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Mathematical model and algorithm for contact stress analysis of gears with multi-pair contact

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ABSTRACT

The problem of contact pressure evaluation in gears with predesigned parabolic function of transmission errors and with localized contact is considered. It is proposed that several tooth pairs are in contact simultaneously. We construct an algorithm to define the torque transmitted by each pair in contact. Number of pairs in simultaneous contact depends on applied load and phase of meshing. This number is not known in advance. The feature of the algorithm is an automatic detection of the tooth pair number that is in contact in any phase of meshing under load. The algorithm allows you to define forces and torques that are transmitted on each of the pairs of teeth being in contact. Moreover, it allows determining the contact pressure and tooth-to-tooth accuracy of transmission. The proposed algorithm is universal and can be used to study the multi-pair contact in any gears.

An application of the algorithm for a spiral bevel gear has been demonstrated. It is shown that tooth overlap factor, dimensions of instant contact patch, tooth bearing contact and tooth-to-tooth accuracy of gears increase with growth of load.

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1. Introduction

One of the most important criteria of strength and durability of the gear set (Fig. 1) is the maximum contact pressure arising in tooth bearing contact and tooth-to-tooth accuracy in the process of torque transmitting. Contact pressure strongly depends on geometry of tooth surfaces. The tooth surfaces are defined by a method of machining and by values of machine-tool settings. These surfaces determine instant contact patches, contact path and tooth overlap (contact ratio). On the one hand to decrease contact pressure, these characteristics are to be maximal. On the other hand, too large values of these quantities lead to edge contact and to a considerable increase in contact pressure. Problem of determining the shape of teeth surfaces and of obtaining machine-tool settings to receive the obtained surfaces is called as synthesis of gear. A large number of algorithms for gear synthesis are known [1–7]. All the above algorithms do not take into account the possibility of simultaneous contact several tooth pairs; therefore the synthesis results require test by using of more advanced analysis procedures. If the results of the analysis demonstrate that the contact is unsatisfactory, it is necessary to correct the input data before re-synthesis. So only a skilled technologist can select the optimal tooth surface geometry.

In the process of the loaded gear operation several teeth of each wheel may be simultaneously in contact. Thus, at any moment the contact zone may consist of one or several simply connected zones (instant contact patches). In each of instant contact patches it is necessary to calculate contact pressure.

Numerical analysis of contact pressure in gear tooth taking into account simultaneous contact of several pairs of teeth is described in [1,8–14]. The algorithm for the solution of a contact problem of the theory of elasticity is given in [8]. It takes into account the

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Nomenclature

β	Spiral angle
γ_i	Coefficient depends only on the elastic characteristics of the contacting bodies
δ_i	The minimum backlash between the tooth pair number i in position where only one pair of teeth is in touch ($i = 1, 2, 3\ldots$)
δt	Backlash between the touching tooth surfaces
δt_ξ, δt_η	Coefficients of the quadratic form that describes backlash between the contacting surfaces
ε	Tooth overlap factor (contact ratio)
μ_i	The ratio of the contact ellipse axes
$\nu^{(n)}$	Poisson's ratio of the contacting elastic solids ($n = 1, 2$)
ν, θ	Surface coordinates
ξ, η	Principal axes
$\boldsymbol{\rho}_{Ca}$	Radius-vector of the contact point C
Σ_a	Cartesian orthogonal coordinate system
τ	Angular pitch of the driving wheel
$\varphi^{(1)}$	Rotation angle of drive wheel in the process of meshing
$\varphi_0^{(2)}$	Rotation angle of the driven wheel will be measured from the touch position in the direction of rotation
$[\varphi_{min}^{(1)}, \varphi_{max}^{(1)}]$	Interval possible meshing of a pair
$[\varphi_{in}^{(1)}, \varphi_{out}^{(1)}]$	The real interval of contact of investigated pair
ψ	Parameter that defines the tooth surface movement in process of wheel machining
$a_{\xi i}$, $a_{\eta i}$	Major axes of the contact ellipse ($i = 0, 1, 2, \ldots, m - 1$)
$E^{(n)}$	Elasticity module of the contacting elastic solids ($n = 1, 2$)
$F_I(\varphi^{(1)})$	Force transmitted the investigated tooth pair
$F_i(\varphi^{(1)})$	Force of contact pressure on arbitrary tooth
f_0	Linear transmission error for investigated pair of teeth
f_p	Linear transmission error for tooth pair number p
I	Number of investigated tooth pair in order of coming into contact
i	Number of tooth pair in order of coming into contact
M_{giv}, $M_\Sigma^{(2)}$	Torque on shaft of driven wheel
$M_i^{(2)}$	Torque of the force F_i on the shaft of the driven wheel
m	Number of tooth pairs in contact simultaneously
m_n	Average normal module
p	Sequence number of tooth pair. The pairs are numbered in the direction of wheel rotation
P_i	Sequence numbers of tooth pairs in order of backlash increase ($i = 0, 1, \ldots$)
$q(\xi, \eta)$	Distributed pressure on the contact ellipse
$\mathbf{R}_a^{(n)}$	Radius-vector of a point of moving generating surface ($n = 1, 2$) in the system Σ_a
r_{Pi}	Distance from contact point of pair number P_i to driven gear axis ($i = 0, 1, 2, \ldots$)
W_i	Elastic displacement along the common normal to contacting bodies ($i = 0, 1, 2, \ldots$)
w_{ti}	Projection of elastic displacement on tangent to the circle of radius r_{Pi}
$z^{(1)}$, $z^{(2)}$	Numbers of teeth of meshing wheels

simultaneous contact of two pairs of teeth. In [10] contact of three tooth pairs in bevel and hypoid gears is investigated. Results of the contact problem solution are presented in [1,12–14]. Two-pair and three-pair contacts for different types of gears are considered. However, the algorithm of analysis, which has been based on a method of finite elements, is not described in details. In [9] the Hertz solution for the solids limited by surfaces of the second order is used to obtain contact pressure. In that paper the possibility of two-pair contact in spiral bevel gear is considered. An algorithm for solving the contact problem for spiroid gear with the possibility of four-pair and five-pair contacts is described in [11]. However, many details of the algorithm were left without explanation. For example, the calculation of the influence function and the distribution of transmitted torque between simultaneously operating tooth pairs are not considered.

An algorithm for computing redistribution for transmitted torque between several pairs of contacting teeth occupies a prominent place in all these works. In some studies [8–10] redistribution algorithm is described in detail. This algorithm is given for the case when the maximum number of pairs in contact is two or three. In other studies [1,11–14] this question is not discussed sufficiently completely.

In this paper we describe an algorithm for redistribution of transmitted torque between several pairs of teeth in contact in gears with predesigned parabolic function of transmission error and with localized contact. The number of pairs may be large and not known in advance. This number depends on applied load and phase of meshing and is determined automatically. The teeth surfaces of all types of gears with localized contact are of non-zero Gaussian curvature are considered.

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