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Analysis and Testing of Gears with Asymmetric Involute Tooth Form and Optimized Fillet Form for Potential Application in Helicopter Main Drives

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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

Gears with an asymmetric involute gear tooth form were analyzed to determine their bending and contact stresses relative to symmetric involute gear tooth designs which are representative of helicopter main drive gears. Asymmetric and baseline (symmetric) toothed gear test specimens were designed, fabricated and tested to experimentally determine their single-tooth bending fatigue strength and scuffing resistance. Also, gears with an analytically optimized root fillet form were tested to determine their single-tooth bending fatigue characteristics relative to baseline specimens with a circular root fillet form. Test results demonstrated higher bending fatigue strength for both the asymmetric tooth form and optimized fillet form compared to baseline designs. Scuffing resistance was significantly increased for the asymmetric tooth form compared to a conventional symmetric involute tooth design.

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Introduction

The objective of the work described in this article is to begin the process of evaluating the potential benefits of asymmetric involute gear teeth and optimized root-fillet geometry for helicopter main transmission applications. This involves not only quantifying performance improvements achieved by these concepts, but evaluating the practicality of manufacturing gears with asymmetric teeth and optimized root-fillet geometry for aerospace applications. This work was performed under the sponsorship of the Center for Rotorcraft Innovation, CRI. The authors are grateful to CRI for the opportunity to investigate these technologies.

In helicopter main drive applications, minimizing gear weight while maintaining the necessary balance of tooth bending strength, pitting resistance and scuffing resistance is given high priority during design of the gears. In many helicopter applications, gears are required to transmit high continuous torque loads in one direction but are lowly loaded in the opposite direction. Traditionally, spur gear designs in helicopter gear boxes utilize conventional (symmetric) involute teeth which provide the same torque capability in both the drive and coast loading directions. An overall weight reduction may be realized by using gears with higher capability than conventional gears in the primary drive direction, even if some capacity is sacrificed in the secondary coast direction.

The design intent of asymmetric gear teeth is to improve performance of the primary drive profiles at the expense of the performance for the opposite coast profiles. In many cases the coast profiles are more lightly loaded, and are loaded only for a relatively short duration. Asymmetric tooth profiles make it possible to simultaneously increase the contact ratio and operating pressure angle in the primary drive direction beyond the conventional gears' limits. The main advantage of asymmetric gears is contact stress reduction on the drive flanks,

resulting in reduced gear weight and higher torque density.

Many traditional helicopter spur gear designs utilize circular root-fillet geometries that are form ground along with the gear flanks. Gear specimens were analyzed, designed and manufactured to compare the single tooth bending fatigue strength of gears with optimized root-fillets with gear specimens having circular root-fillets.

The items addressed in this article include analysis, design, manufacture and test of gear test specimens with asymmetric teeth. Conventional symmetric tooth specimens were also produced and tested to provide a baseline for comparison. The design and manufacturing of the gear specimens is representative of helicopter main drive gears. Testing included single tooth bending fatigue and scuffing tests of both the asymmetric and baseline gears. Additionally, symmetric toothed gear specimens with optimized root fillet geometry were analyzed, designed, manufactured and tested in single tooth bending fatigue and compared to conventional specimens with circular root fillet geometry as a baseline.

Background

Minimizing gear weight while maintaining an acceptable balance of tooth bending strength, pitting resistance and scuffing resistance is given high priority when designing gears for helicopter applications. Typically helicopter main drive gears are required to transmit high continuous torque loads in their primary or drive direction. Torque loads in the opposite (secondary or coast) direction are lower in magnitude and of shorter duration than torques in the primary direction. In simple planetary gear arrangements often used in helicopter gear boxes, the planet gears are required to transmit load on both sides of their teeth due to contact with the sun gear at one mesh and contact with the internal ring gear at the other mesh. In these cases the size of the planet gear teeth are usually dictated by the requirements of the sun-planet mesh and stresses

are lower at the planet-internal ring gear mesh due to the more conforming contact. Traditionally spur gear designs in helicopter gear boxes are symmetric involute teeth which provide essentially the same torque capability in both the drive and coast loading directions. There may be an overall weight benefit from using gears with higher capability in the primary drive direction, even if some capacity is sacrificed in the secondary direction.

The design intent of asymmetric gear teeth is to improve performance of the primary drive profiles at the expense of the performance for the opposite coast profiles. The coast profiles are unloaded or lightly loaded during a relatively short work period. Asymmetric tooth profiles make it possible to simultaneously increase the contact ratio and operating pressure angle beyond the conventional gears' limits. The main advantage of asymmetric gears is contact stress reduction on the drive flanks, resulting in higher torque density.

Gears with asymmetric teeth have been known for many years. Prof. Willis wrote about buttress gears in 1838 [1]. Since then many articles on the subject of asymmetric gears have been published. However, there are very few practical applications of such gears. One of them was an application of the asymmetric teeth in the planetary gearbox in a turboprop engine [2].

The work described herein presents the design, manufacture and test of:

- Asymmetric involute gears with circular root-fillet geometry
- Symmetric gears with optimized root-fillet geometry

The asymmetric tooth geometry and optimized fillet geometry was developed by the Direct Gear Design[®] method [3]. Unlike traditional gear design, this method does not use a preselected basic or generating gear rack to increase the gear tooth profile, but defines the gear tooth formed by two involutes of two different base circles (in case of asymmetric teeth) with the arc distance between them and tooth tip circle to avoid the sharp pointed tooth tip. If these base circles are identical, the gear has symmetric teeth. The fillet between teeth is not in contact with the mating gear teeth. However, this portion of the tooth profile is critical because this is the area of the maximum bending stress concentra-

tion. The fillet profile is designed independently and a subject of optimization providing minimum bending stress concentration and sufficient clearance with the mating gear tooth tip in mesh [4].

Test specimen design and analysis

Test specimen gears designed for this program are representative of helicopter main drive gears in diametral pitch, pressure angle, material and processing. Standardized conventional toothed designs have been developed for bending fatigue and scuffing test rigs that Boeing Rotorcraft uses for gear research. The standardized test specimen designs were modified to incorporate the asymmetric tooth configuration and another for the optimized fillet configuration. Specimens of each type were manufactured using aerospace production techniques and requirements. A manufacturing approach was developed with a goal of reducing material and processing variability.

The single tooth bending fatigue tooth gears are 32 tooth gears with groups of four teeth removed per quadrant to allow for assembly into the single tooth bending fatigue, STBF, test fixture. Table 1 and Table 2 summarize the basic design parameters for the single tooth bending fatigue test gears, and also show these design parameters for the baseline specimen design.

Table 1. Single tooth bending fatigue test gears

Parameters	Symmetric teeth with circular fillets (baseline)	Symmetric teeth with optimized fillets	Asymmetric teeth with circular fillets
Number of teeth	32	32	32
Diametral pitch	5.3333	5.3333	5.3333
Pressure angle	25°	25°	35° drive 15° coast

Table 2. Scuffing test gears

Parameters	Symmetric teeth with circular fillets (baseline)	Asymmetric teeth with circular fillets
Number of teeth	30	30
Diametral pitch	5.3333	5.3333
Pressure angle	25°	35° Drive 18° Coast

The optimized fillet gear is similar to the baseline design with the circular fillet replaced with the optimized root fillet. A comparison of the geometry between the circular fillet and the optimized fillet geometries are shown in Figure 1.

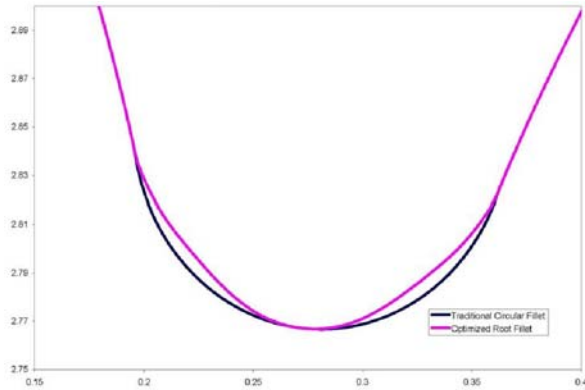


Figure 1. Coordinate plot of circular fillet and optimized fillet design geometries

Similarly, the scuffing test gears are within the design experience range of typical main transmission helicopter power gears. The test gear design is of similar size to a first stage planetary sun-planet mesh that can be found in a medium to large size helicopter. Basic parameters for the scuffing test gears are summarized in Table 2.

Test specimen analysis

The test specimen gear designs were analyzed to predict their bending and contact stresses, and compared to stresses predicted for the baseline test specimens.

Asymmetric tooth geometry – single tooth bending specimens

Single tooth bending fatigue specimens were designed employing asymmetric involute teeth. For comparison, conventional symmetric involute gears were designed and tested. Both asymmetric toothed and conventional baseline specimens employ ground circular root-fillets.

The asymmetric gear tooth form for the STBF (Single tooth bending fatigue) test specimens is nominally based on the standard STBF gear specimen. This enables the asymmetric toothed specimen to fit the existing test fixture with only minor modifications for tooth load angle, and provides a direct comparison between asymmetric and conventional gears of the same diameter and

face width. Finite element analysis (FEA) meshes of the baseline symmetric toothed gear specimen and the asymmetric toothed specimen are shown in Figure 2 and Figure 3.

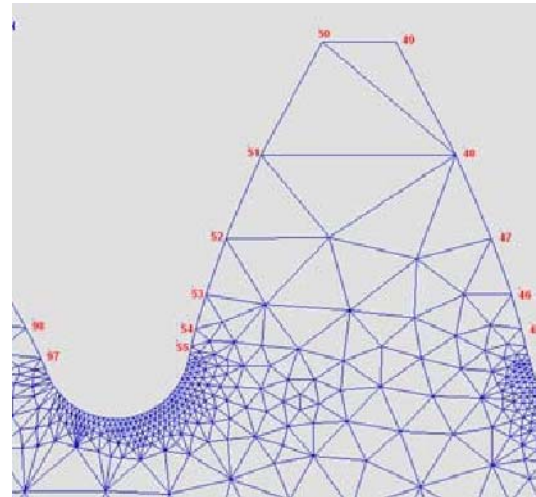


Figure 2. FEA mesh –STBF baseline symmetric tooth

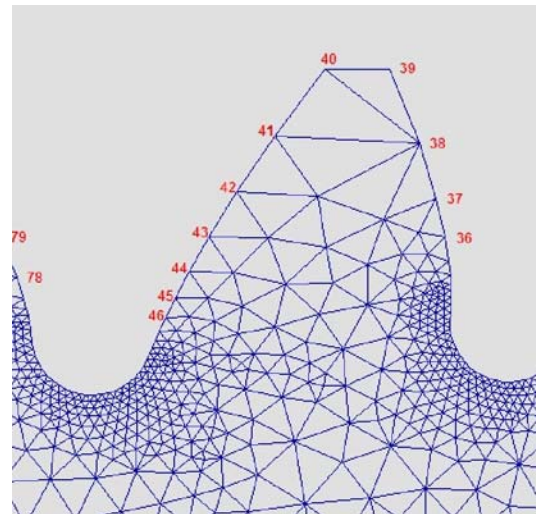


Figure 3. FEA mesh – STBF asymmetric tooth specimen

The gear parameters and calculated bending stresses for the STBF test gears are presented in the Table 3.

Asymmetric tooth geometry – scuffing test specimens

FEA meshes of the baseline (symmetric) scuffing gear tooth and the asymmetric scuffing gear tooth are shown in the Figure 4 and Figure 5 respectively.

The gear parameters and comparison results are presented in the Table 4.