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Transient meshing performance of gears with different modification coefficients and helical angles using explicit dynamic FEA

Yumei Hu [a], Yimin Shao [a,*], Zaigang Chen [a], Ming J. Zuo [b]

[a] State Key Laboratory of Mechanical Transmission, Chongqing University, China
[b] Department of Mechanical Engineering, University of Alberta, Canada

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ABSTRACT

The gearbox, as the main part of power transmission of many mechanical systems, plays a critical role for the performance of the system. The transient meshing performance of the gears is dependent on their structural parameters like modification coefficient and helical angle among others. In this paper, the effects of modification coefficients and helical angles on the transient meshing performance of the gears are investigated using the method of explicit dynamic finite element analysis (FEA) in an energy point of view. The relationships between the transient meshing performance and modification coefficient or helical angle of gears are obtained by explicit dynamic simulation. The simulation results demonstrate that explicit dynamic FEA can be used for choosing these structural parameters in the design and manufacture of gears to enhance their transient meshing performance.

1. Introduction

Gearbox is a critical part of a power transmission system. It plays the role of providing the needed torque and rotational speed. Its performance directly determines the performance of the power transmission system. Optimal design of the gearbox for enhancement of the reliability and safety of the power transmission system has been of interest to engineers and researchers for decades.

There usually are manufacturing errors in gears and assembly errors when mounting gears in a gearbox. When a gearbox is being used, gear teeth experience deformation under load. These manufacturing errors and tooth deformation destroy the theoretical meshing conditions and cause the gearbox's transmission ratio to fluctuate. The consequences of such fluctuation include increased vibration, shock and noise of the gearbox, increased dynamic meshing force on the gear teeth, and decreased transmission accuracy. Analysis of the dynamic performance of a pair of meshing gears looks into such dynamic changes. From such analyses, better designs of gears can be produced.

Different from traditional gear design methods and the static finite element analysis (FEA) method, dynamic performance analysis can provide more information on gears' meshing, such as displacement, velocity, acceleration, stress, and strain of the gear pair at any point of time and at any point on a gear tooth. Much work has been reported on the study of dynamic and transient performance analysis of gearboxes.

Taking the rigidity of the connection between gears and shafts into account, Wang et al. [1] simulated the dynamic performance of a gear system using FEA and a new element type. Litvin et al. [2] employed asymmetric spur gears (different

* Corresponding author.
E-mail address: ymshao@cqu.edu.cn (Y. Shao).

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pressure angles on working and non-working surfaces) to reduce contacting and bending stress. Bajer and Demkowicz [3] simulated the dynamic contact impact problem of a general rigid body.

Shu et al. [4] employed an explicit time integral algorithm considering kinetic and static friction coefficients to analyze three-dimensional dynamic contact in a resisting medium. Lundvall et al. [5] dealt with the dynamic contact problem taking into account simultaneously profile modification and flank errors. Considering the effects of the changing gear stiffness, continuous loading and unloading of gears, friction between gear teeth, and damping and stiffness of bearings, Vedmar and Andersson calculated the dynamic gear tooth force and bearing forces, and analyzed the gears' transient performance at different rotational speeds when the bearings were treated as rigid and non-rigid [6].

Ibrahimbegovic et al. [7] used an explicit–implicit time integral algorithm to analyze the nonlinear dynamic performance of a multi-body. Lin and Kuang [8], considering the effects of meshing stiffness, damping ratio, load distribution, tooth profile, and temperature, applied a new algorithm to simulate the mutual reaction between dynamic contact loads and wear on surfaces of gear teeth. Ambarisha and Parker [9] used a lumped-parameter model and a finite element model, considering the effects of excitation due to meshing stiffness change, angular contact, and gear tooth contact loss, to conduct nonlinear dynamic analysis for planetary spur gears.

Nonlinear vibration analysis of spur gears with machining errors was done by Bonori and Pellicano [10] using a classical model with a single degree of freedom, time-varying stiffness, and backlash. But they did not consider the effects of gear parameters such as modification coefficient, helical angle, and profile modification.

Parker et al. [11,12] did a series of studies on the dynamic behaviors of gear systems. The dynamic responses of a planetary gear system with a semi-analytical finite element formulation that admits precise representation of the tooth geometry and contact forces was studied and the dynamic response of spur gear pair using a finite element/contact mechanics model was investigated, and comparisons were made between the results and those of the experiments. The dynamic transmission errors and contact forces were mainly concerned.

Liu and Parker [13] studied the effects of tooth profile modification on multi-mesh gear-set vibration with considering the dynamic load distribution between the individual gear teeth and the influence of variable mesh stiffness, profile modifications, and contact loss. They also examined the nonlinear, parametrically excited dynamics of idler gearsets and asymptotic perturbation analysis was discussed in their paper [14]. In addition, they studied the influences of tooth friction on parametric instabilities and the dynamic response of a single-mesh gear pair. An iterative integration method and a numerical method were used and the impacts of friction coefficient, bending effect, contact ratio, and modal damping on the stability boundaries were revealed in their paper [15]. Alfredsson et al. [16] studied the role of a single surface asperity in rolling contact fatigue with the FEA approach and their simulation results validated by experiments have the same order of magnitude as ours in this paper.

The reported studies reviewed above can be divided into three categories—the first one is on the effects of different external loading cases on the dynamic behavior of the gear system, the second is on the effects of gear parameters on the dynamic behavior of the gear system, and the last one is a combination of the first two categories.

To obtain the solution on the dynamic behavior of a gear system with the implicit static algorithm, one needs to recalculate a large-scale nonlinear stiffness matrix at every time step and this process needs to be repeated many times for the algorithm to converge. This algorithm requires a large memory space and takes a long CPU time to execute. On the other hand, the explicit dynamic finite element approach has the disadvantages that it is limited by the stability rule "Courant", its time step is very small, and the zero energy mode, also called the hourglass deformation mode, may be produced sometimes with the single point Gauss integral. The zero energy mode problem can be avoided through proper control and this has been implemented in ANSYS. The explicit dynamic finite element approach does not have the disadvantages of the implicit static finite element approach mentioned above and is capable of dealing with large-scale contact problems efficiently.

On the effects of gear parameters on the dynamic performance of the gear system, few studied the transient performance of the gear meshing process with the dynamic explicit finite element approach. The effects of gear parameters such as helical angle and modification coefficient on the transient performance of a gear system have not been reported in the literature. Preliminary studies on the relationships among the modification coefficient, helical angle, and effective stress have been reported in Ref. [17]. There is a need to study the effects of modification coefficient and helical angle on the transient meshing performance of a gear system.

For the way to exhibit our results, analysis in frequency domain can reflect a lot of micro specific information of gear systems, but the statistic parameters in the time domain can also express the our concern results clearly and more directly. The dynamic performances in this paper are described at a macro energy point of view.

In this paper, we provide a complete three-dimensional finite element analysis model of gear meshing based on our earlier work [17]. The transient performance of gears with different modification coefficients and helical angles is investigated with the explicit dynamic finite element approach. For the corner contact problem, its effects on the dynamic performances of gears are negligible by profile modification (see Ref. [13]). Profile modification of this model utilized here has incorporated. And the vibrations of the gears in this paper are induced by the interactive action in the meshing process. They are not separate from each other, and only the inner parametric excitations are investigated here without considering the outside parametric excitation like motors, loads, bearings, etc., which will be studied in the later work. Choosing proper parameters like modification coefficient and helical angle based on the dynamic performance of the gear system is studied in this paper. The simulation results can predict the dynamic performance and can be used as guidelines in the gear design phase. Vibration is just one of the gear dynamic performances, and so is the sound. The coupling of vibration and sound in the gear system will be studied in future work and is out of the scope of this paper.