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A data-driven programming of the human-computer interactions for modeling a collaborative manufacturing system of hypoid gears by considering both geometric and physical performances

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ABSTRACT

Hypoid gears are widely used in transmission systems, which demands low noise and high strength for their hypoid gears. To meet those demands, it is significant to consider the geometric and physical performances of hypoid gears. To obtain the optimal performances, a collaborative manufacturing system of hypoid gears is composed of three interrelated processes: gear machining, measurement and modification. Since each of these three processes is complicated, the modeling of the collaborative manufacturing system is very difficult, especially when human-computer interaction (HCI) is needed in each process. To fulfill this problem, a data-driven programming for HCIs in the collaborative manufacturing system is proposed. For modeling each of those three processes, the data-driven programming is applied to describe the HCI in each process. Subsequently, the collaborative manufacturing system is modeled with full consideration of both geometric and physical performances. To solve this model, a Levenberg-Marquardt algorithm with a trust region strategy is employed to obtain a stable numerical solution. A numerical instance is given to show the validity of the proposed method.

1. Introduction

1.1. Literature review

In industrial applications, due to hypoid gear drive has been continually demanding more strength and less noise from their power transmission [1–2], geometric and physical performances optimization of the tooth flank has been an important stage in hypoid gear design and manufacturing. More recently, the machine setting modification has become an increasingly significant access to this sophisticated tooth flank optimization [3–5]. Machine setting modification mainly includes the flank geometric optimization, identification of machine settings, contact performance evaluations and complex manufacturing processing technology. However, there always exists the gap between the theoretical design and the actual manufacturing, as a result of lacking the combination with manufacturing equipment, process technology and product performance. In recent literature [6–8], it is seldom investigated that the collaborative modification design considering both tooth geometric and physical performances, as well as the manufacturing system pursuing the high precision, high efficiency and high performance [9,10]. Actually, the traditional machine setting modification only considering the ease-off [11] or residual ease-off [12] as geometric performance evaluation. It has been always difficult to get the accurate and stable numerical solution because of the stronger nonlinearity of the established objective function [13,14]. Where, in the establishment of modification model, too many machine tool settings always are designed as unknown variables and represented into a complex over-determined implicit function [15,16]. During the past decades, there are all kinds of numerical algorithms applied to solve this problem. From a numerical optimization perspective, they can be divided into the following categories:

(i) Linear least square solution. The linear regression [17–19] and the generalized inversion [13] are often applied to directly solve the problem, while the singular value decomposition (SVD) [21] is employed to indirectly solve it.
(ii) Nonlinear least square solution. It mainly includes the sequential quadratic programming [22], the Levenberg–Marquardt (L-M) [23] and the trust region with dogleg step [24].

This numerical instability problem of the machine setting modification can be thought of as composed of two main serious and seldom reported issues:

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Nomenclature

E_M	blank offset
X_B	sliding base
q	basic cradle rotation angle
ζ	basic swivel angle
σ	tilt angle
S_r	cutter or wheel radius
R_a	roll ratio
γ_m	root angle
X_D	machine center to back base
V_n	n-th vertical motion coefficients
H_n	n-th helical motion coefficients
C, D, E, F	the coefficients of the linear term of the modified roll
φ	the initial cradle rotation angle
ϕ	the initial blank rotation angle
μ	rotation angle of the cutter
θ	variable of the blade edge
$\mathbf{r}_b$	vector of the tooth flank
$\mathbf{r}_c$	vector of the cutter
$\mathbf{M}_{bf}$, $\mathbf{M}_{fc}$	transformation matrices during transformation from the cutter to the blank
$\boldsymbol{r}_c$	represents the tool blade with edge geometry
$\xi\in\mathbf{R}^n$ n	design variables which generally are machine tool settings.
ξ_0	the initial basic machine settings
ξ^*	new machine settings
$\boldsymbol{p}_i^{(0)}$	i-th grid data point on basic tooth flank
m	the number of flank data points
n	number of the selected machine settings as variables in modification
$\boldsymbol{p}_i^*$	i-th grid data point on target flank
$h_i^{(0)}$	the prescribed ease-off value of the target flank with respect to the basic flank
$\boldsymbol{h}^{(0)}$, $(h_1^{(0)},\ldots, h_m^{(0)})$	the ease-off vector and corresponding numerical items
$\boldsymbol{h}$, $(h_1,\ldots, h_m)$	the vector of the residual ease-off and numerical items
$\boldsymbol{J}$	Jacobian matrix
$\mathbf{R}^{m\times m}$, $\mathbf{R}^{n\times n}$	$m\times m$ and $n\times n$ dimensional spaces
J_{ij}	sensitivity coefficient at corresponding tooth flank point
$\boldsymbol{S}$	well-known sensitivity matrix
$\Delta\xi$	variations of the machine settings ξ
$\boldsymbol{g}_k$	gradient vector of the objective model
$\boldsymbol{G}_k$	Hessian matrix of the objective model
ξ_k	machine tool settings after k iterations
$\boldsymbol{d}$, $\boldsymbol{d}_k$	the iteration step and the step at ξ_k
$f(\xi)$	objective function in modification model
$f_k(\boldsymbol{d}_k)$	the general quadratic Taylor expansion about a point ξ_k of the function $f(\xi)$
μ_k	damping coefficient
$\boldsymbol{I}$	the unit matrix in Levenberg-Marquardt (L-M) algorithm
$\boldsymbol{d}_k^{LM}$	the iteration step of L-M method
Δ_k	radius of a spherical region
v_k	the coefficient in updating the trust region
η_k	gain ratio of the increments of the function f and of the function f_k
ε_1, ε_2, ε_3, k_{max}	the stopping criteria parameters

(i) Coupling influence of unknown design variable. The machine settings have obvious the interaction effect in modification. Selecting too many machine settings as optimization variables can entail a massive amount of calculation and a slow computational speed;

(ii) Ill-conditioning of the Jacobian matrix. In the computation, it can cause the inevitable singularity because of the local convergence rather than the global convergence.

Whereas, it can come down that above two issues derive from the redundancy of unknown machine settings in modification [14]. In this work, the small number of machine settings is selected as the optimal design variables in machine setting modification. It is a very important improvement to the whole modification:

(i) It can improve the efficiency and robustness of the computation process. Typically, a virtual machine incorporates approximately sixty design parameters to determine the geometry of the generated gear tooth flanks [14]. In previous modifications using the universal motion concept (UMC), they generally provide 11 or 17 kinematic machine parameters [23]. In this paper, selecting 3 or 4 machine settings can significantly reduce the impact of nonlinearity.

(ii) It can improve the validity of the machine setting modification technique. Through accurate machine settings with modification variations can be determined by applying some complex algorithms, the some numerical results are insignificant for the practical industrial production. For instances, in the machine settings modification by the L-M algorithm in Ref. [14], the modification variations of radial setting and blank offset were 0.002 mm and 0.007 mm, respectively. And in final modification by the trust region algorithm with dogleg step in Ref. [24], the variations of machine root angle and blank offset were 0.000384° and 0.0087858 mm, respectively. Obviously, the above four modification variations are too small to be useful to the actual manufacturing. Indeed, 0.004 mm is about the order of the grinding tolerances [23], and the order for the gear milling is lager than grinding in practical modification tolerance. In the present paper, the sensitivity analysis method is used to select a small number of machine settings as design variables. The modification objective function is solved for the larger modification variations [10] of the selected machine settings.

Recently, the machine setting modification is accomplished by application of mechanical hypoid generators [4–5]. And the approximation expression of ease-off topography only considers its second-order components [15]. In this work, the universal machine setting modification considering the high-order characteristics is performed by correlating with the development and application of UMC. Where, the sensitivity between the geometric ease-off topography and the machine settings is investigated. In determination of the target flank with the prescribed ease-off, the high-order components may be flexibly modified by using the high-order universal motion coefficients. Besides, if this modification of optimal machine settings can not meet the requirement, it may perform a fast and repeated modification by increasing the order of the universal motion coefficient or the number of optimal parameters [10].

The physical performances are increasingly demanded from the gear contact transmission, in addition to the conventional geometric performance in manufacturing. Furthermore, in actual manufacturing, the uncertain variation of the cutting forces, heat treatment deformation, machine tolerances and some other unpredictable factors will cause the unfavorable operation and premature failure from the edge contact and highly concentrated stresses [15]. In this proposed modification, it also establishes a data-driven model of the collaborative manufacturing system considering both geometric and physical performances for hypoid gears. Here, the tooth contact strength is set as a main evaluation for the physical performances. There is an effective measure to compensate the influence of these noise factors. The reasonable performance items are collaboratively taken account into the modification to provide a comprehensive evaluation of physical performances.