

A Method for Predicting the Dynamic Root Stresses of Helical Gear Teeth

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American Gear Manufacturers Association



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

The AGMA dynamic factor has traditionally been treated as a dynamic "load" factor where tooth load is the sum of all of the tooth forces that are applied along the plane of action at any instant in time. Knowing the total load, however, says little about the degree of load sharing or the load position on a tooth when the dynamic load is a maximum. Hence, the dynamic load factor does not directly address the value of either dynamic contact stress or dynamic root stress; quantities that a gear designer should be more interested in. This paper's main focus is the prediction of dynamic root stresses.

The approach presented in this paper is a relatively simple methodology that does not use finite elements. The method merges the capabilities of a sophisticated load distribution and dynamic excitation prediction method with a time domain gear dynamics simulation. Because a time integration type of simulation is used, the method can handle both steady state and transient inputs. Inputs that are possible include tooth profile and lead modifications, misalignments, and spacing errors. These can take on average values or can have discrete changes applied from tooth to tooth. Examples of the use of some of these errors are provided in this paper.

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INTRODUCTION

The dynamic factor used in gear design has been the subject of numerous studies, most of them analytic in nature. Papers by Ozguven and Houser [1] and Harianto and Houser [2] document many of these analytical studies. In the paper by Harianto and Houser, three types of dynamic factors are used for spur gears. These are the dynamic load factor used by AGMA, a dynamic load intensity factor that is analogous to a dynamic contact stress factor, and a dynamic bending moment factor that is analogous with a dynamic root stress factor. This paper further extends the analyses, such that a dynamic root stress factor may be predicted for both spur and helical gearing. This factor accounts for not only dynamic effects, but also load distribution effects in both the transverse and axial directions. The original method proposed by Harianto and Houser [2] is only appropriate for spur gears while the procedure presented here is also appropriate for helical gears.

METHODOLOGY

Previous work in predicting dynamic root stresses of helical gears is very sparse. Today it is possible to

create a dynamic finite element model that has both the resolution to predict load distribution and root stresses and the ability to function in a time domain dynamic solution. However, this model would still be extensively time consuming, both in creating the model and in executing it. The only approach of this type that the authors are aware of uses Vijayakar's finite quasi-prism methodology, but this method has only been applied to two-dimensional dynamic problems [3]. Another approach that uses vibrational normal modes has been applied by Boerner [4]. Boerner's method uses a Fourier series analysis coupled with knowledge of natural frequencies and mode shapes of the system to solve for steady state responses. Sainsot, Velez, and Berthe [5] also have performed similar analyses using normal mode techniques.

The time domain approach presented by Harianto and Houser [2] uses a load distribution prediction program to obtain the transmission error and mesh stiffness variation as functions of gear rotation. These quantities are then used as excitations to a multi-degree of freedom time domain dynamics simulation. This method works well for spur gears but has limitations for helical gears because it is extremely difficult to carry along all modeled points of contact in the dynamic simulation. The approach presented in this paper allows for the prediction of time domain

values of both root and contact stresses along each contacting line and at any root position.

The basis of the dynamic portion of the analysis presented here is the dynamic transmission error method developed by Ozguven and Houser [6]. The computer program DYTEM that is used to apply this methodology uses a Runge-Kutta time integration procedure to solve the six-degree of freedom dynamic model presented in Fig. 1. Excitations to the system are time varying mesh stiffness, $k(t)$ and displacement transmission error input, $e(t)$, that are depicted in the first segment of Fig. 1. Nonlinearities such as loss of contact and back tooth contact are predicted using this methodology. However, when heavy nonlinearities such as those occurring in gear rattle are being simulated, chaotic solutions and/or non-convergence may arise such that special care must be taken when applying Runge-Kutta type algorithms (Barlow, Padmanabhan and Singh) [7].

Fig. 2 shows the scheme for predicting the dynamic root stresses of helical gear teeth. First, the static transmission error and mesh stiffness variations are predicted using the Load Distribution Program (LDP) [8]. Then these values are used to compute dynamic loads (the values used to compute dynamic load factors in rating procedures) using the time domain simulation called DYTEM [6]. Now the load distribution program is re-run with the loads that are predicted with the dynamics program. This procedure works well in most cases, but will have problems if the dynamic loads are so great that there are significant load distribution shifts when going from the static to the dynamic situation. Experience has shown, however, that for reasonably aligned helical gears, these situations seldom occur. Brief descriptions of the programs used are provided in the Appendix of this paper.

SPUR GEAR EXAMPLE

A spur gear example will be used to present verification that the new method provides similar results for predicting dynamic root stress factors as those obtained with Harianto and Houser's [2] method that predicts dynamic tooth bending moments. Here we define dynamic root stress factor (DRSF) and dynamic bending moment factor (DBMF) as follows:

$$\text{DRSF} = \frac{\text{Peak dynamic root stress}}{\text{Peak static root stress}}$$

$$\text{DBMF} = \frac{\text{Peak dynamic bending moment}}{\text{Peak static bending moment}}$$

where bending moment is found by computing the product of the tooth normal force and the distance from the force application to the critical radius in the tooth root region.

The geometry of the spur gear set used in this example is shown in Table 1. This set has the same 1:1 ratio geometry as was used by Rebbechi, et al [9]. The gears in the analysis were run with no profile modifications so that at the transitions from single to double tooth pair contact there are steps in the loading. This situation is far more severe than most other loading cases that are encountered with gears that have appropriate tip and root relief to reduce the step inputs [10]. In reality there is corner contact that must also be taken into account at these step locations [11]. Corner contact analysis reduces the steps, but results in impacts that are undesirable. The techniques described here have the ability to deal with corner contact, but for this paper's purposes corner contact is not considered.

Fig. 3 shows the static transmission error and mesh stiffness values that are sent from LDP to DYTEM. Fig. 4 shows the dynamic torque that is computed by DYTEM and then used by LDP to compute dynamic stresses. In all simulations, the damping ratio value of 0.06 is used for each uncoupled vibration mode. Fig. 5 shows two modeling situations, one using the original DYTEM procedure that only predicts the dynamic bending moment and the second being the new procedure using a program called DLDP. In each case, the fine line is the predicted result for static loading and the bold line is the predicted dynamic response. The results show that the shapes of the curves are practically identical, thus showing for these spur gears that the two models give similar results. Note that the peak dynamic stress does not occur at the same position in the meshing cycle as the peak static stress. Although not shown, when computing the dynamic root stress factor with DLDP, we must check the root stresses across the entire face width of the gear prior to taking the ratio between the dynamic and static values. Fig. 6 shows a similar comparison, only at a speed at which one of the system natural frequencies is being excited, thus giving a much larger dynamic factor.

Fig. 7 shows the effect of speed on the dynamic factors predicted by the two prediction methods. These plots show that, except for the region at about 13286 rpm (6200 Hz), the predictions are almost identical, thus giving more credence to the new method.

Tip relief was added to each of gears so that the transmission error was minimized. Fig. 8 shows the profile shapes that provide "optimum" tip relief and Fig. 9 shows the gear's predicted bending moment and root