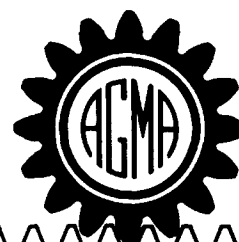


Design, Generation, Stress Analysis and Test of Low-Noise, Increased Strength Face-Milled Spiral Bevel Gears

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TECHNICAL PAPER



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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

A modified geometry of face-milled spiral bevel gears with uniform and tapered teeth that provides a localized bearing contact, reduces the level of noise and increases the strength of the teeth has been developed. The modified geometry is based on application of specially developed machine-tool settings and the generation of the gears is accomplished by application of the commercially available equipment and tools.

The main ideas proposed are the followings:

- (1) The optimization of the geometry is based on the local synthesis of the gear tooth surfaces that provides: (i) a localized bearing contact in the longitudinal and across the surface directions, (ii) a reduced level of transmission errors of a parabolic type, and (iii) the desired magnitude of the major axis of the instantaneous contact ellipse. The optimization is achieved by the mismatch of the surfaces of the generating tools.
- (2) The increase in tooth strength is due to the inherent increase in the total tooth contact ratio produced by the optimized geometry. The stress analysis is based on solid modeling of the tooth and finite element analysis.
- (3) The theory developed was tested by a Tooth Contact Analysis (TCA) computer program. Prototypes of the gears with tapered teeth were manufactured and vibration, noise and stresses have been measured experimentally. In comparison with the existing design, the level of noise was reduced by up to 18 decibels, at the spiral bevel meshing frequencies, and the vibration levels were reduced by 50%. The total stress level for the gear set was reduced enough to permit an increase in the maximum operating torque level.

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1 INTRODUCTION

The worst defects of gear drives are: (i) vibration and

noise, and (ii) the shift of the bearing contact to the edge accompanied in some cases with the edge contact of gear tooth surfaces. Sources of vibration are the transmission errors caused by gear misalignment and deflection of gear shafts due to variation of load. Gear misalignment affects the conditions of transfer of meshing when one pair of teeth is changed for another one. The transfer of meshing is accompanied by piecewise almost linear functions and cause vibrations at the gear meshing frequency determined by $\phi_1 = \frac{2\pi}{N_1}$ (fig. 1).

The main goals of this paper are: (i) to change the shape of function of transmission errors as shown in fig. 2 and reduce the level of transmission errors; (ii) to localize and stabilize the bearing contact and avoid the edge contact of gear tooth surfaces.

A more favorable shape of function of transmission is based on application of a predesigned parabolic function of transmission errors that is able to absorb the almost linear functions of transmission errors caused by misalignment [9].

The localization of bearing contact requires the crowning of surfaces to substitute an instantaneous line of tangency by point tangency. However, if crowning of surfaces is not accompanied with the transformation of the shape of transmission errors (fig. 2) and reduction of the magnitude of such errors, vibration and noise will not be reduced.

A popular way of crowning of surfaces is based on application of two imaginary generating surfaces Σ_p and Σ_g that satisfy the following conditions:

(i) The generating surfaces Σ_p and Σ_g are rigidly connected to each other and they have a common line of tangency.

(ii) The pinion and the gear tooth surfaces Σ_1 and Σ_2 are generated separately: Σ_1 is generated by Σ_p and Σ_2

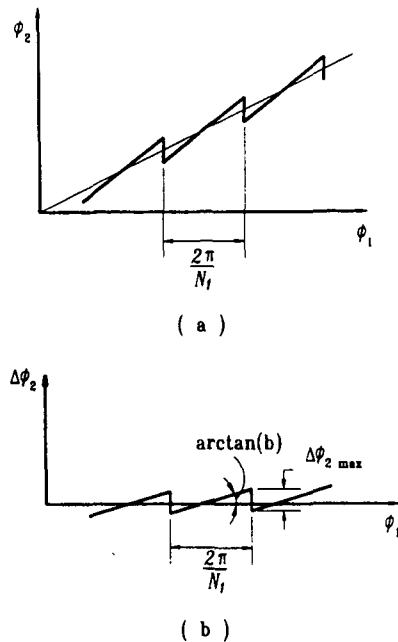


FIGURE 1: Transmission function and transmission errors of a misaligned gear drive

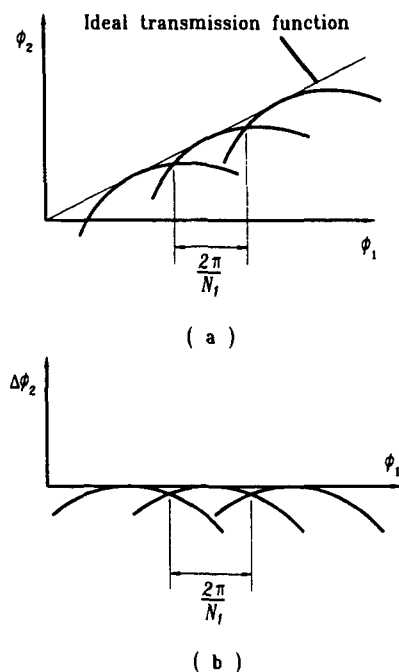


FIGURE 2: Modification of transmission errors by application of a parabolic function

by Σ_g . The analysis of meshing of generated surfaces Σ_1 and Σ_2 shows: (a) the bearing contact is localized, (b) an ideal transmission function is provided only for aligned gear drives; misalignment causes unfavorable transmission errors shown in fig. 1. Therefore, such a method for modification of gear tooth surfaces should not be used for high speed gear drives for avoidance of vibrations. Examples of the described method for generation are as shown in figs. 3-5. The imaginary surfaces of rack-cutters applied for generation of double circular arc Novikov-Wildhaber helical gears (fig. 3) have two common straight lines (lines of tangency) since two zones of meshing are provided. Fig. 4 shows the schematic of rack-cutters that might be applied for generation of modified involute helical gears. The couple of generating surfaces has a common straight line, the line of tangency. In both cases (shown in figs. 3 and 4) the bearing contact is localized since the generated surfaces are in point tangency at every instant, but the shape of transmission errors is unfavorable. Fig. 5 shows the generating surfaces that might be applied for the localization of bearing contact of spiral bevel gears with uniform teeth. In the first case (fig. 5(a)) the generating surfaces are two cones and they are in tangency along a common generatrix of the cones. The path of contact is directed across the gear tooth surface. In the second case (fig. 5(b)) one of the generating surfaces is a cone, and the other one is a surface of revolution. The common line of the generating surfaces is a circle, and the path of contact of the generated surfaces is directed in the longitudinal direction, along the surface. In both cases shown in fig. 5, the transmission function is an ideal linear function only if the gear drive does not have misalignment. The misalignment of the gear drive causes transmission errors of such a shape (fig. 6) that will cause high vibrations.

In this paper, generation of spiral bevel gears with two generating surfaces that are in point tangency (fig. 7) is proposed. The generating surfaces do not have a common line of tangency as shown in fig. 5. The surfaces are mismatched and the magnitude of the mismatch is a powerful tool used for synthesis of the generated pinion-gear tooth surfaces. Fig. 7(a) shows that the generating surfaces are two cones. A cone and a surface of revolution may be applied as shown in fig. 7(b). A generating cone is formed by straight line blades of the head-cutter. A surface of revolution is formed when curved line blades of the head-cutter are applied. In the case of generation of spiral bevel gears with tapered teeth, the generating cones interfere each other in the neighborhood of point M (fig. 7(a)) since the axes of the cones are not collinear. However, it will not cause interference of the generated surfaces due to the proper control of the mismatch of the generating surfaces (by the proper choose of radii R_p and R_g shown in fig. 7(a)).

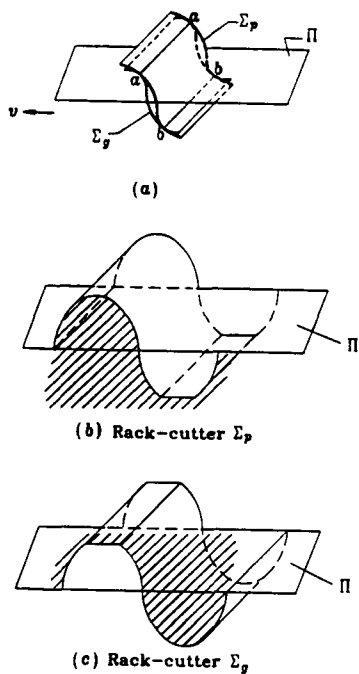


FIGURE 3: Schematic of rack-cutters applied for generation of double-circular arc Novikov-Wildhaber helical gears

The contents of the paper covers:

- (i) Generation of pinion-gear tooth surfaces by generation of spiral bevel gears with tapered and uniform teeth.
- (ii) Synthesis of pinion-gear surfaces that provide improved conditions of meshing achieved by: (a) application of a predesigned parabolic function of transmission errors; (b) observation of the desired magnitude of the major axis of the instantaneous contact ellipse; (c) observation of the prescribed direction of the path of contact (direction of the bearing contact).
- (iii) Development of TCA computer program for the simulation of meshing and contact.
- (iv) Determination of pinion tooth stresses by application of finite element method.
- (v) Detection and avoidance of interference of the fillet surface of one of the gear with the addendum surface of the mating gear.

The developed theory is illustrated with numerical examples.

2 SYSTHESIS AND GENERATION FOR SPIRAL BEVEL GEARS WITH TAPERED TEETH

Local Synthesis

The main goals of the proposed method of synthesis are:

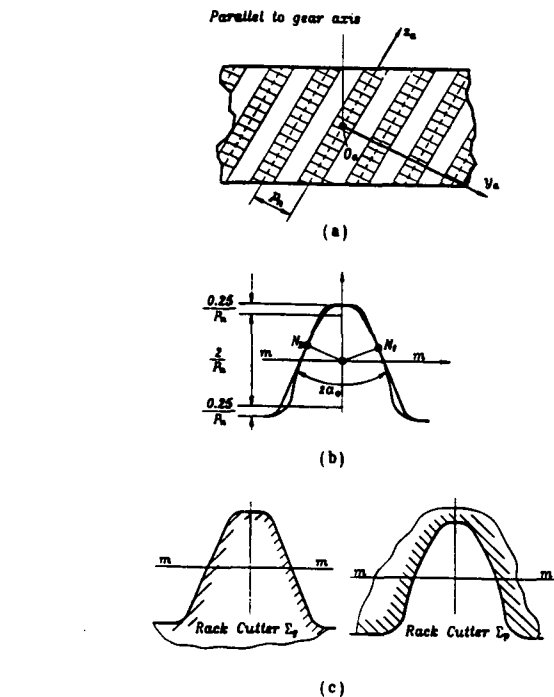


FIGURE 4: Schematic of rack-cutters applied for generation of modified helical involute gears

- (i) reduction of gear noise, (ii) localization and stabilization of the bearing contact, and (iii) reduction of stresses in the fillet. While performing the synthesis of the gear tooth surfaces, we consider that the tooth surfaces will be generated as follows:

(a) Both gear tooth sides are generated simultaneously by straight-line blades of the head-cutter (see Appendix 1). The machine-tool settings and the design parameters of the gear head-cutter are known (such data, for instance, may be adopted from the summary calculation information).

(b) Each pinion tooth side is generated separately by straight-line or curved blades (see Appendix 2). The profile angle of the pinion blade is considered as given. The pinion head-cutter settings (including the cutter point radius of the pinion) must be determined by application of the proposed synthesis method that will guarantee that the pinion-gear tooth surfaces are in point contact, the tooth surfaces are in tangency of the second order at the chosen mean contact point (designated as M), and the following requirements at M are observed: the chosen direction of the tangent to the path of contact, the magnitude of major axis of the instantaneous contact ellipse, and the derivative of the predesigned parabolic function of transmission errors. The method developed for local synthesis is based on the

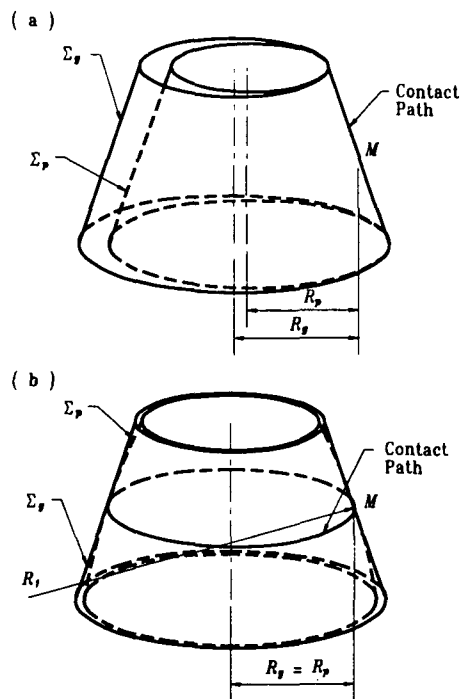


FIGURE 5: Generating cones and generating surface of revolution that might be applied for generation of spiral bevel gears with uniform teeth

following ideas:

- (i) The meshing surfaces are in tangency locally.
- (ii) The first and second order of tangency and meshing are considered. The first order of tangency and meshing means: (a) the tooth surfaces have at the point of contact coinciding surface normals; (b) the relative velocity lies in the plane that is tangent to the tooth surfaces; (c) the prescribed instantaneous gear ratio is satisfied at the point of tangency. The instantaneous gear ratio is the first derivative of function $\phi_2(\phi_1)$. The second order of tangency and meshing in addition to the conditions stated above, requires the relationship between the curvatures and directions of the contacting surfaces at the point of tangency. This relationship permits the determination of the second order derivative of function $\phi_2(\phi_1)$.

An advantage of the proposed approach is that the tilt of the pinion head-cutter is not required and the variation of the transmission function inside of the cycle of the meshing (the modified roll) is obtained by the proper control of the mismatch of surfaces. The procedure for the synthesis method developed is as follows:

Step 1: Since the gear and gear head-cutter settings and design parameters are known, it becomes possible to

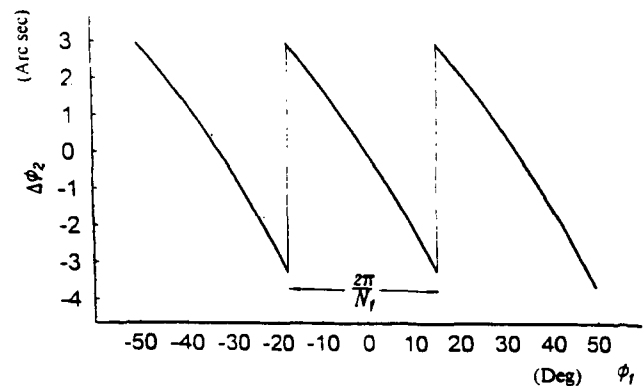


FIGURE 6: Transmission errors for a misaligned spiral bevel gear drive with uniform teeth ($\Delta\gamma = 3$ arc. min.)

determine analytically any point of gear tooth surface Σ_2 and the surface unit normal at such point. Particularly, this data can be obtained for the mean contact point M . In addition, the principal curvatures and directions of Σ_2 at M can be determined.

Step 2: The next goal is to determine locally the pinion tooth surface Σ_1 (as a small piece of Σ_1) at the point of tangency of Σ_1 and Σ_2 . This will require the determination at such a point of the position vector and the surface unit normal of Σ_1 , and the principal curvatures and directions of Σ_1 . For this purpose in auxiliary coordinate system S_ℓ (fig. 8) the meshing of surfaces Σ_1 and Σ_2 are simulated at M and within the neighborhood of M . The pinion and gear perform rotations about their axes Z_1 and Z_2 with angular velocities $\omega^{(1)}$ and $\omega^{(2)}$, and the prescribed gear ratio at M must be satisfied. The equation of meshing of Σ_1 and Σ_2 at M is represented as [9]

$$\mathbf{N}^{(2)} \cdot \mathbf{v}^{(12)} = 0 \quad (1)$$

Surfaces Σ_1 and Σ_2 are therefore in tangency and meshing at M and within the neighborhood of M . Equation (1) permits the determination of angle $\phi_2^{(0)}$ for orientation of coordinate system S_2 with respect to S_ℓ at the initial position of S_2 . Coordinate system S_1 coincides initially with S_ℓ .

To provide the second order tangency of Σ_1 and Σ_2 , the principal curvatures and directions of Σ_1 and Σ_2 at point M are related, taking into account the following requirements:

- (a) Surface Σ_1 and Σ_2 must be in point contact at point M , (b) the conditions of meshing and contact at point M must provide: (i) the prescribed direction of the tangent to the contact path, (ii) the prescribed magnitude of the major axis of the instantaneous contact ellipse, and (iii) the magnitude of the derivative of the parabolic function of transmission errors. Then at point M the locally determined