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Design of face-hobbed spiral bevel gears with reduced maximum tooth contact pressure and transmission errors

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Abstract The aim of this study is to define optimal tooth modifications, introduced by appropriately chosen head-cutter geometry and machine tool setting, to simultaneously minimize tooth contact pressure and angular displacement error of the driven gear (transmission error) of face-hobbed spiral bevel gears. As a result of these modifications, the gear pair becomes mismatched, and a point contact replaces the theoretical line contact. In the applied loaded tooth contact analysis it is assumed that the point contact under load is spreading over a surface along the whole or part of the "potential" contact line. A computer program was developed to implement the formulation provided above. By using this program the influence of tooth modifications introduced by the variation in machine tool settings and in head cutter data on load and pressure distributions, transmission errors, and fillet stresses is investigated and discussed. The correlation between the ease-off obtained by pinion tooth modifications and the corresponding tooth contact pressure distribution is investigated and the obtained results are presented.

1. Introduction

Face-hobbed spiral bevel gears are widely applied in helicopters and automobiles for transmitting rotation and torque. The most important criteria for the quality of meshing of gears are the transmission error, the proper location of bearing contact, and the maximum tooth contact pressure. The aim of this study is to reduce the maximum tooth contact pressure and transmission errors in face-hobbed spiral bevel gears.

Since many decades, numerous authors have carried out many studies about representation and design of spiral bevel and hypoid gears cut by face-milling method. On the contrary, about gear cut by continuous indexing process, very few 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 tooth surface of spiral bevel gears in Klingelnberg cyclo-palloid system is described and a method for the

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Nomenclature

e	radial machine-tool setting, m
$e_n(z_D)$	composite tooth error, m
h_d	tilt distance from tilt center to reference plane of head-cutter, m
i_{g1}, i_{g2}	ratios of roll in the generation of pinion and gear tooth-surfaces, respectively
N_1, N_2	numbers of pinion and gear teeth, respectively
p_{max}	maximum tooth contact pressure, Pa
r_{prof}	radius of circular cutting edge, m
r_{t0}	radius of the head-cutter, m
s	geometrical separation of tooth surfaces, m
T	transmitted torque, N·m
u	coordinate of the straight-lined cutter blade profile point, m
x_{ep}, z_{ep}	coordinates of the center of the circular cutting edge, m
w	total tooth deflection, m
α	profile angle of straight-lined cutting edge, (°)
β_F	load distribution factor
δ_{01}, δ_{02}	pitch angles of the pinion and the gear, respectively, (°)
Δe	radial machine-tool setting variation, m
ΔF	concentrated load acting in the midpoint of the segment, N
Δi_{g1}	roll ratio variation
Δr_{t0}	difference in head-cutter radii, m
Δy_n	composite displacement of contacting surfaces, m
$\Delta\Phi_2$	angular displacement of the driven gear, (°)
Φ_1, Φ_2	rotational angles of the pinion and the gear in mesh, (°)
Φ_{10}, Φ_{20}	initial rotational angles of the pinion and the gear in mesh, (°)
γ	initial setting angle of head-cutter axis, (°)
η_i	initial setting angle of head-cutter, (°)
v	coordinate of the circular cutter blade profile point, (°)
κ	tilt angle of cutter spindle with respect to cradle rotation axis, (°)
μ	swivel angle of cutter tilt, (°)
$\omega^{(c)}$	angular velocity of the imaginary generating crown gear, 1/s
$\omega^{(t)}$	angular velocity of the head-cutter, 1/s
$\omega^{(1)}$, $\omega^{(2)}$	angular velocities of the pinion and the gear in mesh, 1/s
ρ_c	radius of the rolling circle of the imaginary generating crown gear, m
ρ_t	radius of the rolling circle of the head-cutter, m
$\sigma_{fil.max(g)}$, $\sigma_{fil.max(p)}$	maximum fillet stresses in the gear and in the pinion, Pa
ξ_i	offset angle of cutter blade, (°)

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 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. Procedure to obtain the correction values of machine settings for tooth surface modification in the case 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 gear and hypoid gears, based on the ease-off topography of the gear drive. A novel ease-off flank modification methodology for spiral bevel and hypoid gears made by a modern Cartesian-type hypoid gear generator was proposed in Ref. 15. Vimercati[16] presented a mathematical model able to represent tooth surfaces of a complex gear drive: hypoid gears cut by face-hobbing method. Zhang and Wu[17] presented a systematic approach for the determination of complete tooth geometry of hypoid and spiral bevel gears that are generated by face-hobbing process.

Methods for load and stress distribution calculations in face-milled spiral bevel and hypoid gears were presented in Refs. 18–35. Wilcox[18] in his paper outlined the general theory for calculating stresses in spiral bevel and hypoid gears using flexibility matrix method in combination with the finite element method. Bibel et al.[19] 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, was presented by Gosselin et al.[20] Handschuh and Bibel[21] analytically and experimentally rolled through mesh a spiral bevel gearset to investigate the tooth bending stress by finite element method. The research reported in paper[22] presented 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 spiral bevel gears, Linke et al.[23] presented a method that takes into account any additional