Mechanism and Machine Theory 101 (2016) 75–94

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Numerical tooth contact analysis of gear transmissions through the discretization and adaptive refinement of the contact surfaces

Francisco Sanchez-Marin*, Jose L. Iserte, Victor Roda-Casanova

Department of Mechanical Engineering and Construction, Universitat Jaume I, Castellon, Spain

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 23 February 2016
Accepted 13 March 2016
Available online 31 March 2016

Keywords:
Gear transmissions
Tooth contact analysis
Contact pattern
Transmission error

ABSTRACT

The tooth contact analysis (TCA) is an important resource for the design of gear drives. This widely used analysis provides the contact pattern, contact path and the function of transmission errors that are directly related to the performance of the gear set. In this work, a new geometric approach for the TCA is proposed. This approach is general, deterministic and independent from the type or alignment status of the gears. It is based on the discretization of the contact surfaces of the reference teeth pair and on a geometrically adaptive refinement to solve the contact problem and to compute the instantaneous contact area for each position of the gear set along the gearing cycle. The new algorithm demonstrated to be versatile, robust and efficient through different test cases, obtaining accurate results with a relatively low computational cost.

1. Introduction

The unloaded tooth contact analysis (TCA) is a classic test applied to gear transmissions that consists in the virtual simulation of the gear meshing allowing the designer to predict the performance of the transmission. The main hypothesis of the TCA is that the tooth contact surfaces of the gears are rigid. Consequently, the TCA constitutes a pure geometric problem where no deformations are taken into account. On the other hand, the main results of the TCA are the contact pattern and the function of transmission errors. Being both related to each other, the contact pattern is mostly related to the contact pressure distribution, that is related to the durability of the gears, while the function of transmission errors is mostly related to the dynamic performance of the gear set. In summary, the TCA is an excellent tool to predict the resulting performance of new designs of gears with both standard and modified tooth surfaces and to test the sensitivity of the gear meshing to the misalignment of the gears.

Regarding the contact pattern, the TCA can be described as the virtual version of the unloaded gear tooth contact pattern test in which one gear is painted with a marking compound and, then, the teeth are rolled through the mesh so the compound is transferred to the unpainted gear through the contact area, obtaining the contact pattern. In the real test, the result depends on the thickness of the painted layer and, correspondingly, the contact pattern computed with the TCA depends on a parameter called virtual marking compound thickness (δ) that represents the thickness of the real layer.

* Corresponding author.
E-mail address: francisco.sanchez@uji.es (F. Sanchez-Marin).

http://dx.doi.org/10.1016/j.mechmachtheory.2016.03.009

Under the consideration of the tooth contact surfaces as rigid surfaces, the instantaneous locus of contact of two mating teeth is always a point or a line. Then, the locus of points of each tooth surface around the contact point (or line) where the distance to the contact surface of the opposite tooth is lower than the virtual marking compound thickness is called instantaneous contact area. Taking this into account, the contact pattern on each gear can be defined as the envelope of the infinite instantaneous contact areas obtained along the gearing cycle.

The first works of development of the TCA were done by Litvin and Kai [1,2], and Baxter [3], followed by the engineers of Gleason Works [4], Klingelnberg [5] and Oerlikon [6], where the first approximation to the problem was analytic. In these methods, the contact problem for a specific position of the gear set is solved using a surface tangency condition (coincidence of normal vectors), leading to a system of non-linear equations that, in the most general case, must be solved numerically. This allows the computation of the contact point and the transmission errors associated to that position of the gear set. After that, the instantaneous contact area (defined as an ellipse in these analytic approaches) is calculated from the relative curvature of the contacting surfaces. Using this strategy, a considerable number of researchers solved the TCA problem for a variety of gear types with different objectives, being the most common the study of the sensitiveness of the gear set to the misalignment of the gears and the use of the TCA to verify the resulting performance of the gear set under certain modifications of the tooth flanks. Thus, with the analytic approach, the TCA has been extensively applied to spur gears [7–10], helical gears [11–15], face gears [16–20], spiral bevel gears [21–25], hypoid gears [26–30] and other gear types, to cite a few works. The high number of papers reveals the importance of the TCA for the simulation and design of gear drives.

However, Lin and Fong [31] stated that the analytical methods based on the surface tangency condition may fail solving the contact problem when an edge-contact occurs during the gear tooth meshing process because that condition is not necessary fulfilled. Additionally, when there is a perfect line contact between the mating teeth (for example, in the case of perfectly aligned involute spur gears), the approach may not be robust because the contact point is not unique. And, finally, in this last case, the estimation of the instantaneous contact ellipse from the relative curvature of the surfaces may have numerical complications because the semi-major axis of the ellipse tends to infinity. In fact, the inherent difficulty of these two cases (edge contact and line contact) makes them the most difficult cases to solve for any TCA approach and, consequently, they constitute the best test cases to evaluate the robustness and numerical stability of new TCA algorithms.

To prevent the described problems, different researches proposed numerical approaches to solve the tooth contact analysis problem. Among them, Sheveleva [32] developed an algorithm based on the examination of the distance field between the mating tooth surfaces using a quad mesh in a tangent plane as reference. Kolivand and Kahraman [33] used the ease-off topography, surface of action and roll angle surface to predict the unloaded transmission error and contact pattern. Vijayakar [34] proposed an discrete optimization method for finding the points of minimum distance in both tooth surfaces to solve the contact problem. Lin and Fong [31] proposed the use of a numerical approach to determine the coordinates of the contacting points according to the surface position vector exclusively, avoiding the use of the normal vector. In a previous work, Bracci [35] proposed an interesting fast geometric approach for the estimation of the contact pattern without the need of taking into account the curvature of the surface. In that work, the instantaneous contact area is estimated employing a surface intersection procedure that mimics the marking compound removal during meshing. Following the line of these papers, a new approach for unloaded TCA is proposed in the present work. The objectives considered during the design of the algorithm were the following: (i) it had to be robust, general and applicable to any type of gear, including types with line contact and types with point contact; (ii) it had to work properly for any relative position of the tooth contact surfaces (from aligned to misaligned), including edge and non-edge contacts; (iii) the final accuracy had to be parameter dependent, to be able to be controlled by the client of the algorithm, and (iv) the computational cost had to be as low as possible.

The proposed method is a geometric approach based on the discretization of the tooth contact surfaces and the progressive adaptive refinement of the obtained meshes to solve the contact problem and to compute the instantaneous contact area for each position of the gear set along the gearing cycle. This approach is based on a previous work of the authors [36], that was tested with spur gears and supposed a first approximation to this final approach. In that work, the algorithm was simple, and not very efficient. However, in the algorithm presented here, important refinement and update steps were introduced to improve the ratio accuracy vs computational cost. The final algorithm has been tested with several cases to demonstrate its robustness and efficiency.

2. Prerequisites

The proposed approach has been formulated assuming the existence of an analytical model of the tooth contact surfaces. Consequently, the approach requires the existence of some algorithms (or functions) to compute the geometry of the teeth and certain parameters along the gearing cycle. Most of these functions involve simple geometric calculations while others have been extensively studied and can be found in the literature. For these reasons and for the aim of brevity, only a concise description of these required resources is presented.

R1. Parametric functions defining the tooth contact surfaces. The contact surface of a gear tooth is considered as defined as a parametric function ($\vec{S} : \Omega \in \mathbb{R}^2 \to \mathbb{R}^3$) that provides the 3D spatial coordinates (x, y, z) of a surface point from its parametric coordinates (u, v). Since there are two possible contact surfaces in one tooth (left and right sides, Fig. 1a), the contact side must be specified as well. Furthermore, the formulation of the parametric function is different from one gear