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Research paper

Multi-objective optimization of hypoid gears to improve operating characteristics

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ABSTRACT

In this paper a multi-objective optimization method of hypoid gears correlating to the operating characteristics is presented. Optimal design of hypoid gears demands that multiple objectives be simultaneously achieved. Four objectives considered in this study are the minimization of the maximum tooth contact pressure, transmission error and the average temperature in the gear mesh, and the maximization of the mechanical efficiency of the gear pair. The goals of the optimization are achieved by the optimal modification of meshing teeth surfaces. In practice, these modifications are introduced by applying the appropriate machine tool setting for the manufacture of the pinion and the gear, and/or by using a tool with an optimized profile. The proposed optimization procedure relies heavily on the loaded tooth contact analysis for the prediction of tooth contact pressure distribution and transmission errors, and on the mixed elastohydrodynamic analysis of lubrication to determine temperature and efficiency. A fast elitist nondominated sorting genetic algorithm (NSGA-II) is applied to solve the model. The effectiveness of the method is demonstrated by using hypoid gear examples. The obtained results have shown that by the optimization considerable improvements in the operating characteristics of the gear pair are achieved.

1. Introduction

More strength, less transmission error, higher efficiency and lower temperature in the gear mesh are major demands in the design of hypoid gear transmissions. These goals can be achieved by introduction of optimal tooth surface modifications. In practice, these modifications are introduced by applying the appropriate machine tool setting for the manufacture of the pinion and the gear, and/or by using a tool with an optimized profile. Therefore, the main goal of this study is to systematically define optimal tool geometry and machine tool settings to simultaneously minimize tooth contact pressure, angular displacement error of the driven gear and average temperature in the gear mesh, and to maximize the efficiency of the gear pair. During the last decades many research works have been directed towards the design and manufacture of spiral bevel and hypoid gears with optimal tooth surface modifications to reduce the maximum tooth contact pressure and transmission error [1–43]. The most relevant papers to the present work are as follows: Ding et al. [34] propose a novel multi-objective correction of machine settings correlating to the loaded tooth contact performance using nonlinear interval optimization algorithm for spiral bevel gears. The research [35] deals with the multi-objective optimization of gear tooth

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Nomenclature

a	pinion offset, mm
c	sliding base setting, mm
e	basic radial, mm
f	basic machine center to back increment, mm
g	basic offset, mm
i_{g1}	velocity ratio in the kinematic scheme of the machine tool for the generation of the pinion tooth surface
p	tooth contact pressure, oil film pressure, Pa
r_{prof1}, r_{prof2}	radii of the circular arc head-cutter profile, mm
r_{t1}, r_{t2}	radii of the head-cutter for pinion and gear finishing, mm
T	oil film temperature, K
T_{average}	average temperature, K
β	tilt angle, deg
δ	swivel angle, deg
$\Delta\phi_2$	angular displacement error of the driven gear, arcsec
η_{eff}	efficiency of the gear pair
ϕ_1, ϕ_2	rotation angles of the pinion and the gear rolling through mesh, deg
ψ	cradle angle, deg

surface to help design tooth corrections in order to simultaneously optimize several objective physical quantities. Wang et al. [36] propose a methodology for optimizing the loaded contact pattern of spiral bevel and hypoid gears by a surrogate Kriging-based model. The paper [37] presents a six sigma (6σ) robust multi-objective optimization of machine-tool settings for hypoid gears having higher quality requirements. In the work [38] Artoni details an algorithmic framework inspired by deterministic multi-objective optimization methods, specially combined with a direct-search global optimization algorithm to obtain globally Pareto-optimal solutions. In the paper published by Mogal and Wakchaure [39] attempt has been made to optimize worm and worm wheel with multiple objectives, which takes gear ratio, face width of worm and worm wheel and pitch circle diameters of worm and worm wheel as design variables by using the Genetic Algorithm (GA). A novel fitness predicted genetic algorithm is developed by Qui et al. [40] to improve the herringbone gear performance over a wide range of operating conditions. Regular mechanical and critical tribological constraints (scuffing and wear) are optimized by Patil et al. [41] to obtain a Pareto front for the two-stage gearbox using a specially formulated discrete version of non-dominated sorting genetic algorithm (NSGA-II). With the help of the genetic algorithm search technique the optimal design of the dynamic load sharing performance for an in-wheel motor planetary gear reducer is completed by Zhang et al. [42]. The research paper published by Chandrasekarana et al. [43] aims to optimize the design of a pair of spiral bevel gears, using NSGA-II, a nondominated sorting genetic algorithm for optimization of multiple objective functions.

In no conformal contacts, such as is in gears, forces are transmitted through a thin film of lubricant, which separates the two solid mating components. However, under usual operating conditions (high load), the thin film of lubricant is not sufficient to completely separate the tooth surfaces, and the asperities on opposing surfaces come in contact. This is the regime of mixed elastohydrodynamic lubrication (mixed EHL) in which the applied load is shared by the asperities and the lubricant film. Predicting performance of gears operating in the mixed EHL regime is of significant importance because the asperity contacts give rise to high local pressures, which can significantly lower the fatigue life of the gears. At the same time, the asperity contact friction and lubricant shearing in mixed lubricated contacts generate heat, which results in extreme local temperature raise. All these factors have big influence on the efficiency of the gear pair and on the temperatures in the gear mesh.

The early models of mixed lubrication were developed based on a stochastic approach [44]. In the last decades many theoretical and experimental research works were directed towards the more sophisticated deterministic model of mixed elastohydrodynamic lubrication. Only some of the related papers are referenced [45–63].

The first paper on the full thermo-elastohydrodynamic lubrication analysis of gears was published in 1981 [64]. Later, many research works were directed towards the EHL analysis in different types of gears [65–80]. The investigations have shown that in the case of full elastohydrodynamic lubrication, only a relatively small load (torque) can be transmitted. By applying a torque usually employed in gear pairs, mixed elastohydrodynamic lubrication appears. Recently, a considerable number of papers were published on mixed EHL in different types of gears. Some of them are referenced [81–100].

A multi-objective optimization method of hypoid gears correlating to the operating characteristics is presented. Optimal design of hypoid gears demands that multiple objectives be simultaneously achieved. Four objectives considered in this study are the minimization of the maximum tooth contact pressure, transmission error and the average temperature in the gear mesh, and the maximization of the mechanical efficiency of the gear pair. The goals of the optimization are achieved by the optimal modification of meshing teeth surfaces. In practice, these modifications are introduced by applying the appropriate machine tool settings for the manufacture of the pinion and the gear, and/or by using a tool with an optimized profile. The proposed optimization procedure relies heavily on the loaded tooth contact analysis for the prediction of tooth