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Gear Resonance Analysis and Experimental Verification Using Rapid Prototyped Gears

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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

Determination of gear resonance frequencies is necessary in the design of light weight aerospace gears. Resonant frequencies and mode shapes calculated are then identified as damaging or non-damaging and compared to the gear's mesh frequencies to determine if gear tooth bending stresses will be amplified in a particular operating speed range. Finite Element Analysis (FEA) is well suited to determining gear resonant frequencies and modes. In order to verify the analysis quickly, rough gear geometry is fabricated and tested using accelerometers and a calibrated hammer in a modal excitation test. In past efforts, rough geometry fabricated was a simplified version of the final part minus gear teeth or other features. To reduce the time of fabrication and to increase the accuracy of the prototype part, modern rapid prototyping manufacturing techniques may hold promise in approaching the realism of the actual part with material properties that are similar to material properties of gear steels.

This paper studies gear resonance modal excitation testing of two stage idler spur gear rapid prototyped parts, using two different rapid prototyping techniques and compares results to the final production part and FEA model. Damaging and non-damaging modes and nomenclature will be reviewed as well as the testing method.

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Introduction

Weight reduction is of great importance in the design of gearing for aerospace applications. Natural resonance responses of the gear head and shaft change in frequency and amplitude as weight is reduced for aerospace gears. Care should be taken to understand the gear resonance modes and compare the modes with operating speeds. Modes should be evaluated and characterized by their impact on amplifying gear tooth root bending stresses. If not addressed, damaging modes could magnify fatigue bending stresses and cause tooth bending failures of the gear. Once determined, damaging modes can be shifted or gear damping techniques applied to the design. Finite Element Analysis (FEA) is used to determine gear resonance frequencies which are compared to the usage of the aerospace gear.

Due to the costs and time involved in the design and build of an aerospace gearbox, tests to reduce risk are used to build confidence in the design and analysis techniques before the final product reaches an aircraft. In main power drive applications for helicopters as well as aircraft mounted accessory drives, gear resonance response tests, known as rap tests, are conducted to determine by test, the frequencies and shapes of gear resonance modes. Due to the long lead time involved in manufacturing light weight, carburized steel gears, rap tests are sometimes conducted on non-carburized test parts that approximate the final shape of the completed gear design. In aerospace, our internal culture is one of demonstration of an acceptable design by test. We step through the gates shown in Figure 1 for a gear design as it relates to gear resonance.

The focus of this paper is to reduce the time of step 3 validation of the FEA result and not on the overall method used. Tests help to mitigate a potential cost and scheduling debacle if damaging modes are not predicted correctly before the transmission enters test or service. All cost effective opportunities to reduce risk along the development process of aerospace gearing should be taken advantage of, particularly those which can happen early in the development phase.

A test was conducted to evaluate rapid prototyping techniques available on the market. A two stage idler gear was fabricated by using two different rapid prototyping techniques. The two rapid-prototype test specimens as well as the production part were rap tested to experimentally determine resonant frequencies and mode shapes. FEA results were compared to the experimental test results as well. The test gave us a chance to "try-out" rapid prototyped metal parts, now known as 'additive manufacturing' and attempt to reduce a portion of our risk reduction test time. This paper summarizes the testing conducted, FEA result predictions, and compares rapid-prototype gears to production gear resonance results. The modal excitation test, whether done on the production part late in the program or on rapid-prototyping parts early in program verify that the FEA analysis has been done correctly and reduce overall program risk.

Background

Aerospace gears are designed to be as light as possible to transmit speed and torque from one location to another. Understanding loads and environment help to define a solution which minimizes weight and space required. Gear resonance excitation is a phenomenon where natural frequencies of the gear and shaft are excited by operating speeds. Depending upon the mode shape of the natural frequency, tooth root bending stresses can be amplified beyond intended design limits. If not accounted for during the design, unknown elevated bending stresses can lead to crack initiation in the gear tooth root and subsequent failure of torque and speed transmission.

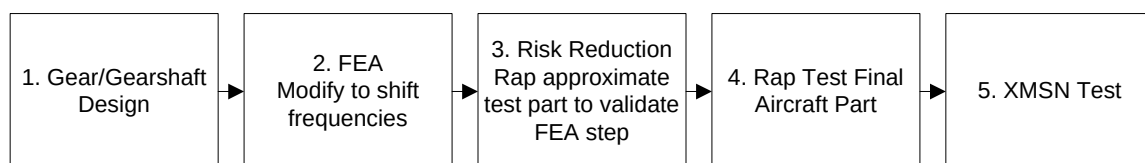


Figure 1. Gear/gear shaft development for resonance

Analysis of gear resonance in the design stage consists of using FEA software to mesh three dimensional computer aided geometry and analyzing the geometry under different boundary conditions. Traditionally modal analysis of gears is done using a free-free boundary condition. The main advantage to free-free analysis is the convenient comparison with experimental test results which are collected by suspending the test gear on elastic strings. The most damaging vibration modes of interest involve vibration of the gear in diametral modes which are largely unaffected by bearing support boundary conditions. Shaft modes which lie on or near gear mesh frequencies can be further investigated by performing frequency analysis of a finite element model with boundary conditions simulating bearing supports.

In order to verify analysis of the gear geometry, testing can be conducted before the final part is fabricated on a test gear that is similar in geometry, stiffness and density. In past efforts, rough test gear geometry fabricated was a simplified version of the final part minus gear teeth or other features (Reference 1). Part fabrication was simplified to reduce the time needed and traded for accuracy of predicting the final part gear resonance frequency and mode shapes. The goal of the rap test is to cost effectively validate the FEA results with a focus on not all the modes, but the ones that we believe amplify bending stress. With the evolution of computing power and FEA packages, increasingly complex parts with denser meshes can be analyzed that more closely match testing of final part geometries. On the manufacturing front, advancements in five axis machining and rapid prototyping, or additive manufacturing, hold promise for more accurate test gear geometries without sacrificing the fabrication time.

Test specimen design and analysis

A two stage spur gear design with an integral shaft was chosen for the test which is used in an aircraft transmission design. A cross section of the idler gear is shown in Figure 2.

Basic parameters of the two gears are listed in Table 1.

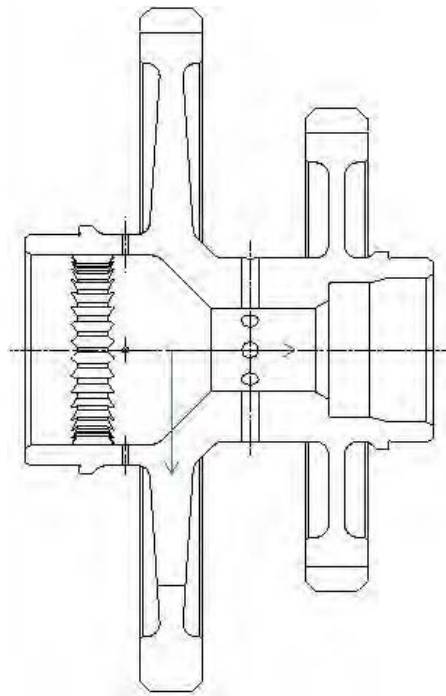


Figure 2. Cross section of Idler 4/5

Table 1. Test gear description

	Idler 4	Idler 5
Diametral pitch [1/inch]	10	10
Number of teeth	44	63
Pitch diameter [inches]	4.400	6.300
Face width [inch]	0.600	0.600
NOTE: Gear teeth and bearing races are carburized and ground.		