Trade Studies for a High Torque Density Planetary Gearbox

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Abstract

Sierra Nevada Corporation (SNC) has developed planetary gearbox design guidelines that significantly improve the torque capacity per unit volume for an optimized gearbox under a study funded through the NASA Phase II SBIR Lightweight Gearbox Technology Program. The design was based upon optimizing both the physical configuration and material selection of the gearbox design. As a part of this study, many different materials and material processes were evaluated for their suitability for use in lightweight planetary gearboxes for space applications. Calculation methods used to predict gearbox load ratings and expected life were also validated through test. This paper presents findings that have been extracted and edited from the final Phase II report published by SNC.

Introduction

Traditionally, planetary gearboxes used in aerospace mechanisms are based on conventional materials, processes, and designs. This usage has been primarily the result of rapidly paced schedules, and events taking place in a risk-adverse environment. Developing or honing new technology in the midst of a program is often impractical. This study provided the opportunity to research new combinations of materials and processes, as well as the opportunity to validate calculated gearbox ratings for capacity and life. The goal was to capitalize on this endeavor, in an effort to advance the technology used in the common gearboxes employed on planetary rovers and other similar space applications.

Alternate materials and material processes have the potential to improve the load capacity and/or life of planetary gearbox designs. But many of those materials and material processes have little to no heritage in space mechanisms. The key is to develop optimum material combinations that balance the performance limiting factors within a planetary gearbox. One of the limiting factors is the radial load capacity of the planet bearing or bushing. Though ball bearing analysis remains uncomplicated, a general concern with journal bearings is the limited availability of data. Such data includes information regarding pressure, velocity, and pressure-velocity ratings for specific material combinations, and space applications which differ from standard journal bearing testing.

Typical planetary gearbox designs used in space applications are not only based on the conservative guidelines set forth by the AGMA, but build additional margin throughout the system design. If confidence can be built in the calculated gear capacities for the applications and materials seen in space planetary gearbox designs, then it is possible to reduce the amount of margin in order to reduce the torque/mass ratio and still result in a highly reliable gearbox.

Prototypical Gearbox Design

A prototypical gearbox design was developed for use as both an analytical and test model. Every component in the prototypical gearbox design was carefully reviewed to optimize weight, facilitate the use of high capacity materials, and to ensure that manufacturability is maintained. The design was also easily reconfigurable with a variety of materials and finishes which facilitated its usage in further developing the proposed technologies. For the purposes of this study, the gearbox was designed to use a ring gear with five planetary gear stages with a ~1500:1 overall gear ratio, 48.3-mm (1.9-in) housing diameter (excluding flanges), and a 78.7 mm (3.1 in) overall length (excluding shaft extensions). Each stage uses optimized

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geometry, materials and construction techniques that are best suited for the individual stage. The design goal was to achieve the maximum torque capacity with an output speed of 3.33 rpm. The overall gearbox weight was 0.59 kg (1.31 lb). An overall view of the resulting prototypical gearbox is shown in Figure 1.

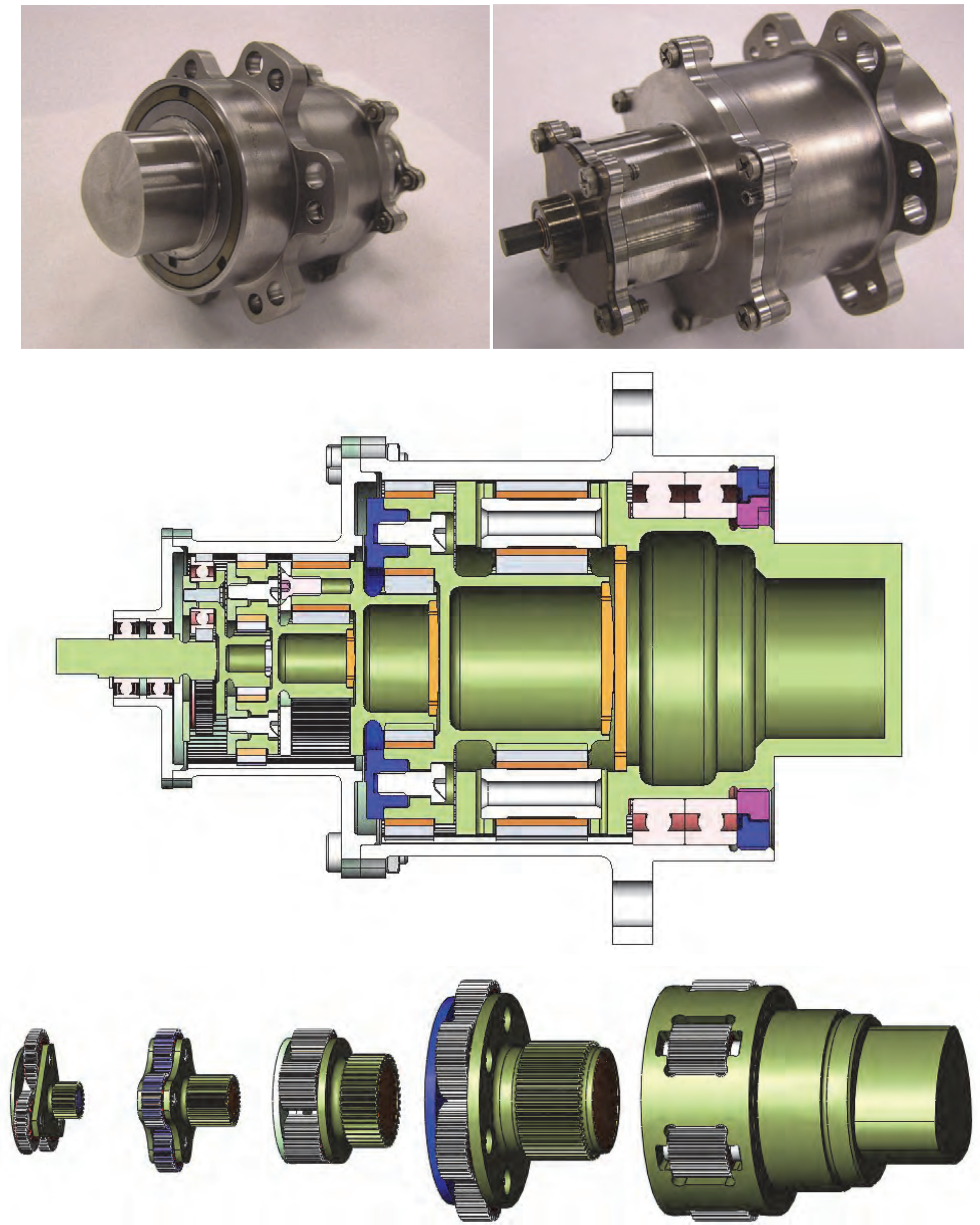

Figure 1 - Prototypical gearbox design

Prototypical Gearbox Rated Capacity

The prototypical gearbox design was analyzed per ANSI/AGMA 2001-C95. Allowable bending stress versus cycles and allowable contact stress versus cycles was extrapolated from the AGMA standard based on the material hardness used. Stress factors were selected to match typical space planetary gearbox applications as much as possible. Based upon the analysis, the following capacities were predicted (assuming a 1.5 Reliability Factor for 99.99% reliability):

- 38.6 N-m (342 in-lb) operating torque against the endurance limit (1E7 Cycles)
- 56.2 N-m (497 in-lb) operating torque at 3.33 RPM for 205.1 hr (Pitting Life = Bending Life)
- 89.5 N-m (792 in-lb) for short term operation of 4 hr or less
- 137.5 N-m (1217 in-lb) operating torque for momentary operation (bushing dynamic limit, ≤5 minutes rated gear operation at this load)
- 205 N-m (1812 in-lb) static torque limit for gears (2.0 Safety Factor)

Test Evaluation Parameters

Bushing Materials

For applications in which rolling element bearings are not suitable due to either capacity or packaging constraints, heritage planetary gearbox designs have traditionally utilized oil-impregnated SAE 841 bronze bushings. SAE 841 bushings have a Pressure-Velocity (PV) rating of 1.75 MPA-m/s (50 kpsi-ft/min) with a peak intermittent pressure of 28 MPa (4 kpsi). Often the bushing will be the limiting factor in the dynamic and/or static rating of the gear stage.

An alternate material under consideration is Toughmet 3AT by Materion Brush, a spinodal/copper/nickel/tin alloy. Toughmet 3AT has a published PV rating of 4.6 to 9.0 MPa-m/s (132,000 to 260,000 psi-ft/min) depending upon the surface finish of mating parts. Maximum low-speed pressure was not provided and the testing that generated the PV ratings for the Toughmet 3AT material was performed at speeds of 1.5-2.0 m/s (300-400 ft/min) with additional lubricant added during the test. Space planetary gearboxes do not allow any lubrication to be added during life and often operate at speeds at or below 0.5 m/s (100 ft/min).

It was decided to test both SAE 841 bronze and Toughmet 3AT bushings without providing additional lubrication and over a speed range closer to the typical space planetary applications. The purpose of the test was to determine if published PV ratings are valid and also to show a direct comparison between the two materials.

Gear and Journal Surface Treatments

The literature for Toughmet AT recommended Metalife Industries MLP as a surface treatment that could provide lower friction, higher PV ratings, and longer life in lubricant starved conditions. Metalife MLP is a thin dense chrome coating with a proprietary polymer compound added.

Oerlikon recommended adding their Balinit C coating to gear teeth and mating surfaces of bushings to extend life and capability. Balinit C is an amorphous carbon-tungsten carbide coating (WC/C) with a high surface hardness and a low coefficient of friction that claims higher bearing load capacity, lower sliding wear, improved scuffing resistance, and reduced pitting particularly in applications with boundary lubrication conditions such as slow moving gears in contact.

REM Chemicals recommended their Isotropic Superfinish (ISF) process which claims to eliminate break-in, reduce friction, and reduce contact fatigue. The ISF process involves a chemical conversion creating a micro thin soft layer that is removed by ceramic media. Multiple passes through the process resulted in removal of the peaks from the surface, while leaving the valleys as location for lubricant to remain during contact operation.

Shot peening of gear tooth faces was also considered as a method to increase the localized surface hardness of the tooth, thereby increasing gear pitting fatigue resistance. Another expected benefit of shot peening of gears is an increase in the bending fatigue resistance at the root of the tooth.

Many of these processes had not been previously performed on fine pitch gearing (64DP & 96DP) that is typical of lightweight gearboxes in space applications. These processes also had not been tested with space-grade lubricants which traditionally do not perform as well as their higher outgassing terrestrial counterparts. A development test was needed to determine which processes or combination of processes would add to the life and/or capacity of planetary gearboxes and may be suitable for future consideration.

Capacity Validation

AGMA analysis guidelines are typically conservative and do not always directly correlate to lightweight planetary gearboxes for space applications. Additionally, the parameters used in AGMA gear calculations were developed from testing larger gears, different environments, different materials, different lubricants, and different load conditions than typically experienced in Space applications. When testing is traditionally performed on a program, gearing is only tested to the loads and life specified for the application, and not tested up to or beyond the calculated rated loads and life of the design. Development testing was needed to validate the calculated allowable loads and life for the various base gear materials used and ensures that the calculations are not over stating the capability of the gearboxes.

Testing

Journal Bearing Test

In order to directly compare combinations of bushing material (SAE 841 sintered bronze vs. Toughmet 3AT), shaft/planet finishes (as-machined vs. Superfinished vs. Metalife MLP vs. Balinit C), and lubricant (Bray vs. Pennzane), a journal bearing test was formulated. Various combinations were tested to determine relative pressure and velocity limitations for both high speed/low torque and low speed/high torque scenarios. Testing was performed in ambient temperature and pressure due to numerous required test setup changes to accommodate each combination.

The oil impregnation from the SAE 841 bronze bushings coupled with relatively low hardness allowed the SAE 841 bushings to replenish the interface lubricant, absorb wear debris, and wear in any bushing surface damage to provide operation at levels higher than rated. The inherent hardness of Toughmet 3AT provided more uniform initial torque measurements, but in general these bushings failed at PV levels lower than the SAE 841 bushings and initial friction increases moved quickly to catastrophic increases in friction. REM Superfinishing displayed slightly reduced friction at the start of test, but overall results were mixed and there was not a conclusive improvement in life as a result of the process. Metalife MLP, when run against the Toughmet 3AT bushings, revealed a pressure limit of around 3.45 MPa (500 psi) at which point the coating began to break down regardless of speed. Balinit C shafts and gear blanks showed distinctly higher friction than other finishes and appeared to limit the SAE 841 material from recovering from initial onsets of increased friction. Pennzane formulated lubricants (Nye 2001 oil / 2000 grease) performed somewhat better than Bray formulated lubricants (815Z oil / 601 grease), but there was not a conclusive nor definitive trend.

The optimal configuration was determined to be SAE 841 bronze bushings running on hardened steel shafts and planet bores with no additional surface coating or treatment except for surface finishes held as tightly as feasible. One of the lessons learned was that any chamfers, fillets, or edge breaks on the contacting surfaces should be performed prior to performing the final machining operation on the journal surfaces to minimize the risk of concentrated areas of high contact pressure.

Heritage Phoenix SSI Gearhead Test

In order to obtain advanced test results on some of the materials and finishes while the Prototypical Gearbox parts were being fabricated, spare gear parts from heritage Phoenix SSI Actuators were modified, assembled, and tested. One gearhead was assembled with Balinit C coated parts and one was fabricated with Metalife MLP coated parts. Both gearheads contained a mixture of shot peened and non shot peened parts. Both gearboxes were assembled with Toughmet 3AT bushings, Bray 815Z oil and Braycote 601 grease. The gearheads were operated at constant speed with increasing torque until a significant friction increase was detected at the input. Units were then disassembled and inspected.

The Toughmet 3AT bushings displayed significant interface damage against both the planet posts and planet gears, in some cases seizing on the planet shaft. Due to the reduction in contact area and corresponding increase in contact pressure, shot peening increased the likelihood that both the Balinit C and Metalife MLP coatings would breakdown during operation. All of the Metalife MLP gear tooth wear surfaces showed some degree of coating breakdown, with the breakdown being more severe on the shot peened parts.

Metalife MLP was determined to not be as durable as Balinit C for gear teeth under the pressures seen. Test results supported the journal bearing test data which indicated that Toughmet 3AT bushing material is not appropriate for this application. Additionally, it was determined that shot peening is a detrimental process for fine pitch gearing, particularly if surface coatings are desired.

Prototypical Gearbox Test

Gearboxes representing each finish (No Finish, Superfinish, Balinit C) and lubricant (Bray, Pennzane) combination were assembled for test. One combination, Bray/Balinit C, was not tested due to damage sustained to a carrier pinion during assembly. The remaining gearboxes were run-in at 14.1 N-m (125 in-lb) for 4 hours and characterized for baseline efficiency at loads up to 56.5 N-m (500 in-lb). Two gearboxes with No Finish were loaded with a static output torque ranging up to 282.5 N-m (2500 in-lb) to verify static capacity. Both units held the applied load with no sign of damage, verifying the static torque rating.

One gearbox from each of the five configurations was tested through a 250 hr life test at 56.5 N-m (500 in-lb) external torque to verify rated life. This test was followed by 4 hours at 90.4 N-m (800 in-lb) to verify short term life. The Pennzane/No Finish, Bray/No Finish, and Pennzane/Superfinish gearboxes ran smoothly with no erratic torque spikes or significant changes in efficiency through the entire test. The Bray/Superfinish gearbox ran smoothly for the first 150 hours of the life test, and then started to show sporadic input torque spikes that would recover and recur, but never reached runaway levels. Efficiency testing on the Bray/Superfinish gearbox showed a reduction from 74% baseline to 56% post life. The Pennzane/Balinit C gearbox ran smoothly for the first 190 hours of the life test and then also started to show erratic torque spikes would recover and recur, but never reached runaway levels. Efficiency testing on the Pennzane/Balinit C gearbox showed a reduction from 73% baseline to 60% post life.

One Bray/No Finish gearbox and one Pennzane/No Finish gearbox were operated up to and beyond the rated maximum momentary operational torque limit or 137.5 N-m (1217 in-lb) with no signs of erratic input torque which would have indicated bushing failure. The test was halted at the capacity of the input drive motor. The Bray gearbox reached 175.4 N-m (1552 in-lb) while the Pennzane gearbox reached 145.5 N-m (1288 in-lb) maximum momentary torque.

Each of the life test gearboxes was disassembled and inspected. In general, Bray lubricant appeared darker and drier than Pennzane lubricant. The unfinished gearboxes revealed polishing at the gear meshes with no signs of significant surface degradation. The Superfinish/Pennzane gearbox appeared very similar to the No Finish/Pennzane gearbox. The Superfinish/Bray gearbox showed significant bushing wear in the 2nd stage. The Balinit C gearbox with Pennzane (only Balinit C gearbox tested) showed significant bushing wear in the 2nd and 3rd gear stages with several of the bushings cracked. Even with significant bushing degradation, these units continued to function with reduced efficiency, but no sign of imminent catastrophic failure. The external static torque on one of the No Finish gearboxes was increased up to 425.7 N-m (3768 in-lb) with no sign of internal damage, significantly exceeding the rated capacity of the gearhead. The load applied was halted due to the output shaft rotating within the mating interface of the external coupling.

Conclusion

SAE 841 Bronze proved to perform at rated levels even in a lubrication-starved environment with space grade lubricants. SAE 841 Bronze also provides extensive additional margin between initial friction increase and catastrophic failure due to the ability to replenish lubricant and absorb debris.

Toughmet 3AT did not perform to rated capacity most likely due to the inherent lubrication starved environment and the use of space grade lubricants instead of higher performing commercial alternatives. Unlike the SAE 841 bronze, initial onsets of friction quickly turned to catastrophic friction increases.

Metalife MLP provided lower initial friction than bare steel, but the coating broke down at relatively low operating levels, generating abrasive debris which resulted in a high wear rate. This coating may be suitable for bearing journals in high speed/low load applications but extreme caution would need to be taken. Metalife MLP did not appear suitable for use on gear teeth with any significant load.

Balinit C displayed higher friction in journal bearings than bare steel and was detrimental to the performance of the SAE 841 bronze material. It is therefore not recommended for use against bushings. While Balinit C was more durable on gears than Metalife MLP, once the coating was broken down the debris was very abrasive and resulted in extreme wear. Balinit C may help fatigue life on higher speed, lower torque gear stages, but should be avoided in higher torque stages of fine pitch gears to prevent coating breakthrough.

Shot peening resulted in significant surface roughness that could not be overcome by Superfinishing and resulted in swifter degradation of subsequent coatings of Metalife MLP or Balinit C. Shot peening is not recommended on 64DP or 96DP gears unless the process can be refined with extra fine media and reduced pressure, in which case additional testing should be performed.

REM Isotropic Superfinishing provided mixed results. Initial friction levels were improved and there was less debris observed in the lubricant after gearbox run-in. However, overall gearbox life was not conclusively improved by the process. Superfinishing should be considered for 64DP and coarser gearing that cannot be cleaned and re-lubed after run-in. There remained concern over the impact of Superfinishing on the gear profile for 96DP gears (and finer).

Gearbox rated capacities for short term, momentary torque, and static capacity were all validated through the testing of the standard No Finish gearboxes with additional margin shown. This data gives confidence moving forward that calculation techniques and assumed parameters are valid and gear designs can be pushed closer to their calculated limits to minimize mass and volume.

Flight Application

Sierra Nevada has incorporated design elements from this SBIR study into several programs that have been qualified, acceptance tested, and delivered. Significant programs included JPL Mars Science Laboratory Descent Braking Mechanism, JPL Mars Science Laboratory Low Torque Actuator Gearboxes (5 different gearbox designs), as well as other commercial Aerospace applications.

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