Hybrid Gear Preliminary Results — Application of Composites to Dynamic Mechanical Components

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Composite spur gears were designed, fabricated and tested at NASA Glenn Research Center. The composite web was bonded only to the inner and outer hexagonal features that were machined from an initially all-metallic aerospace quality spur gear. The hybrid gear was tested against an all-steel gear and against a mating hybrid gear. Initial results indicate that this type of hybrid design may have a dramatic effect on drive system weight without sacrificing strength.

Introduction

The components used in rotorcraft applications are designed such that the minimum weight is attained without sacrificing reliability or safety. Since the drive system is an appreciable percentage of the overall rotorcraft vehicle weight (~10 percent), many approaches have been applied to improve the power to weight ratio of these components.

Past and current government-funded efforts for drive system technology (Refs. 1–2) have used power to weight ratio as the most critical performance metric. Through clever design modifications, configuration arrangements and advanced materials, great progress has been made.

Material properties of composites make them very desirable. Having a very low density and high strength are two important properties that directly impact power to weight ratio. Therefore application of these materials to rotorcraft transmission static and dynamic components can have a drastic effect on overall drive system weight (Refs. 3–4).

The use of composites has been mostly limited in drive systems to housings and shafts (Ref. 5). A number of critical issues were identified and addressed in these applications. These issues include metal—composite attachment, corrosion, strength, etc. The objective of this research reported herein is to expand the use of composite materials to gears and to identify critical issues that may result in this application. Several tests were performed on the composite gears to identify the issues that need to be addressed to allow this technology to be suitable for rotorcraft drive systems.

Composite Material—Metallic Gear Hybrid

Components that are lightweight and high-strength are very important for aerospace drive systems. The composite portion of the hybrid gear was fabricated using a tri-axial braid prepreg (*Ed.'s Note: A fibrous material pre-impregnated with a particular synthetic resin, used in making reinforced plastics*) material made with T700SC 12K carbon fiber tows and a 350°F epoxy matrix material. A 0 ± 60 braid architecture was used so that in-plane stiffness properties would be nearly equal in all directions. Representative composite material properties are compared to that of the typical gear material AISI 9310 (Table 1). Materials with these characteristics have the potential to produce a design with a very high power-to-weight ratio.

There are other reasons for using a hybrid of composite and metallic elements in a gear. For example, gear meshing vibration and noise should benefit from this configuration by altering the acoustic path between the gear mesh generating the noise and the housing that re-radiates the vibration and noise.

In theory it may be possible to produce a hybrid gear at reduced cost, as a portion of the machining required to reduce component weight would be eliminated. But the manufacturing process would have to be altered when making a hybrid gear to attain aerospace precision of the components.

Unfortunately, for all the positive implications of using this technology for dynamic drive system components, there are also some negative aspects. Some of these include:

Attachment to the metallic features to produce a hybrid gear (gear teeth-to-web, web-to-shaft, and bearings-to-shaft)

Heat conduction issues—composite material through thickness conductivity

Operation during extreme thermal events such as loss-of-lubrication. In current drive system component design, the

Table 1 Materials as used in the test gears

	Composite Material	AISI 9310 Gear Steel
Modulus of elasticity (psi)	Tensile - 6.4×10^6 Compression - 6.1×10^6	29×10^6
Poisson's ratio	0.3	0.29
Density (kg/m3)	1800	7861
Thermal conductivity (W/(m°C))	9.4 (T700 fiber – axial)	55
Useful maximum temperature (°C) as gear material	150	175
Coefficient of thermal expansion (micro-m/m)	2 (in-plane)	13.0
	Failure Strain (%) Tension - 1.89 Compression - 0.94	Elongation (%) 15

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gears and shafts are one piece and the bearing inner raceway is typically part of the gear shaft component. Use of a hybrid gear would require attachment in some manner from the composite material web shaft to the gear teeth.

Hybrid Gear Design and Manufacturing

The basic gear design used for this study is summarized (Table 2). These gears have been used in the past for loss-of-lubrication testing and other experimental work within NASA (Refs. 6–8). Gears used were representative of aerospace precision prior to modification to a hybrid configuration.

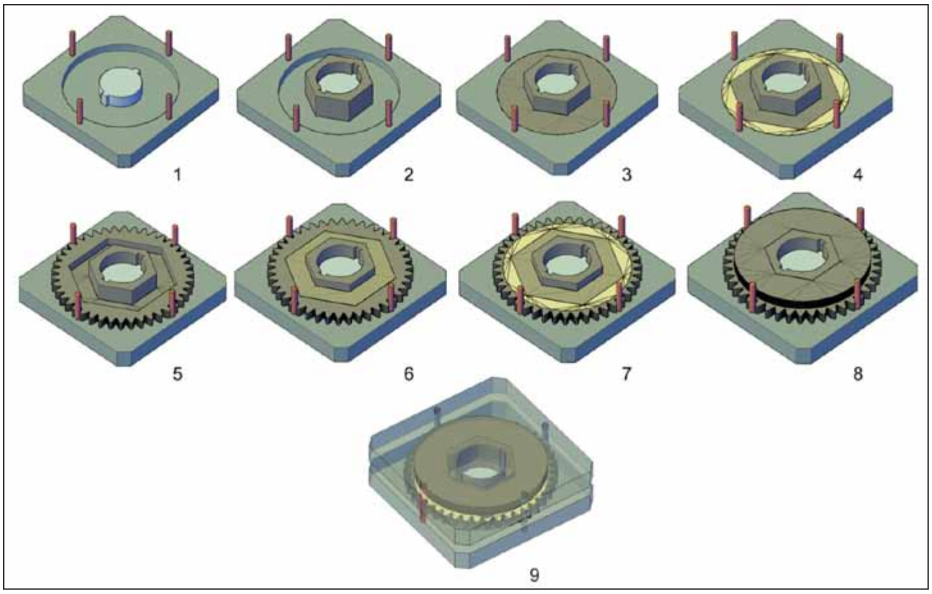

Figure 1 Hybrid gear assembly steps.

Turning the gears into a hybrid configuration started with a portion of the web being machined away; the metallic teeth and attachment regions were kept. A hexagonal region was removed; this arrangement was chosen due to the number of teeth (42) on the gear to be modified. By using a six-sided feature, no sharp edge was located near a tooth fillet/root region where the highest bending stress is reached.

Two unique ply stacks were used for this configuration. The first ply stack was larger than the metallic portion that was machined away and had a circular, outside geometry. This created an overlap onto the surface of the outer rim. This overlap created a bonding surface that was critical for proper composite-to-metal adhesion. The second ply stack configuration was cut to match the hexagonal region that was machined away from the metal gear. This tight fit provided a load path from the outer rim to the metallic inner hub.

An epoxy prepreg, in conjunction with a quasi-isotropic braided fabric, was chosen as the composite material. The fabric provides nearly in-plane isotropic properties that react similarly to that of the metallic features.

Prior to molding, any portion of the metallic features that was to come in contact with the composite was sandblasted and surface-primed to promote good adhesion and increase bond-line strength.

A special fixture was then designed and fabricated to locate the gear rim and the gear hub prior to composite material layup. The gear teeth outer rim was located using "measurement-over-pins" (Ref. 9). The inner metallic hub was located via its inner bore.

The first step in the lay-up process was to place the inner metallic hub by locating it around the feature in the mold center. During the assembly process the larger ply stack was created by 12 layers of the prepreg; each layer was rotated 60° in one direction to encourage the best isotropic behavior. With the first ply stack positioned and debulked, a film adhesive was added and the outer metallic ring was placed on top. The second ply stack was created in the void between the two metal features. The same "clocking" procedure was performed on these plies. Another layer of film adhesive was added and the final ply stack was added in the same fashion as the first. The composite material lay-up process is shown (Fig. 1).

Table 2 Basic gear data for components tested

Number of teeth	42
Diametral pitch	12
Circular pitch	0.2618
Whole depth	0.196
Addendum (in.)	0.083
Chordal tooth thickness (in.)	0.1279
Pressure angle (deg)	25
Pitch diameter (in.)	3.5
Outside diameter (in.)	3.667
Root fillet (in.)	0.04 to 0.06
Measurement over pins (in.)	3.6956
Pin diameter (in.)	0.144
Backlash ref. (in.)	0.006
Tip relief (in.)	0.0005 to 0.0007
Weight all-steel gear (lbf)	0.8375
Weight hybrid gear (lbf)	0.7147

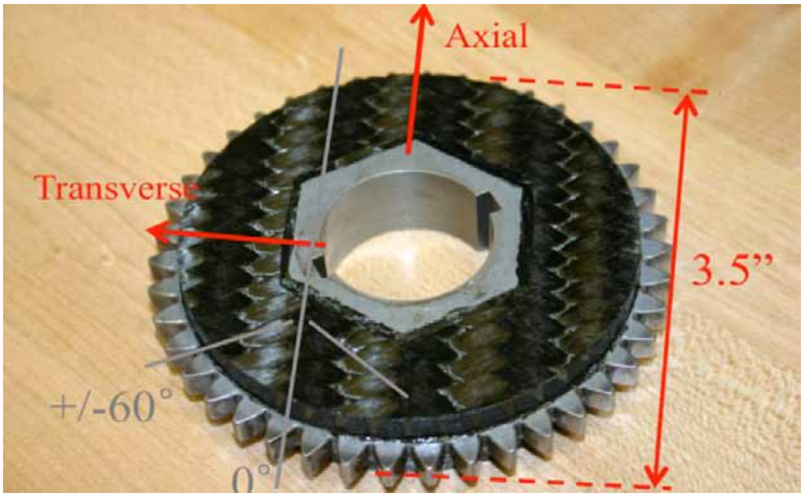

Figure 2 Hybrid gear.

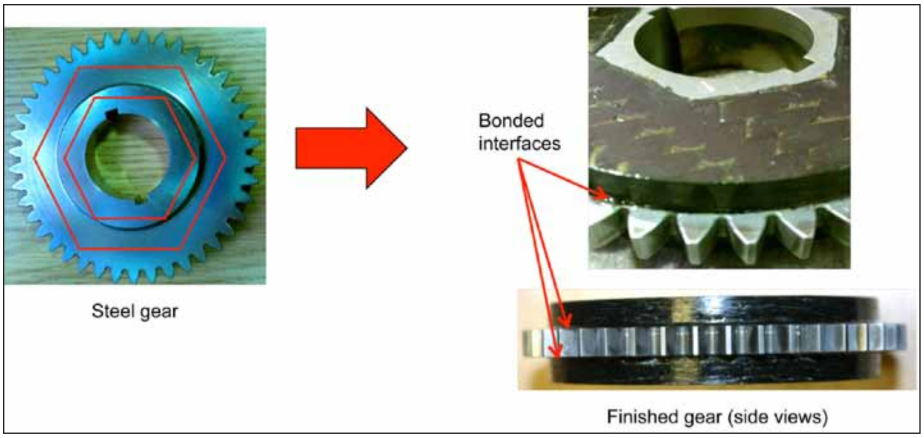

Figure 3 Hybrid gear manufacturing details.

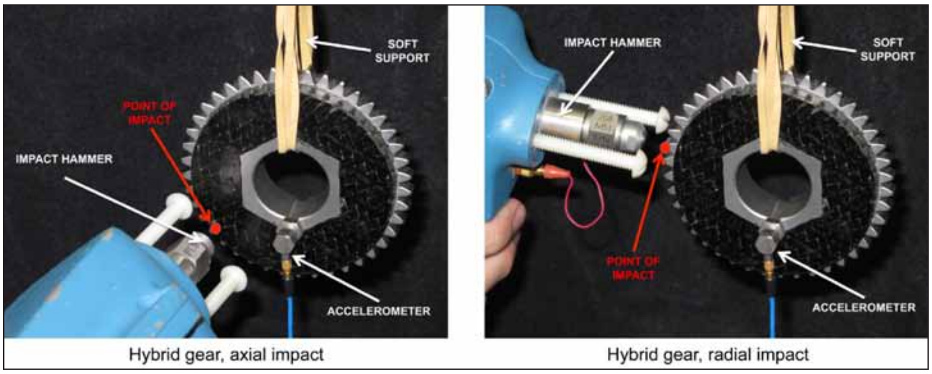

Figure 4. Impact locations shown for hybrid gears (similar for all-steel gear).

This figure shows the assembly procedure used prior to curing the finished part.

The gear mold assembly was placed into a press and subjected to a 100 psi load. The press was then heated at a ramp rate of 4°F-per-minute to a temperature of 250°F. A one-hour dwell was held at 250°F to allow time for the metal and composite to reach a consistent temperature. The temperature was then increased to 350°F using the same ramp rate. The temperature was held at 350°F to fully cure the composite prepreg. After the cure cycle was complete the part was removed from the mold and any excess resin flashing was removed.

The finished hybrid gear is shown (Figs. 2–3). There was no optimization of the arrangement at this point, but the gear produced was still on the order of 20 percent lighter than the all-metal one.

Free/Free Vibration Modes

A series of experiments using a modal impact hammer was conducted on a standard AISI 9310 steel spur gear and a hybrid spur gear specimen. The objective was to experimentally determine the modal properties of the hybrid spur gear and compare them to those of its conventional steel counterpart.

Additionally, a model of the conventional spur gear was generated using finite element software and subsequently compared with experimental data obtained from the test specimen. A further effort is underway to include hybrid material parameters into the model and correlate with modal data acquired from these experiments.

A series of modal experiments was conducted on a baseline steel gear and the hybrid gear to identify natural frequencies and calculate modal damping. An electric impact hammer was used to impact the gears in multiple orientations, with an accelerometer at the tip of hammer providing a trigger for the acquisition of acceleration data from the gear. In all cases, the single accelerometer was placed on the metal hub of the test gear with the accelerometer axis parallel to the rotational axis of the gear. This placement was chosen for convenience because it was accessible on both test specimens. Finite element analysis (FEA) demonstrated that most displacement would be in the axial direction for the modes of interest.

Figure 4 shows the experimental configurations in which the impact experiments were performed. The test gear was suspended on rubber bands hanging on a rubber cord, with this soft support at the twelve o'clock position. The accelerometer was mounted on the metal hub in the six o'clock position. Both the steel gear and the composite gear were subjected to a series of impacts in the radial direction and a series of impacts in the axial direction. Axial impacts were concentrated at approximately the seven o'clock position on the gear, at a radius just inboard of the teeth. For the composite gear, this location was at the edge of the composite portion of the gear. For radial impacts, a tooth near the ten o'clock position was impacted at the tip. A nylon bolt on either side of the tip was used to more effectively set the standoff distance between the tip and the gear, enabling more consistent impacts between tests. A total of 10 impacts were performed in each of these four configurations.

Impact Study

The time-domain data signal was imported into an automated signal analysis and filtering software package. The data was then filtered to isolate the signal associated with the natural frequency corresponding to the first non-rigid body

Table 3 Specimen modal property estimates

	Impact position	Axial		Radial	
	Gear specimen	9310-T42	Hybrid 42	9310-T42	Hybrid 42
Log decrement (δ)	Mean	0.0145	0.1296	0.0261	0.0543
	Standard deviation	0.0004	0.0263	0.0028	0.0122
Damping ratio (ζ)	Mean	0.0023	0.0206	0.0042	0.0086
	Standard deviation	0.0001	0.0042	0.0004	0.0019
General damping constant (c) (lbf-sec/in.)	Mean	0.4843	2.9887	0.8725	1.2520
	Standard deviation	0.0143	0.6053	0.0928	0.2821
Natural frequency (ω_n) (Hz)	9310-T42	7219 ± 43		n=19 data samples	
	Hybrid 42	6236 ± 62		n=14 data samples	

Table 4 All-steel gear frequencies for modes 7–12	
Mode number	Frequency, Hz
7	7187
8	7270
9	12304
10	12853
11	12924
12	15237

mode. The log decrement was calculated for each filtered data set. From this calculation modal parameters of the hybrid specimen and its steel counterpart were estimated and compared. Figure 5 depicts an example of both a raw and filtered data set.

Additionally, the unfiltered results of each impact were viewed in the frequency domain to compare results within configuration groups (Fig. 6). These figures each show the frequency data from four of the 10 impacts for each configuration.

Using the basic log decrement relationships, modal properties of the gears were estimated (Table 3). As expected, the hybrid gear exhibits higher damping properties than its steel counterpart. This has the potential to reduce transmitted vibration as compared to all-steel gears. Note that the damping properties vary somewhat, depending upon the impact position. The experimentally determined mean and standard deviation of the natural frequency corresponding to the first non-rigid mode are also provided.

FEA Modal Study: Steel Gear

A modal analysis was conducted for the 42-tooth steel gear to verify natural frequencies identified in the experiment and to provide information on the associated mode shapes. The solid model of the gear captures the tooth geometry to a reasonable extent but does not include subtle, geometric features such as tip relief. For the purposes of a modal analysis however, the solid model is a close approximation to the test specimens.

The finite element mesh is a solid mesh consisting of 19,152 linear tetrahedron elements and having a total of 31,002 nodes. The characteristic element size is approximately 0.10 in. The gear specimens are made from AISI 9310 steel, which is represented in the analysis as a linear isotropic material with Young's modulus of 29×10^6 psi (2.0×10^{11} Pa), Poisson's ratio of 0.29, and mass density of 0.284 lbm/in^3 (7,861 kg/m^3). The anal-

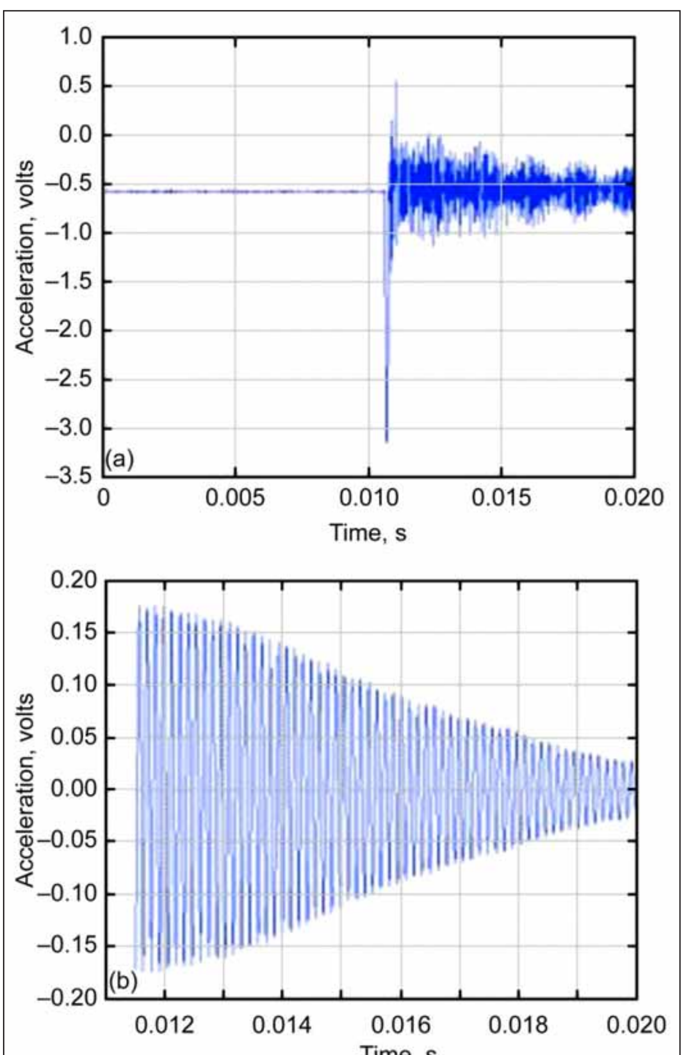

Figure 5 Sample, raw data raw: (a) time domain signal; (b) filtered data.

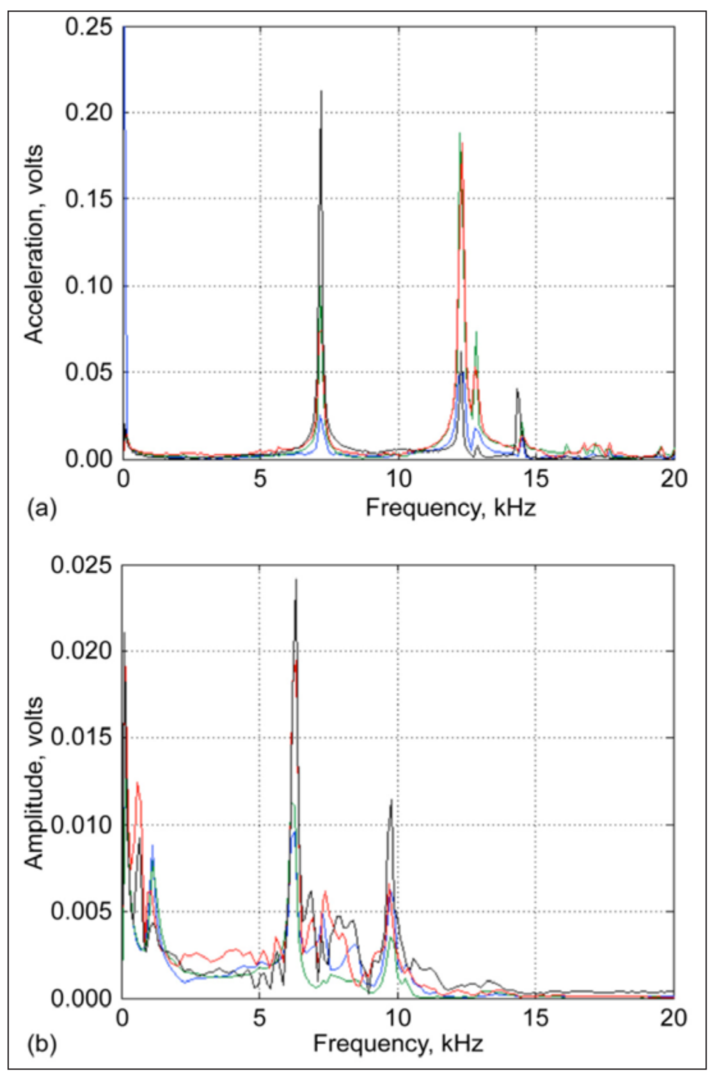

Figure 6 Frequency domain results—axial location impacts: (a) all-steel gear; (b) hybrid gear.

ysis is conducted on the unconstrained gear (free-free).

The first six modes identified in the analysis are rigid body translations and rigid body rotations; one mode is associated with each translational- or rotational-degree-of- freedom. Therefore, starting at mode 7 to 12, the frequencies associated with these modes are shown (Table 4); the mode shape for mode 7 is shown (Fig. 7). The mode shapes found illustrated that the modal displacements are primarily in the axial direction for the modes of interest, guiding accelerometer placement.

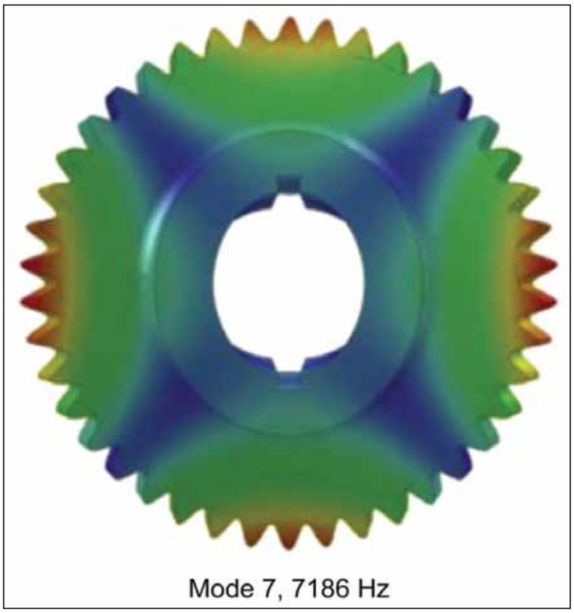

Figure 7 All-metallic gear mode shape.

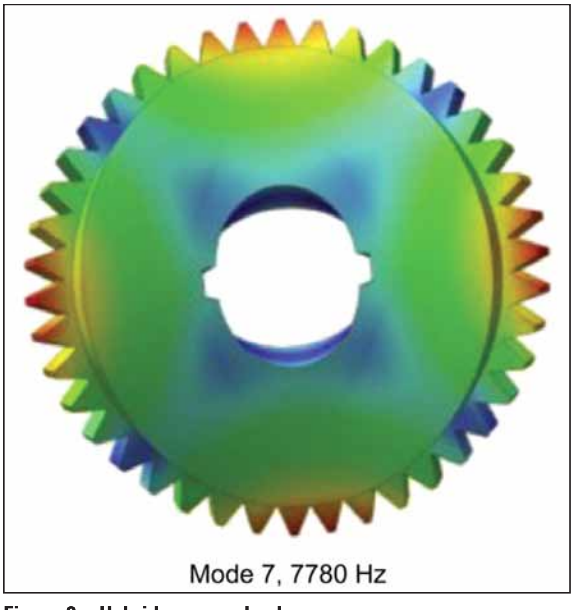

Figure 8 Hybrid gear mode shape.

FEA Modal Study: Hybrid Gear

A modal analysis was also conducted for the 42-tooth hybrid gear to verify natural frequencies identified in the experiment and to determine the associated mode shapes. As in the case of the steel gear, the tooth geometry is a reasonable representation but does not include all subtle features of the teeth. The deviation of the model geometry from the physical specimens is expected to have a negligible effect on the modal results.

The finite element mesh is a solid mesh consisting of 25,672 linear tetrahedron elements and having a total of 39,166 nodes. The characteristic element size is approximately 0.10 in. The composite portion of the gear is constructed of prepreg triaxial-braided carbon fiber with alternating orientation between adjacent layers, and resin. Due to the anisotropic nature of the material, consideration was given to modeling each individual ply with orthotropic properties. However, due to the large number of plies, it was determined that the composite portion of the gear could be modeled using isotropic properties.

The hub and ring portions of the gear were modeled using properties of AISI 9310 steel, which is represented in the analysis as a linear isotropic material with Young's modulus of 29×10^6 psi (2.0×10^{11} Pa), Poisson's ratio of 0.29 and mass density of 0.284 lbm/in^3 (7,861 kg/m^3). The composite portion of the gear is modeled as a linear isotropic material with Young's modulus of 6.4×10^6 psi (4.4×10^{10} Pa), Poisson's ratio of 0.30 and mass density of 0.055 lbm/in^3 (1,522 kg/m^3). The analysis is conducted on the unconstrained gear (free-free); the components are treated as welded together (node-to-node constraint at the interfaces). It is notable that the calculated bulk modulus properties for the composite are not linear, as the tensile elastic modulus of 6.4×10^6 psi compares to a compressive elastic modulus of 6.1×10^6 psi when using bulk properties—a difference of 5 percent. Based on the relatively minor difference and the square-root- dependence-of-frequency on stiffness, the bulk tensile modulus was used in this simplified case. Based on these small differences it was decided to use the bulk properties to simplify the analysis.

Modes 7–12, identified in the analysis, are shown (Table 5). The first six modes are related to the rigid body translations and rigid body rotations. The mode shape for mode 7 is shown (Fig. 8).

Comparison of FEA to Experiment: Natural Frequencies

A comparison between the FE output and the experimental results was conducted in the first step of validating the FEA model. Figure 9 depicts a comparison between the measured frequencies of the steel spur gear specimen and the predicted frequencies of the FE model; an exact frequency match falls directly on the diagonal. The result shows good agreement between model predictions and the experimental results.

For the hybrid gear, however, modes identified in the experiment generally shifted to lower frequencies, whereas the *model* predicted a shift to higher frequencies. In the model, this is an expected result since the composite has a higher ratio of elastic-modulus-to-density than steel, and the area moment of inertia is considerably larger for the cross sec-

Table 5 Hybrid gear finite element vibration modes and frequencies

Mode number	Frequency, Hz
7	7,780
8	7,913
9	13,745
10	14,592
11	15,725
12	16,483

tion of the hybrid gear. However, the FE model assumes adjacent surfaces in the components are bonded together.

Based on actual construction methods the interfaces may have a lower effective stiffness such that the experiment would produce modes at frequencies lower than predicted. Changes to the interfaces can be made in the model to bring the natural frequencies within the ranges of the experiment, but this may not provide additional physical insight to the properties of the interface. However, such an approach may be employed to improve the model for subsequent stress analysis.

Unlike the steel gear, a comparison between the hybrid gear finite element results and the experimental results did not produce similar mode frequencies as the all steel gear. From the experiments, the hybrid gear exhibits two significant peaks: approximately 6,270 and 9,743 Hz. The modes found from FEA did not compare well to the experiments. It is expected that further model development will reduce some of these inconsistencies with the experimental data.

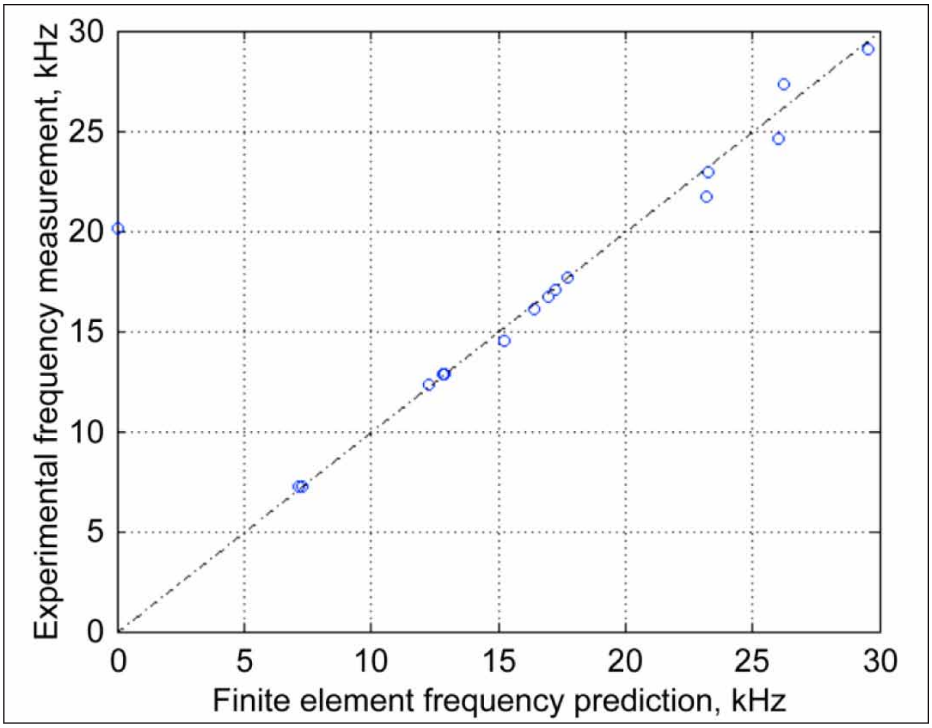

Figure 9 Comparison of experimental and finite element natural frequencies.

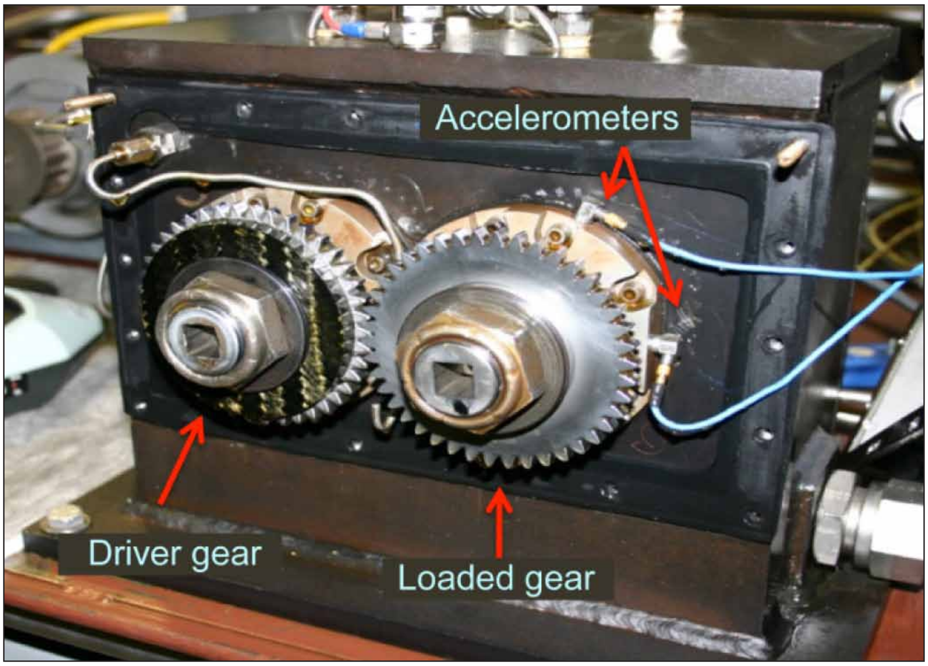

Figure 10 Test facility shown with cover removed.

Dynamic Testing

Two types of dynamic tests were conducted to determine if gears could be considered as possible composite candidates in future rotorcraft drive systems. The first set of tests measured vibration and noise at four speeds and four levels of torque. The second test was an operational endurance test.

The dynamic tests for noise and vibration were conducted with four different gear arrangements, at four different rotational speeds, and four different levels of load. The gears were installed in the test rig in the following configurations: (1) all-steel both sides; (2) hybrid gear left side; all-steel gear right side; (3) all-steel gear left side, hybrid gear right side; and (4) hybrid gear, both sides. When the facility is operating, the left- side gear is the driving gear and the right-side is the driven gear. All vibration measurements were made on the driven side support bearing housing (Fig. 10).

For the four configurations mentioned above tests were run at 2,500, 5,000, 7,500 and 10,000 rpm and at 133, 238, 448 and 658 in.*lb torque. The vibration level in "gs" is shown (Fig. 11). The noise level was measured via a hand-held sound level meter at a distance of one in. from the test gearbox cover. The sound level was recorded on an A-weighted scale. The results of the sound level data are shown (Fig. 12). The four test rig configurations are shown at four speed and load conditions.

From the vibration data shown (Fig. 11) the hybrid gear generally reduced the overall vibration level with mixed- or all-hybrid configurations. For the noise data (Fig. 12) the mixed-hybrid gear arrangement and all hybrid arrangement produced less noise for the two higher speed conditions.

Although some vibration and noise reduction were seen with the hybrid gears, the results were not as dramatic as expected. There are several reasons why noise and vibration had only modest reduction. First, the manufacturing process used to fabricate the hybrid gear did not result in aerospace-quality accuracy. The composite curing actually reduced the backlash of the components due to stretching of the metal outside rim. The backlash also was not consistent around the gear. Both of these "manufacturing errors" could be corrected by post-composite-attachment, final grinding of the gear teeth. The noise data is related to how well the teeth mesh during operation. In effect, the noise measured at a small distance from the cover is a combination of airborne and structure-borne from the meshing gear teeth being reradiated from the test facility cover.

Long-Term Testing

An endurance test was conducted on the hybrid gears in NASA's spur gear test facility. The hybrid gear arrangement was run for over 300×10^6 cycles (gear revolutions) at 10,000 rpm, 250 psi torque load (553 in.*lb torque) with an oil inlet temperature of ~120°F. The hybrid gears operated without any problem during this extended test period. The gears did not show any signs of fatigue during post-test inspection.

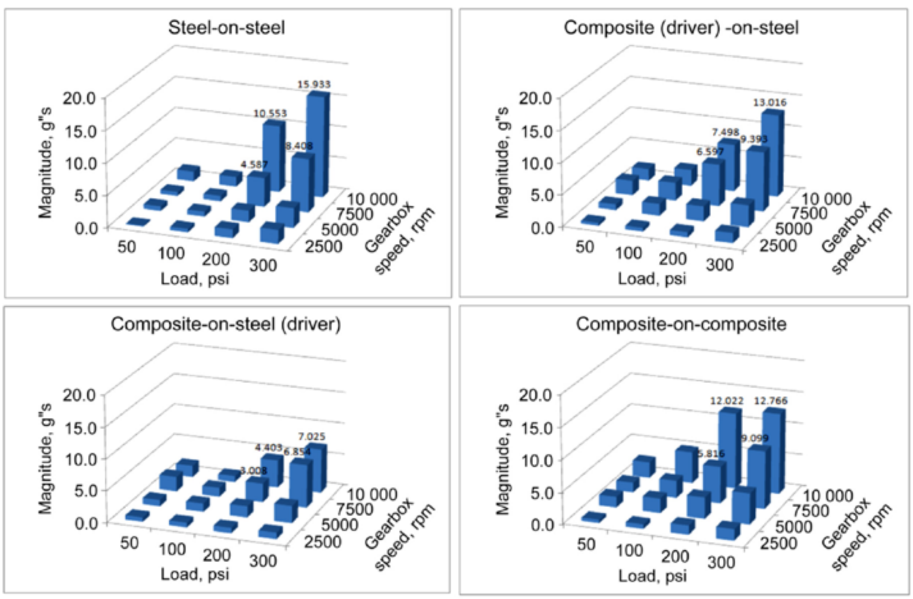

Figure 11 Vibration data taken for four speeds and four load levels.

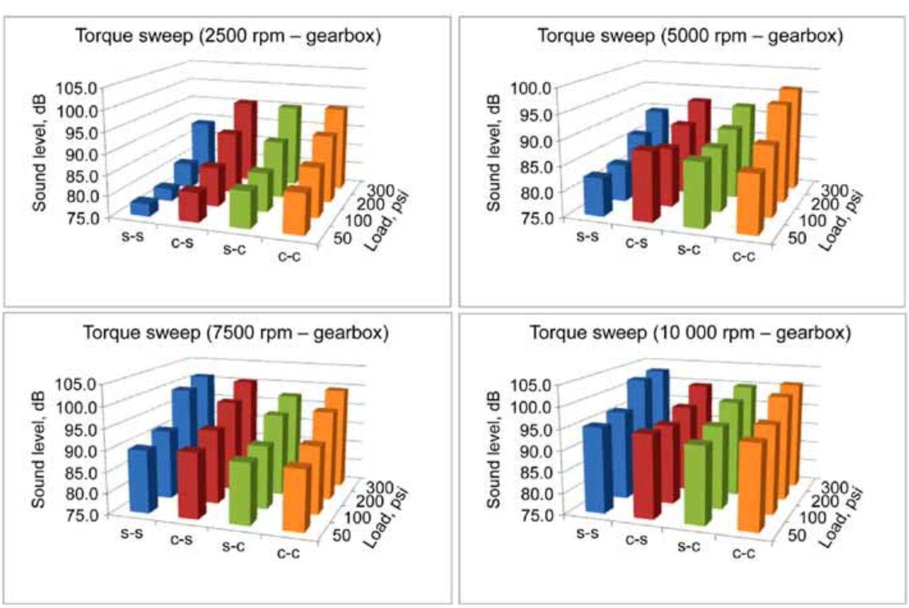

Figure 12 Sound level measurements made for the four different test arrangements, made at four different speed and load conditions.

Conclusions

Based on the results attained in this study the following conclusions can be made:

Hybrid gear arrangement shows promise, as the gears were operated for an extended period of time at a relatively high speed and torque.

Power-to-weight improvement could be possible, as steel webs could be replaced by lightweight, composite material. For the gears tested, a ~20 percent decrease in weight was realized without optimization of the components.

Reduced noise and vibration would be expected, when manufacturing processing produces aerospace quality gears; the hybrid gears tested show only modest improvements in vibration and noise. More significant improvements are possible with improved manufacturing processes and possible material tailoring through the composite structure.

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Dr. Robert Handschuh has over 30 years of experience with NASA and Department of Defense rotorcraft drive system analysis and experimental methods. He has served as the Drive Systems team leader for the Tribology & Mechanical Components Branch at NASA Glenn Research Center in Cleveland, Ohio for over 15 years, and currently leads the research there in high-speed gearing, including windage, loss-of-lubrication technology, and hybrid gearing. Handschuh is credited with successfully developing many experimental research test facilities at Glenn, and has conducted testing in the following areas: high-temperature, ceramic seal erosion; blade-shroud seal rub; planetary geartrains; spiral bevel gears and face gears; high-speed, helical geartrains; single-tooth-bending fatigue; and high-speed gear windage.

Dr. Gary D. Roberts has a master of science degree (physics) from the University of Waterloo, Ontario, Canada and a PhD (polymer science) from the University of Akron, Akron, Ohio. He has been at NASA for 30 years, where his primary area of research has been polymeric and composite materials, with emphasis on light-weight aero engine structures. More recently, Roberts has focused on composite and hybrid structures for rotorcraft drive systems. In addition, Roberts has served as a Technical Lead for several projects in the NASA Fundamental Aeronautics Program and the Aviation Safety Program.

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Lieutenant Colonel Blake Stringer, PhD., is an active-duty army officer with 19 years of military experience as an army aviator and research engineer. He has a bachelor of science degree in aerospace engineering from the U.S. Military, a master of science in aerospace engineering from Georgia Tech University, and a doctorate in mechanical and aerospace engineering from the University of Virginia. Colonel Blake has performed fundamental research on aerospace mechanical components, focusing on gear fatigue, health monitoring and the rotor-dynamic modeling of transmission systems. He has also served as instructor and assistant professor on the engineering faculty at West Point. As a military aviator, he has over 1,000 flight hours of rotary-wing and fixed-wing experience, and is rated in the UH-1 and CH-7D helicopters and C-12 airplane. Colonel Blake also holds a FAA commercial airman's certificate.

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Dr. Lee W. Kohlman has a bachelor of science degree (physics) and a PhD (engineering) from the University of Akron, Akron, Ohio. He has been at NASA for two years, following two years under NASA's GSRP program. His primary area of research is composite materials, including testing and failure mechanics. Kohlman's more recent research is focused on composite and hybrid structure for rotorcraft drive systems. In addition, he is working on material concepts for thin and adaptive fan blades, ballistic penetration of cryogenic water ice, and electrospun, thermoplastic nanofiber deposition for composite toughening.