Mechanism and Machine Theory 126 (2018) 210–224

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

A nonlinear multi-point meshing model of spur gears for determining the face load factor

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ARTICLE INFO

Article history:
Received 6 December 2017
Revised 25 February 2018
Accepted 12 April 2018

Keywords:
Spur gears
Face load factor
Load distribution
Finite element method
Beam elements
Nonlinear stiffness

ABSTRACT

The face load factor, which takes into account the influence of the non-uniform distribution of the load over the face width on the resulting stresses, is a significant coefficient of the load capacity calculation of spur gears. In this study, a practical nonlinear multi-point meshing model of spur gears is proposed for the determination of the face load factor. Nonlinear gear meshing conditions over the face width can be simulated precisely and efficiently using the proposed nonlinear multi-point meshing model, which is composed of multiple nonlinear springs along the line of action and rigid bars connected with shaft beam element models. The static equilibrium condition of the entire spur gear system is obtained through an iterative calculation process, and both the load distribution and face load factor are obtained. The effectiveness and advantages of the proposed model are demonstrated through comparisons with different types of contact analysis models presented by previous studies.

1. Introduction

Spur gears are very common in mechanical transmission systems. Calculation methods based on influence factors are widely used by gear designers to predict the load capacity of spur gears, such as the ISO Standard 6336 [1–6] and the AGMA Standard 2001-D04 [7]. Among the influence factors, the face load factor, which takes into account the effect of the non-uniform distribution of the load over the face width on the resulting stresses, significantly influences the load capacity calculation for spur gears. Although both the ISO and AGMA standards supply analytical approaches for face load factor calculations, the accuracies of these calculations are limited by the simplifications and assumptions of the shaft deflection calculations; these calculations are sufficiently accurate only for common gear structures under simple load conditions [8].

Gear meshing conditions can be obtained more visually and precisely by contact analysis methods than by the analytical methods supplied by the standards. Atanasovska and Nikolic [9] developed a three-dimensional (3D) finite element model of a spur gear for a numerical calculation of its face load factor and studied different influence factors on the load capacity of spur gears, including the addendum modification coefficient [10], the stiffness and base pitch deviation [11], and the nominal load [12]. Li conducted a series of research studies on the effects of machining errors, assembly errors, tooth modifications, transmitted torque [13–15], addendums and contact ratios [16], and the shape of gear webs [17] on the contact strength, bending strength, and basic performance parameters of spur gears based on the finite element method. To reflect the influence of the deflections of shaft supports on the gear meshing tendency, a group of authors proposed a shaft-gear

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https://doi.org/10.1016/j.mechmachtheory.2018.04.010
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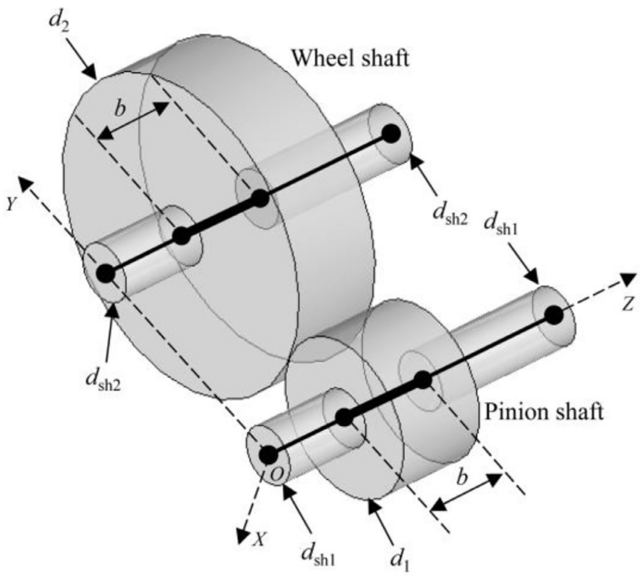

Fig. 1. Illustration of the beam element models of the shafts.

model for the computation of the face load factor and misalignments of spur gears based on the finite element method [8,18]; however, because of the single rigid connection between the gear and the shaft, the model cannot reflect the influence of the portion of the shaft under the gear rims that deflects due to torsion. They improved the shaft-gear model by considering the torsional deflection via distributed rigid connections between the gear and the shaft [19]; however, the modeling process when using multiple rigid connections is inconvenient.

In conclusion, to accurately obtain the load distribution and the face load factor of spur gears, many of the previous studies relied on 3D contact analysis executed in commercial finite element analysis software, such as ANSYS or ABAQUS, which demands precise modeling of the gears and system components, and both of the modeling and analysis processes are time-consuming.

This study aims to provide a method to calculate the load distribution and face load factor of spur gears that is more efficient than the 3D contact analysis method and has a reasonable sacrifice of accuracy. A nonlinear multi-point meshing model is proposed for the simulation of the nonlinear meshing conditions of the spur gears. The shaft supports of the gears are modeled by beam elements with shear effects, and the influences of both the bending and torsional deflections of the shafts on the gear meshing are considered in the model. The static equilibrium condition of the entire gear system is obtained through an iterative calculation process, and the load distribution and face load factor are obtained. The effectiveness and advantages of the proposed model are demonstrated through comparisons with different types of contact analysis models presented by previous studies.

2. Numerical model of a spur gear system

2.1. Shaft beam element model

An improved type of classical Euler-Bernoulli beam element with shear effects is adopted to model the pinion shaft and the wheel shaft, and the stiffness matrices of the beam elements can be calculated according to Appendix A [20]. This beam element model has 3D compatibility and has been widely used in gear drive studies [8,18,19,21]. Moreover, to take into account the stiffness of the gear bodies (including the rims and webs), the diameters d_{sh1} and d_{sh2} of the circular sections of the beam elements within the range of face width b are replaced by the reference diameters d_1 and d_2 of the pinion and wheel, respectively, as shown in Fig. 1 [8,18,19]. The stiffness matrices of the pinion shaft and wheel shaft are expressed as $\mathbf{K}_{s1}$ and $\mathbf{K}_{s2}$, respectively, which are obtained by the assembly from the stiffness matrices of the beam elements.

2.2. Nonlinear multi-point meshing model of a spur gear pair

To simulate the gear meshing over the face width, N equivalent meshing elements are built, i.e., the shafts within the range of the face width b are divided into N–1 beam elements evenly with N nodes, as shown in Fig. 2. $OXYZ$ is the global coordinate system, and the origin O is the node of the beam element model that lies on the left face of the pinion shaft. Nodes o_1^1 and o_2^1 are the nodes of the beam element models that lie on the left faces of the pinion and wheel, respectively,