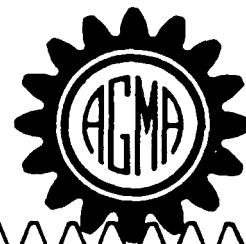


Refinements in Root Stress Predictions for Edges of Helical Gear Teeth

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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

Industry demands for higher power density gearboxes to improve product performance require utilization of the load carrying capability of every inch of available face width. As a result, load distributions and the resulting root stresses are of considerable importance. Current analytical methods include three dimensional finite element analysis (FEA) and combinations of Wellauer and Seireg's moment image method with two dimensional boundary element analysis or beam bending formulas. Three dimensional FEA, although reliable, is time consuming and of great expense in comparison to the use of classical techniques and approximations. In helical gears these approximations give reasonable estimates of root stress distributions along the face width but lack the accuracy to design to engineering limits.

Based upon finite element and experimental results, a discrepancy in the approximate methods is the stiffness change in the normal plane associated with the ends of helical gear teeth. Tooth stiffness is lower at the acute edge, where the normal force associated with tooth contact protrudes beyond the transverse edge of the gear on the back side of the tooth. The opposite result occurs at the obtuse edge, where the normal force is not producing beyond the transverse edge of the tooth.

Analytical and experimental studies for a limited number of cases have been completed. The experimental results are used to verify the simplified three dimensional FEA parametric study on the effect of helix angle. The parametric study results, when completed, will be used to determine a root stress correction factor. The focus of this paper is on the initial parametric results and experimental studies, with an introduction to possible correction techniques. The correction factors are currently being researched and will be the topic of future publications.

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Introduction

Variation in root stresses at the edges of helical gear teeth due to geometric differences is conceptually realistic and easily grasped. By placing a point load at each edge of a helical gear tooth as in Figure 1, it is easy to see two distinct geometries are involved. At the left end the normal plane of the load protrudes beyond the tooth edge and is referred to as the acute edge. This edge can be thought of as 'less stiff' than an equivalent spur tooth edge since less material exists directly behind the load. At the opposite end, called the obtuse edge, the load is supported by the additional material that extends beyond the plane of the load. This material can be thought of as a slight 'buttress', effectively making the edge more stiff than an equivalent spur gear tooth. Past research efforts have mentioned this potential effect [1] [2] and some work has been completed in this area [3]. Current approximations are considered to be adequate for practical gear design, especially when safety factors and lead modifications designed to centralize contact are taken into account. However, these effects may become important in high power density applications and improved predictions are always beneficial to gear design.

The driving factor behind the omission of edge effects in helical gear analysis is computational speed. Full three dimensional finite element analysis can accurately predict root stresses and can include the edge effects but is costly in terms of preparation time, program costs, and computational time. Special purpose gear design programs greatly reduce the computational time involved but rely more heavily on empirical mathematical formulations which do not easily lend themselves to the inclusion of edge effects.

Therefore, the most desirable solution is to find an appropriate modification or 'adjustment' to the current calculation techniques which includes the edge effects with a reasonable degree of accuracy.

The goal of this research is to further develop the root stress prediction capability of the Load Distribution Program (LDP) [4] and the associated post processor, GGRAPH. LDP and GGRAPH, computer programs for general gear analysis, are the result of research and development carried out at the Ohio State University's Gear Dynamics and Gear Noise Research Laboratory. Currently these programs account for stiffness reduction at the edges of gear teeth by application of Wellauer and Seireg's [5] moment image method to a two-dimensional boundary element model that analyzes the normal cross section of the gear tooth. For helical gears the edges of the teeth are assumed to be the spur equivalent, meaning that the tooth edge runs parallel to the normal plane of the tooth. This simplification is a reasonable approximation, especially for small helix angles. However, variations in the stresses due to edge effects will increase with increasing helix angle.

The results and information presented focus upon experimental data taken for a 14 degree helix angle gear, three-dimensional finite element analysis for an approximation of the gear tooth, and the helix angle parametric studies generated using the finite element model. Based upon a comparison of the values and properties of the experimental and analytical results, the FEA model is believed to be adequate for use in the determination of a correction for LDP. Corrections are currently being researched and one preliminary concept is presented.

Background

The following is a brief summary of the calculations involved with root stress predictions in the current calculation method. Determination of load distribution for the desired positions in the mesh cycle is accomplished using the elastic body contact method of Conry and Seireg [6]. Jaramillo's [7] solution for bending moments in an infinite cantilever plate, in conjunction with the moment image method of Wellauer and Seireg, uses the calculated load distribution to determine the moment distribution at the root of the gear tooth. The appropriate stress concentration factor is determined using two dimensional boundary element analysis for the normal plane tooth geometry. A more complete description of the process is given by Clapper [1].

Several previous studies involving root stress measurement and prediction have shown good correlation between experimental results, finite element analysis, and gear analysis programs. Yoshida [8] performed experimental measurements on 33 degree helical gears and found good agreement when proper misalignment was included in the LDP analysis. The same experimental data also shows good agreement with Borner [9]. Clapper [10] analyzed fully reversed root base stresses on 33 degree helical gears with the finite element program of Vijayakar [11]. However, the focus of these experiments was not to predict edge effects. The current edge effect studies are a logical extension to these successful research efforts.

Experimental Data

Extensive experimental data has been collected for a 14 degree helical gear using the instrumentation and data acquisition system developed by O'Neal [12]. A series of strain gages have been placed at each edge of a tooth at the critical radius determined by a two dimensional boundary element analysis [13]. The test gearset consists of a 23 tooth pinion and 43 tooth gear with 4.621 normal diametral pitch, 25 degree normal pressure angle, 3 inch face width, operating at a 7.5 inch center distance. The outer diameter and root diameter of the pinion are 5.704 and 4.663 inches respectively. The normal chordal thickness on the pinion is .345 inches at a diameter of 5.227. The corresponding values for the gear are 10.168, 9.127 and

.345 at a diameter of 9.773 inches. The gear geometry used in this experiment is quite advantageous for several reasons. The coarse pitch allows enough room in the root of the gear for proper placement of the strips of gages. The 3 inch face width insures that moment reflection from the opposite edge of the tooth will not convolute the test data. Placing the gages on the gear (10.168 OD) minimizes the amount of twisting that occurs in the gage strips.

In order to identify the effect of loading at various distances from the edge of the tooth, a piece of shim stock is placed on the tooth to simulate point loading as shown in Figure 2. The selected shim stock is thick enough so that the only point of contact during mesh occurs at the shim location but is less than the backlash setting. The shim is also made wide enough to support the contact load without crushing. The length of the shim is selected such that contact is maintained throughout a large portion of the mesh cycle without the risk of interfering with or damaging the gages. The selected shim for these experiments is 0.1X0.004X0.4 inches. The shim is placed on the gear in the transverse plane and is held in place by a small amount of grease. The shim starts at the edge and is indexed towards the center of the tooth by one shim width each test run.

A sample of one data run is shown in Figure 3. In this particular case the shim is located at the edge of the tooth. Gage 1 is located closest to the edge of the tooth and each proceeding gage is located farther in on the tooth. As expected, gage 1, located directly below the load point, shows the highest stress while gage 10, located over an inch away from the load point, shows no stress at all. The 'notch' in the data is attributed to friction. The normal load on the tooth results in a tensile bending stress in the strain gage. Due to friction, an additional load is seen in the data which changes sign dependent upon the direction of sliding. At the tip contact is sliding towards the strain gage, causing a compressive stress which subtracts from the bending stress. Once contact passes through the pitch point the direction of sliding reverses, and the friction force produces a tensile stress in the gage which adds to the bending stress.

A complete 'set' of data runs for tip loading at the acute and obtuse edges can be plotted together as shown in Figure 4 and Figure 5 respectively. Each data series represents a different point load location with the