high-performance gear manufacturing. However, in the actual process, some problems affecting tooth performance involving to geometric shape and tooth contact are ubiquitous. For instance, the variation of cutting forces, heat treatment deformation and some other unpredictable factors may cause noisy operation and premature failure from the edge contact and highly concentrated stresses. Therefore, in addition to ease-off, it is more important to consider the relationship of tooth contact performance with respect to the machine-tool settings in machine-tool setting modification. Besides, it would be more meaningful in practice if required tooth contact performance can be obtained by just modifying a few machine-tool settings. This means that it is of no use for the designed accuracy as mentioned above to be infinitely close to zero since this is impossible to achieve or needs more time and cost in the actual process. Today, the tooth contact analysis (TCA), especially the loaded tooth contact analysis (LTCA) based on finite element method (FEM), as a primary means is always applied to evaluate the relative gear tooth contact performance items such as the contact pressure, transmission error, contact pattern, mechanical efficiency and contact ratio.

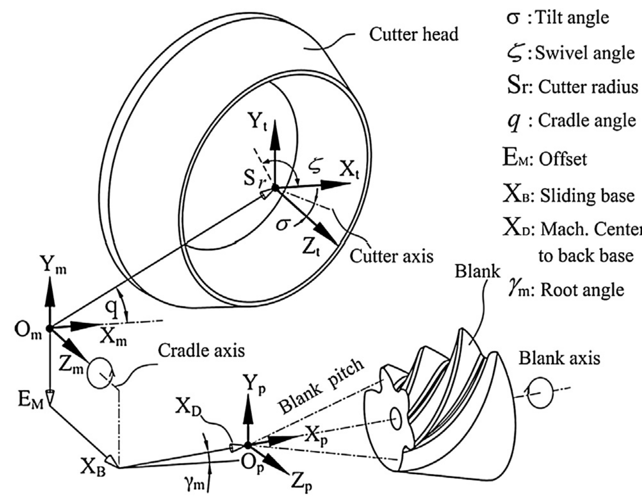

Fig. 1. UGM based on universal machine-tool settings.

In the present paper, with the synthesis and analysis of the above mentioned manufacturing concepts [5–8,10,11] and advanced design methods [12–20] in previous literature, it provides some significant improvements about modification system, operation strategy and tooth performance evaluation and so on, and then presents a novel hybrid systematic method of machine-tool settings to obtain spiral bevel gears with high tooth contact performance. As optimization objectives, in addition to the traditional item, namely, minimization of the root mean square error (RMSE) of residual ease-off, other three items: (i) minimization of the maximum contact pressure, (ii) minimization of the maximum loaded transmission error, and (iii) maximization of the contact ratio are used to evaluate the gear tooth contact performance. The whole hybrid system can be thought of as composed of two subsystems which are connected with each other. Firstly, a universal machine-tool setting modification only considering the residual ease-off is applied to identify an initial set of machine-tool settings with modification variation. Then, the relationships of high tooth contact performance items with machine-tool settings are established by extracting these items based on the loaded tooth contact analysis (LTCA). After selecting a few machine-tool settings as the optimal variables based on the sensitivity analysis method, a novel proportional modification is performed by prescribing different modification schemes with different proportions. Where, the multi-objective optimization is proposed to synthetically evaluate tooth contact performance. Finally, above two subsystems are integrated into a new hybrid modification system to identify the accurate machine settings and the numerical and experimental instances are given to verify its validity.

2. Universal machine-tool setting modification considering residual ease-off

2.1. Mathematical model of universal face-milling spiral bevel and hypoid gear

The proposed methodology stems from a mathematical model of the gear generation process, which can be obtained by formulating the gear equation of meshing based on the actual generation process. Whether for a mechanical machine tool or a Six-axis CNC free-form one, and whether for a Gleason's machine or a Klingelnberg's one, the generation motion can be executed by a so-called universal generation model (UGM) based on universal machine-tool settings [22]. Fig. 1 is a schematic representation of UGM based on a virtual cradle-type generator. It has been devel-