



AGMA Technical Paper

Gear Failure Analysis and Lessons Learned in Aircraft High-Lift Actuation

By A. Wang, S. Gitnes,
L. El-Bayoumy and J. Davies,
MOOG Inc. Aircraft Group

Gear Failure Analysis and Lessons Learned in Aircraft High-Lift Actuation

Anngwo Wang, Seth Gitnes, Lotfi El-Bayoumy and Jonathan Davies, MOOG Inc. Aircraft Group

[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

Several gear failure cases and lessons learned in the development phase of aircraft high lift actuation systems are presented, including leading edge geared rotary actuators, and trailing edge geared rotary actuators, sector gears and pinions, and offset gearboxes. The high lift system of an aircraft, which contains trailing edge flaps and/or leading edge slats, increases lift for takeoff, controls flight during cruise, and reduces speed while increasing lift for shorter landing distance.

Many of these components contain highly loaded gears to increase the power to weight ratio. Because of requirements on weight or envelope and consideration of cost, the gears are always designed to the limit with reasonable margins of safety in a high lift system. The structure which supports the gears is limited in size and simplified, and the gear material and heat treatment are selected for easy manufacturing. Therefore, when misalignment and/or deflection of the gears are large enough to cause reduction in tooth contact area, the stress on gears becomes large enough to cause damage. The failure modes can be classified as spalling or pitting at the location of concentrated loads. Most of the problems can be resolved by providing correct lead modification to alleviate the concentrated loading, while some need increase of the gear diameters, design modifications, or introduction of materials with higher allowable.

Copyright © 2013

American Gear Manufacturers Association
1001 N. Fairfax Street, Suite 500
Alexandria, Virginia 22314

September 2013

ISBN: 978-1-61481-070-4

Gear Failure Analysis and Lessons Learned in Aircraft High-Lift Actuation

Anngwo Wang, Seth Gitnes, Lotfi El-Bayoumy and Jonathan Davies,
MOOG Inc. Aircraft Group

Introduction

The high lift system of an aircraft, including trailing and/or leading edge slats/flaps, increases lift for take-off, controls flight during cruise, and reduces landing distance for touch-down. This flight control system is usually composed of power drive units (PDUs), torque tubes, bevel gear boxes, offset gearboxes, leading edge (LE) geared rotary actuators (GRAs), trailing edge (TE) GRAs, and leading edge sector gears and pinions (Figure 1). The system also includes other components, such as torque limiters, slip clutches, no-back drive devices, and wing tip brakes to provide system protection from overloading. Many of these components contain different types of gears that are usually highly loaded to increase the power to weight ratio. Because of the requirements on weight or envelope and consideration of cost, the gears in a high lift system are always designed with minimal margins.

The structure which supports the gears is limited in size or simplified, and the gear material and heat treatment are selected for easy manufacturing. Deflections and misalignments between meshing gears cause edge loading which generates noise and high bending and contact stresses. The deflection emanates from the high loading and the misalignment comes from wing bending or the deflection of gear shafts and housings. Irrespective of the load, once the misalignment and/or deflection cause the contact area to shift and diminish, the stress becomes large enough to cause problems.

AGMA publishes an atlas of failure modes [1] that identify some common types of wear. Bajpai et. al. [2] combines a contact analysis model and a wear prediction model to describe the evaluation of tooth surface wear of spur and helical gear pairs. In these previous papers, the focus is on the outcome of failures, and not the reasons and sources of gear wear. Drago [3] discussed spalling caused by tip interference and showed that a contact failure can lead to a more severe tooth fracture. Drago et. al. [4] also discussed the relation between micropitting to specific lubrication additive package combinations, gear quality and surface finish, which can be resolved by profile modifications. Errichello et. al. [5] investigated that the root cause of macropitting is the geometric stress concentration caused by tip-to-root interference. All these previous three papers deal with failures caused by tooth geometries and quality of gears. Errichello [6] investigated a gear set which failed due to lubrication breakdown.

The main objective of this presentation is to find out how to solve these problems if the cause is due to edge loading from the misalignment of gear mounting and/or deflection of supporting structure. In this paper, several different gear failure cases in the development phase of high lift systems are presented, including leading edge geared rotary actuators, and trailing edge geared rotary actuators, sector gears and pinions, and offset gearboxes. The failure modes can be classified as spalling or pitting at the location of concentrated loads. Most of the problems can be resolved by providing correct lead modifications to alleviate the concentrated loading, while some can only be corrected by increasing the gear diameters, design modifications, or introduction of materials with higher allowable. Detailed analyses to predict deflections and misalignments on system and component levels is the key to the amount of lead modification, from which increased local contact stresses can be calculated.

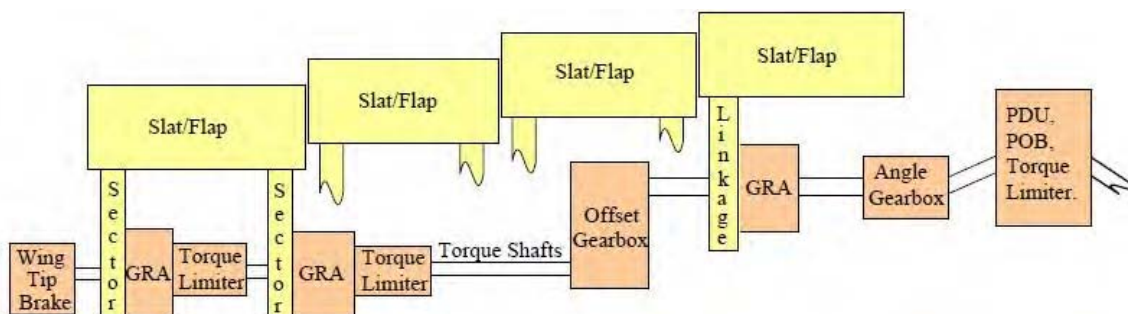


Figure 1. Schematic of the high lift system of an aircraft (left LE shown, TE similar)

The cases presented in this paper are from the pre-production risk mitigation units (RMUs). Normally the RMUs were designed with little margin to achieve minimum weight. Most system or component deflections can be predicted by analyses during the design phase. If there are any unanticipated misalignments or deflections, then failures will show up and the situation can be improved with corrections in the production units. In this way designs are optimized for minimum weight.

Leading edge rotary geared actuators

The cross section of a typical leading edge geared rotary actuator is shown in Figure 2. There are three gear meshes on each one of the planet gears. The output is on the left side of the actuator. The output planet gears are overhung and balanced by the planet gears on the right. The center planet gears act as a pivot point. Because the output planet gears are overhung, it is called a cantilever GRA.

Trailing edge geared rotary actuators

The cross section of a typical trailing edge geared rotary actuator is shown in Figure 3, and the gear schematic is shown in Figure 4. The output consists of two load paths from two end ring gears. The sun gear drives the right end planet gears. The stiffness difference between the right and left load paths causes the compound planet gear to tilt. Thus, not only the planet gear loads due to meshing with the ring gears have to be considered, but also the misalignment from the two load paths needs to be included for selecting the optimum crowning which also reduces load mal-distribution across the gear tooth faces and increases local contact stresses. Therefore, excessive crowning must be avoided.

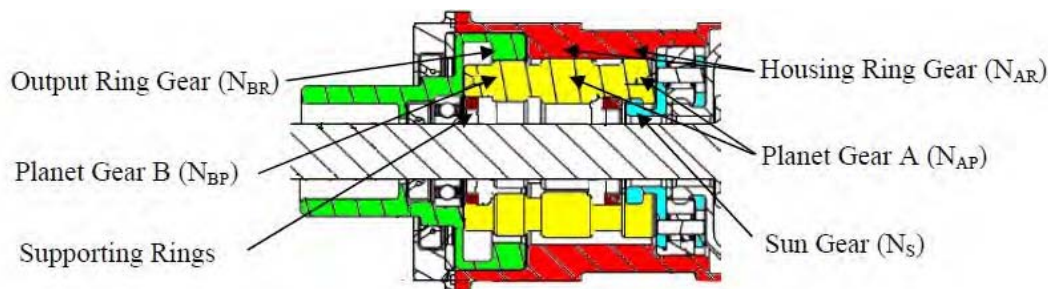


Figure 2. Typical leading edge GRA

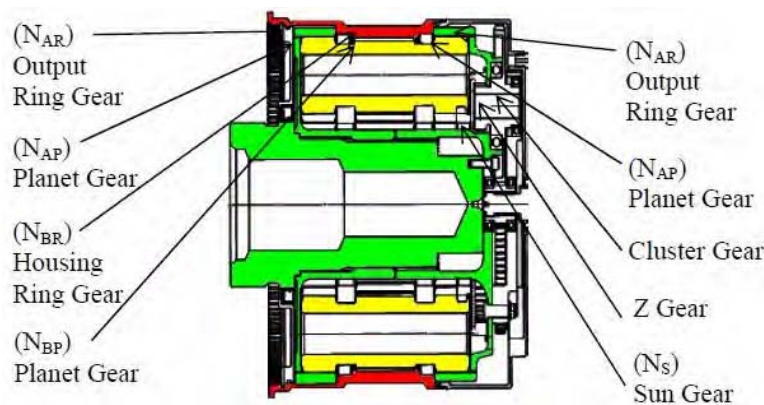


Figure 3. Typical trailing edge GRA

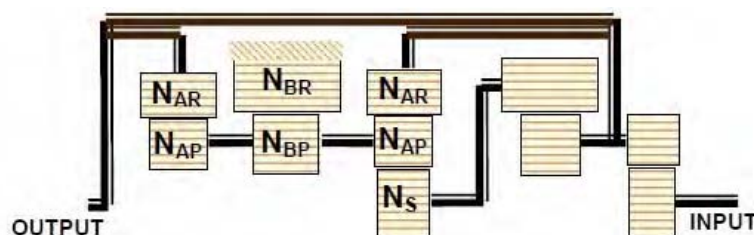


Figure 4. Schematic of the output stage of a typical trailing edge GRA

Leading edge sector gears and pinions

A typical leading edge sector gear and pinion set is shown in Figure 5. The pinion has to be crowned to allow for wing bending if a spherical bearing mount is not possible. This gear set is exposed to outside environment and grease or dry film lubrication may be depleted between service intervals. Crowning radii have to be optimized so that contact stresses can be minimized and the risk of running dry can be mitigated.

From all the above applications in a high lift system, we can understand the importance of a good face load distribution between mating gear teeth. If misalignments become excessive, gears will suffer edge loading. Five different failure examples from pre-production risk mitigation units are the subject of the next section.

Failure examples

Example 1, Offset Idler Gear Set

An offset gear set with one bearing very close to one end of the gearbox and another support far at the other end is shown in Figure 6. This is a very special layout, and is not the normal offset gearbox straddle mounted between two bearings. One can calculate the face load distribution according to AGMA [9]. Because of the deflection, gears are edge loaded and pitted as shown in the figure. To solve the problem, the gears need to be crowned to accommodate this misalignment. The face width is 0.80 inch. The total slope including the deflection and manufacturing errors is 0.0048 in/in. After solving the equations as discussed in [7], the crowning radius is 91 inch, and the crowning center is at the end of the tooth. A contact stress of 266 ksi is calculated under the max tangential load of 1000 lbf. From Figure 7, we can see that the crowning has eliminated the pitting problem, so that the full tooth is now sharing the load.

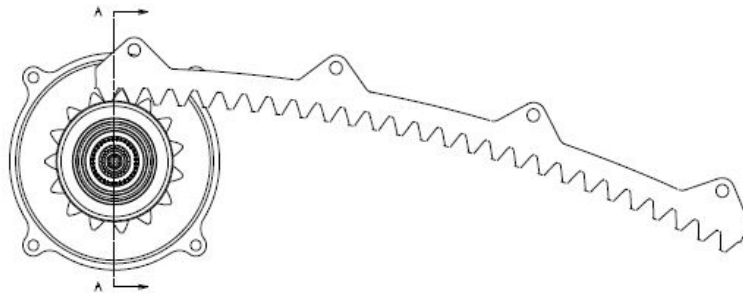


Figure 5. Typical leading edge sector gear and pinion set



Figure 6. Damaged gear without crowning [7]