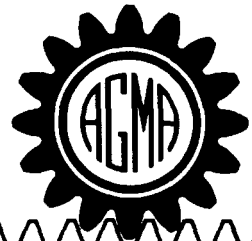


UltraSafe Gear Systems - Single Tooth Bending Fatigue Test Results

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American Gear Manufacturers Association



TECHNICAL PAPER

UltraSafe Gear Systems - Single Tooth Bending Fatigue Test Results

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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

Current design methodologies as applied to rotorcraft transmissions yield reliable, safe, and weight effective systems. In general, weight and performance (i.e., torque transmission per pound of transmission weight) are the primary active variables while safety is addressed by monitoring the design so that conventional criteria, such as calculated stresses, are kept within established allowable levels. This procedure is almost universally applied and has been quite successful both at Boeing and at other major rotary wing firms. It is possible, however, to raise these already good safety characteristics to ultra safe levels through the use of certain design approaches. UltraSafe gear system design will require a basic change in the overall philosophy of design as it is practiced today. This change must be revolutionary rather than evolutionary.

In order to develop an UltraSafe transmission a basic paradigm shift will be required. In addition to addressing the design process from the typical "prevent a failure from occurring" point of view, it will also be necessary to view the system from the point of view of "what happens when a failure occurs." This design philosophy was presented in 1997.¹⁾ The currently reported effort describes single tooth bending fatigue testing which was accomplished to test the viability of certain UltraSafe design features.

A dual rim gear blank configuration was developed to be compatible with existing single tooth bending fatigue test equipment. Gears were manufactured and seeded faults were implanted to simulate unexpected defects in various portions of the highly loaded gear tooth and rim sections. High loads were applied to initiate cracks at the seeded faults after which the loads were reduced to allow the cracks to propagate. Crack propagation was monitored by measuring effective mesh stiffness and applied loading. This paper presents the results of this testing which demonstrate the feasibility of creating redundant structural load paths in a portion of a typical gear blank. This redundancy provides both warning of an impending failure and a reasonable period of safe operation after initiation of a failure during which a safe landing may be affected.

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¹⁾ AGMA Paper No. 97FTM10, "UltraSafe Gear Systems For Critical Applications Initial Development," Raymond J. Drago, et. al., AGMA Fall Technical Meeting, 1997

Background

The gear system in a helicopter is a very critical system. A single failure in a single gear can cause a loss of power to a rotor which could then result in a loss of the aircraft's ability to remain aloft. In the event of a gear failure, the aircraft must land immediately, however, depending on the location and mission of the helicopter, an immediate landing may not be possible. It is therefore important that a rotary winged aircraft have the ability to continue flying for a reasonable period of time after a failure has been detected. This, of course, assumes that the failure has been detected at an early stage in its progression. Improvements have been made in failure detection^{1,2,3} but some failure modes progress quickly thus, detection alone may not be a sufficient safeguard. Because of these circumstances, Boeing has been conducting a program to identify design characteristics for UltraSafe gear systems for these rotorcraft applications^{4,5,6}.

One of the areas under investigation is the configuration of the gear blank itself and its relation to the direction and manner in which a crack from an unanticipated failure might initiate and propagate. The development of a dual rim concept shows promise, based on both Finite Element Analysis (FEA) and Boundary Integral Element Method (BIE) based studies, of providing enhanced safe operation under these conditions. The BIE and FEA analyses, Figure 1, were carried out cooperatively and in parallel by Boeing and NASA Glenn Research Center⁷.

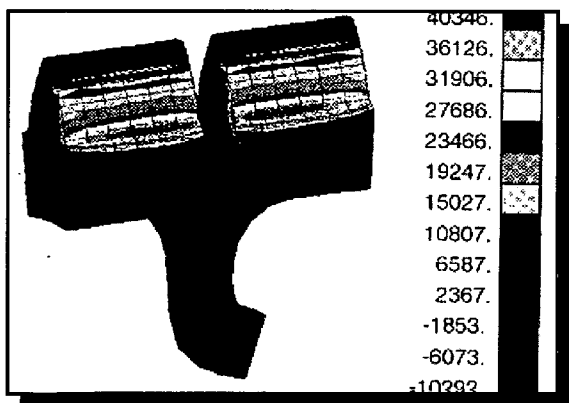


Figure 1 - Dual Rim FEA Stress Analysis Results

In order to test this hypothesis and to identify a correlation between the FEA/BIE studies and crack initiation and propagation (both rate and direction) a Single Tooth Bending Fatigue Test (STBFT) program was conducted developed by Boeing and conducted at Penn State University under Boeing direction. This program obtained controlled, experimental data and investigated the safety characteristics of the dual rim test gear design. The theory of the dual rim concept is that a randomly generated crack will progress through one half of the gear blank while

leaving the other half intact to carry the load, albeit at a higher stress. While carrying the load after a crack has initiated and is propagating is very important, it is even more important that warning be provided that a crack exists and is propagating. Added operating time combined with adequate warning yield UltraSafe gears.

Program Objectives and Tasks

The objectives of the program were to design a dual rim test gear which is reasonably representative of a typical aircraft gear and then to devise and conduct a test program at which would yield information upon which the effectiveness of the concept could be evaluated. The test gear selected is the standard Boeing STBFT gear, Figure 2, which is roughly representative of the tooth configuration used in typical tandem rotor helicopter main rotor planetary stages, modified to include the dual rim design.

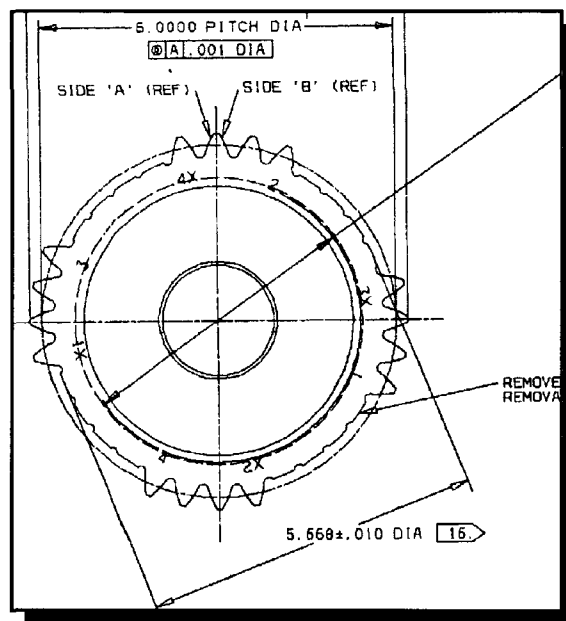


Figure 2 - Single Tooth Bending Fatigue Test Gear

The STBFT test facility at Penn State was modeled after the STBFT facility in use at Boeing with the added feature of computer monitoring of both load and deflection. These combined capabilities allowed us to test the dual rim concept safely and to use deflections as a measure of crack propagation. The test program conducted at Penn State, therefore, investigated the safety characteristics of the dual rim gear design, characterized the crack initiation, propagation path and propagation rate, and determined the relative cycles to failure. The unique features of the Penn State test rig were required to successfully test the UltraSafe concept.

Seeded Faults

A test methodology was established for detecting cracks

which were initiated from seeded faults, and to monitor crack progression rate, as well as path of crack growth. A total of eight tooth bending fatigue tests were conducted, each with a seeded fault in a different location. The seeded faults were small notches produced by Electrical Discharge Machining (EDM) at various locations in the toothed region of the test gear. Figure 3 shows a typical seeded fault notch while Figure 4 shows a typical crack initiated from a seeded fault notch.

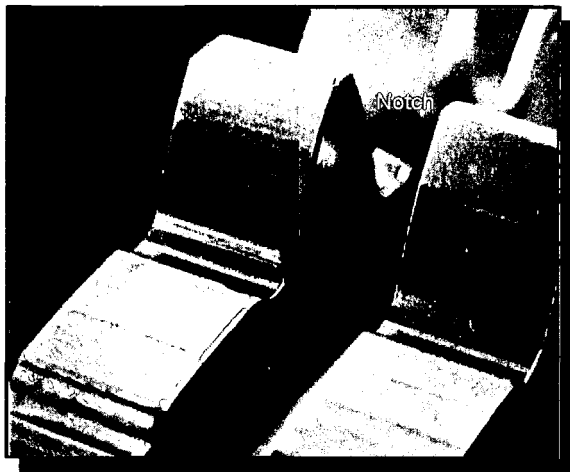


Figure 3 - Typical Seeded Fault Notch

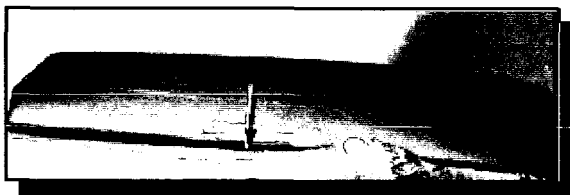


Figure 4 - Crack Initiated From Seeded Fault, Arrow indicates seeded fault (EDM Notch) location

Seeded faults were created in the high stress regions of tooth roots at several locations across the face width to simulate various potential failure locations. Within the root fillet region, some were located relatively high up, close to the involute tangency point while others were located further down in the fillet, closer to the root diameter.

While our primary goal was to investigate the fail safe characteristics of the dual rim configuration, we also wanted to determine if the dual rim itself created any stress conditions which would introduce new potential failure modes. The FEA and BIE analyses both indicated that the highest stresses will still occur in the tooth roots and the groove fillet region between the two rims were in no way critical, however, in order to investigate this experimentally, seeded faults were also introduced into the groove region between the rims, as Figure 5 shows.

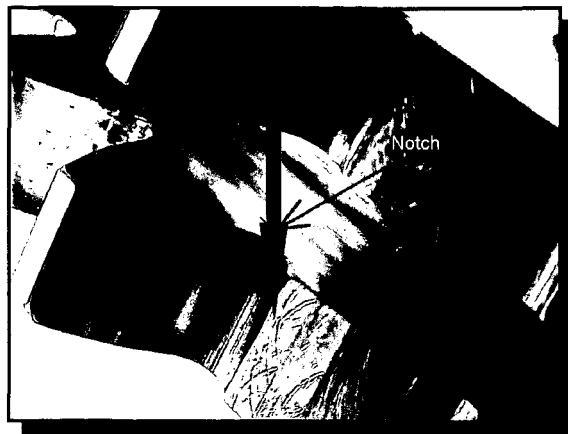


Figure 5 - Seeded Fault In Groove Region

Test Rig Modification

In order to test the dual rim configuration, some modifications were required to the standard single tooth bending fatigue test rig at Penn State. The Boeing dual rim test gear, Figure 6, is a 5.3333 DP, 32 teeth spur gear with a total face width of 1.0 inch and an effective face width of 0.75 inch (0.25 groove width). Furthermore, the Boeing gear has a web thickness of 0.25 inch which is less than a standard STBFT gear.

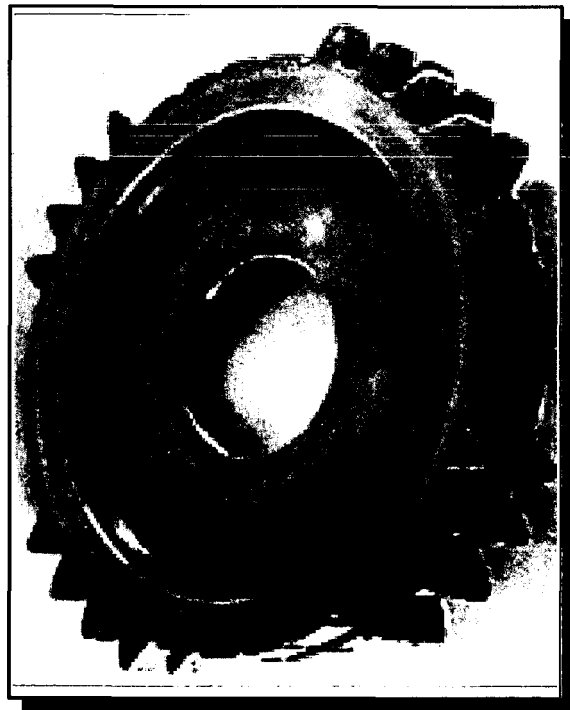


Figure 6 - STBFT Gear

Although, the Penn State STBFT rig is designed for the same tooth geometry, it accepts test gears with a uniform face width of 0.375 inch. The largest face width that could previously be accommodated based on available clearance