

# Performance Investigation of a Full-Scale Hybrid Composite Bull Gear

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## ABSTRACT

Hybrid composite gears have been investigated as a weight saving technology for rotorcraft transmissions. These gears differ from conventional steel gears in that the structural material between the shaft interface and the gear rim is replaced with a lightweight carbon fiber composite. The work discussed here is an extension of previous coupon level hybrid gear tests to a full-scale bull gear. The NASA Glenn Research Center High-Speed Helical Gear Rig was modified for this program, allowing several hybrid gear web configurations to be tested while utilizing the same gear rim. Testing was performed on both a baseline (steel) web configuration and a hybrid (steel-composite) configuration. Vibration, orbit and temperature data were recorded and compared between configurations. Vibration levels did not differ greatly between the hybrid and steel configurations, nor did temperature differential between inlet and outlet. While orbit shape displayed differences between the hybrid and baseline configurations, the general overall amplitude was comparable. The hybrid configuration discussed here successfully ran at 3300 hp (2,460 kW), however, progressive growth of the orbit while running at this test condition discontinued the test. Further studies are planned to determine the cause of this behavior.

## INTRODUCTION

The civil and military rotorcraft communities are consistently striving to increase power density, while reducing maintenance, noise and cost. Past government-funded research and technology development efforts have used power density as the most critical performance metric (Ref. 1, 2). This metric becomes increasingly important with the interest in advanced concept rotorcraft (i.e. tiltrotors, compound helicopters) that require the ability to change rotor speed between the forward and vertical flight regimes. The implementation of multi- and variable-speed rotorcraft transmissions will come with added components, further increasing the need to remove weight from individual transmissions components.

In recent years, composite materials have been considered for use in drive system components as a means of reducing component weight (e.g. housings, drive shafts, and gears) (Ref. 3, 4). While a suitable replacement material for steel has yet to be identified when considering durable high-stress contacts, there are some promising benefits to incorporating composites into the intermediate structure of a gear (i.e. the web between the gear teeth and the shaft interface). As such, NASA Glenn Research Center has partnered with the Army Research Laboratory (ARL) and A&P Technology to investigate hybrid (composite-steel) gears as a means of reducing gear weight, with additional potential benefits such

as vibration damping and embedded sensing. This concept replaces the steel connecting the gear teeth and the shaft with a braided carbon fiber composite.

Past hybrid gear work performed by NASA and ARL mainly focused on small coupon level spur gears that were 3.5 in (8.9 cm) in diameter (Ref. 5, 6). Several tests were performed with these coupon level gears including static torque tests, endurance tests and loss-of-lubrication tests. The work described here builds on the feasibility study and extends the hybrid gear concept to a 16.5 in (41.9 cm) pitch diameter aerospace gear. Larger gears offer a greater opportunity for weight reduction by increasing the amount of steel that can be replaced with composite material.

## EXPERIMENTAL SETUP

Experiments for this study were performed in the NASA Glenn Research Center High-Speed Helical Gear Rig. The facility is a closed-loop, torque-regenerative testing system. The rig consists of test and slave gearboxes that are mirror images of each other. Each gearbox has an input gear, three idlers, and one bull gear. The gearboxes are joined together through the input gears and bull gears via shafting (see Figure 1).

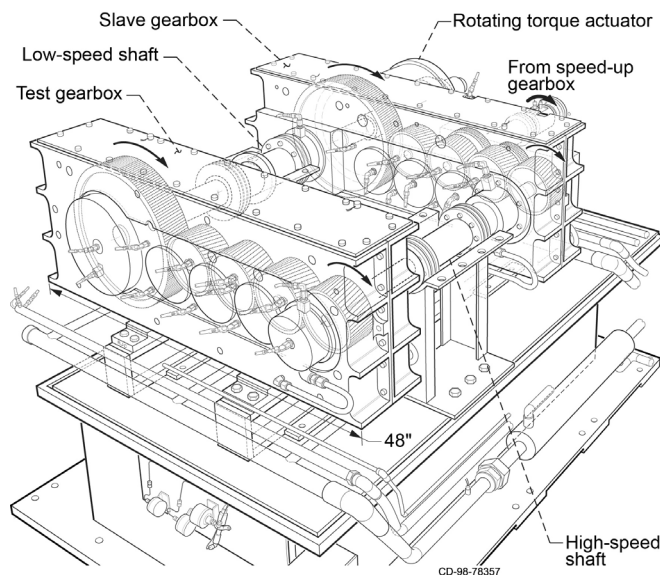
In this type of facility, only the closed-loop losses (friction losses) are necessary to overcome, therefore a drive motor of considerably less power can drive the entire facility. Within the slave gearbox is a rotating torque actuator that is used to rotate the bull gear in the slave gearbox relative to the shafting from the test gearbox. This ability to rotate the bull gear relative to the shaft permits adjustable loop torque during operation. The facility is powered by a 500 hp (373

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kW) DC drive motor and its output speed is increased using a speed-increasing gearbox. The output of the speed-increasing gearbox then passes through a torque and speed sensor before connecting to the slave gearbox (Ref. 7).

Each gearbox has separate supply and scavenge pumps and reservoirs. Lubrication system flow rate is controlled by the supply pressure. Temperature is controlled via immersion heaters in the reservoir and heat exchangers that cool the lubricant returned from the gearboxes. Each lubrication system has 3-micron filtration. The lubricant used in the tests to be described was a synthetic turbine engine lubricant (DoD-L-85734). This lubricant is used in gas turbine engines as well as some drive systems for rotorcraft.

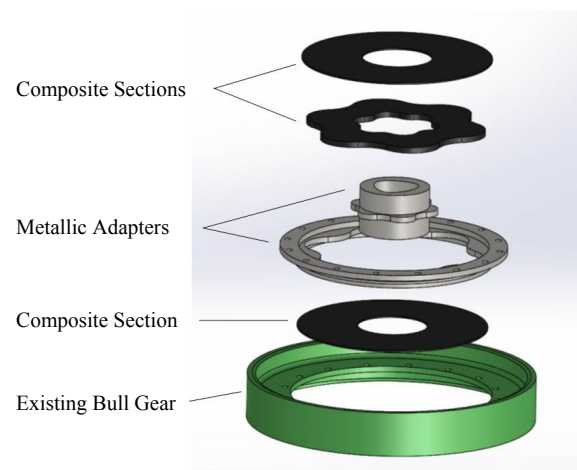


**Figure 1: NASA Glenn Research Center High-Speed Helical Gear Rig.**

The High-Speed Helical Gear Rig was designed to allow several different gear configurations (single helical, double helical, fine and course pitch, etc.) to be tested utilizing much of the same hardware. This is made possible by bolting the gears onto the gear web. This configuration was of particular interest for this study because it allowed researchers to create a modular design, such that several different web configurations could be tested, while using the same gear rim. The original design included the bearing inner races integral to the gear web. This was redesigned to separate the bearing races from the web. The new shaft/web arrangement included the use of a polygon drive rather than the original spline. This modular design allowed the same shafting, bearing races, and gear to be utilized while testing several web designs. For the work presented here, a double helical gear configuration was chosen to eliminate the axial load found in single helical gear systems.

## HYBRID BULL GEAR DESIGN

The hybrid composite gears used in this study are designed and manufactured as follows. As mentioned previously, the design of the test rig utilized for these experiments has a bolted gear configuration. The hybrid test articles investigated here consist of three main components: an outer steel adapter, an inner steel adapter, and a composite portion that interfaces with both the inner and outer adapters (Figure 2). The composite portion of the web consists of 3 sections. The inner section includes an inner and outer sinusoidal lobed pattern used as a torque interlock. This center section is captured on either side with additional composite sections referred to as capture plies which contain the inner section axially and provide an additional bond surface at the steel/composite interfaces perpendicular to the axis of rotation.

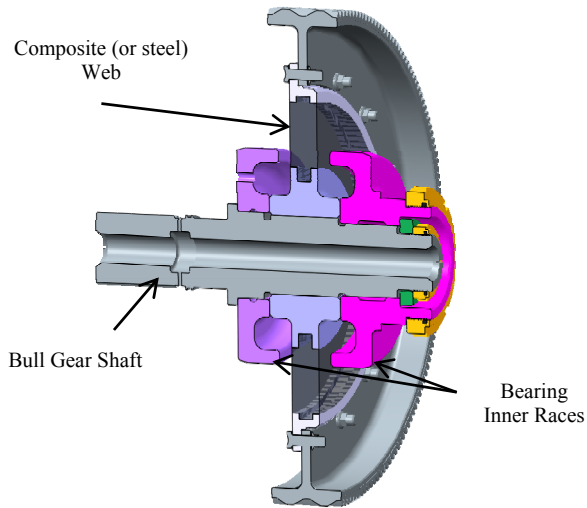


**Figure 2: Exploded view of hybrid bull gear design.**

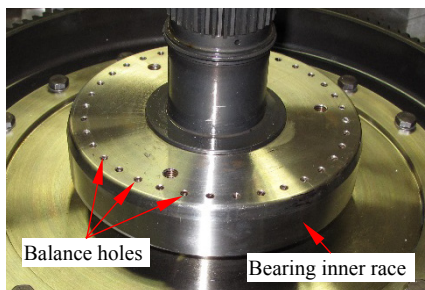
The hybrid web test articles used for this program were designed and manufactured by A&P Technology as part of a Phase II SBIR. The composite used for the hybrid web was made using a braided prepreg material consisting of T-700 SC carbon fibers and Tencate TC-250 resin. A  $0^{\circ}$ ,  $\pm 60^{\circ}$  tri-axial braid architecture with equal fiber volume in all three directions was used to provide quasi-isotropic in-plane stiffness. The web discussed here was co-cured, where both the composite layers and the adhesive bond layer were assembled and cured at the same time. Cytec MTA-241 was used as a film adhesive at the steel/composite interface.

A view of the cross section of the assembled bull gear used in this test program is shown in Figure 3. The hybrid web was provided to the research team with additional material around the outer circumference of the web, where it interfaces with the gear. This allowed the web to be installed on the shaft and then finish-ground to the required run-out tolerance for the test rig. In addition, the balance of the gear assembly was kept in tight tolerance. The web itself was balanced before assembly. Because the shaft, bearing

races and gear are reused from test to test, material could not be removed from these components for assembly balancing. Instead, assembly balancing was performed by strategically adding set screws into an array of tapped holes machined into the bearing races at a fixed radius (Figure 4).

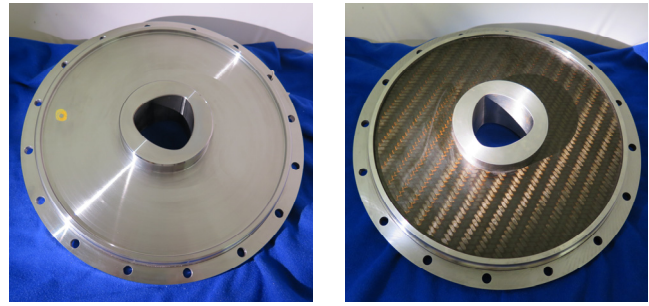


**Figure 3: Hybrid bull gear assembly detail.**



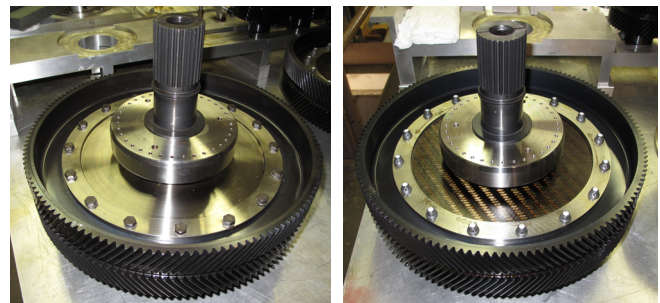
**Figure 4: Tapped holes in bearing race for assembly balancing.**

The experiments discussed here were performed on two separate web designs. The first design utilized a steel web with a thickness of 0.573 in (14.6 mm). This configuration was used as a baseline. The second design was a hybrid web, as discussed above, with a total composite thickness of 0.833 in (21.2 mm). This thickness was chosen to provide a comparable plate bending stiffness between the steel and hybrid gear. Photographs of the steel and hybrid webs are shown in Figure 5 with the complete bull gear assemblies shown in Figure 6.



**Figure 5: Steel (left) and hybrid (right) web.**

As mentioned previously, the design was chosen to allow several web concepts to be tested while reusing the same support shaft, bearing races, and gear. The design was not selected to be light weight nor was it optimized to be so. Optimized configurations would likely remove the metallic adapters and have the composite mate directly with the shaft and/or gear, further reducing the weight of the assembly. That being said, the hybrid web discussed here offered more than a 7 lb reduction in weight over the baseline steel web.



**Figure 6: Steel (left) and hybrid (right) bull gear assemblies.**

## TEST PROCEDURE

Experiments were run in the High-Speed Helical Gear Rig as follows. Prior to experimentation, the lubrication system was heated to an oil inlet temperature of approximately 120 °F. The temperature was chosen as a conservative starting temperature that would not cause issues with the integrity of the composite and adhesive bond. Once the rig was heated to the desired inlet temperature, the testing was performed at the run conditions for the bull gear outlined in Table 1. Each run condition was held for a few minutes to obtain research data prior to proceeding to the next condition. Note that these were “planned” run conditions. Runtime behavior and static torque limited the torque and speed levels researchers were willing to run at for certain configurations.

Previous static torque test results for the co-cured composite configuration demonstrated a suspected compromise of the



adhesive bond between the steel and composite at approximately 100,000 in-lb (11,300 N-m) and a mechanical interlock failure at 140,000 in-lb (15,800 N-m). Engineers chose to limit the torque applied during dynamic tests to 40% of the static bond failure limit for hybrid gear tests, eliminating the highest torque run condition for the hybrid web. This is conservative because the web used for static torque testing had fewer outer composite capture plies than the test article used for dynamic testing.

For these experiments, accelerometers were installed radially and axially on the bearing support for the bull gear. Two proximity probes were also used during testing. The probes were installed targeting the outer diameter of the bull gear, rather than the supporting shaft. Probes were installed 90 degrees out of phase on the shroud surrounding the gear circumference and targeted at the space between double helical teeth. An optical speed pickup was also installed on the bull gear shaft, providing a 5 V pulse at the start of each shaft revolution. These signals were passed through an anti-aliasing filter with the frequency cutoff set at 40 kHz. The signals were then routed to an analog to digital converter and recorded. One second of data was collected every 30 seconds at 100 kHz.

**Table 1: Planned bull gear nominal test matrix.**

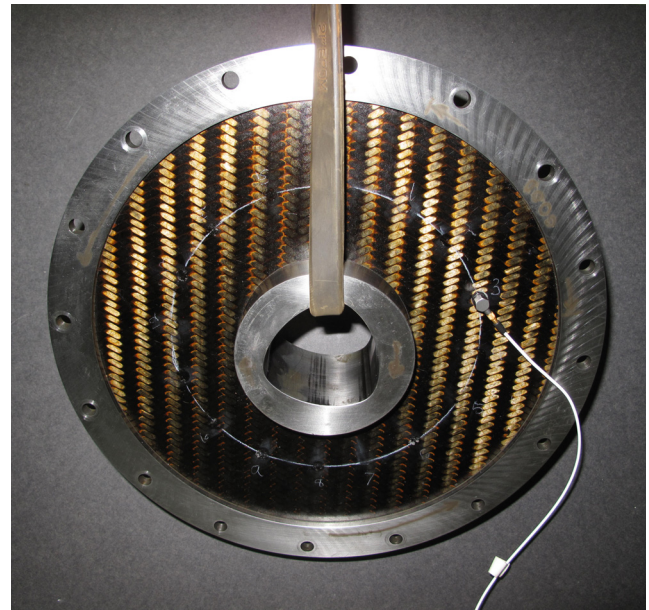
Run Condition	Shaft Speed (RPM)	Torque in-lb (N-m)	Power hp (kW)
1	900	5,000 (560)	8 (53)
2	900	10,000 (1,130)	16 (106)
3	900	15,000 (1,690)	24 (160)
4	1,800	5,000 (560)	16 (106)
5	1,800	10,000 (1,130)	32 (213)
6	1,800	15,000 (1,690)	48 (319)
7	2,700	5,000 (560)	24 (160)
8	2,700	10,000 (1,130)	48 (319)
9	2,700	15,000 (1,690)	72 (479)
10	3,600	15,000 (1,690)	97 (639)
11	3,600	19,300 (2,180)	125 (822)
12	4,500	19,300 (2,180)	156 (1,028)
13	4,500	38,600 (4,360)	311 (2,055)
14	4,500	58,400 (6,600)	471 (3,109)
15	5,400	19,300 (2,180)	187 (1,233)
16	5,400	38,600 (4,360)	374 (2,466)
17	5,400	58,400 (6,600)	565 (3,731)

Thermal data was recorded from a large number of strategically placed thermocouples. Of particular interest during these tests were thermocouples located at the test

gearbox oil inlet and oil exit. Data was recorded from these thermocouples every two seconds.

## MODAL TESTS

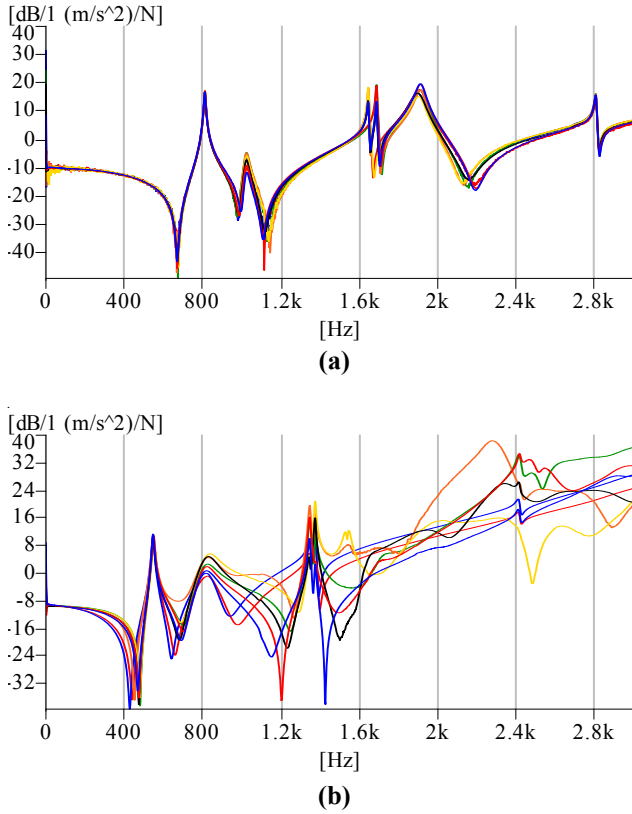
As part of this research, methods are being investigated as a means of determining the integrity of the composite and identifying any damage or damage progression before and after testing. One method being investigated is through modal testing of the web itself. Modal testing discussed here was performed with an instrumented modal hammer and accelerometer, with the web supported on an elastic mount through the internal polygon. Initial driving point measurements were taken around the circumference of the outer steel adapter. While readings using this method were taken both before and after testing, this method did not turn out to be sensitive to voids in the composite.



**Figure 7: Modal test setup.**

Additional modal measurements were taken after dynamic testing by wax mounting the accelerometer at the mid span of the composite and impacting in the same location, but on the opposite side of the web (See Figure 7). Results were fairly repeatable around the circumference of the web, when examining a well manufactured web. In contrast, identical tests were run on the first hybrid web manufactured that had known voids in the composite. The frequency responses from both the dynamically tested web and the flawed web are shown in figures 8(a) and 8(b) respectively, taken at 8 equally spaced locations around the circumference. There is a noticeable difference in the repeatability of the measurement around the circumference for the two webs, with the flawed web measurements showing extensive scatter, particularly at frequencies above 800 Hz. The shift in natural frequencies between the two webs is partially due to a different number of capture plies uses for the two webs.

While this is a fairly simple check for composite integrity, this is by no means the best method for identifying voids in the composite. Additional non-destructive evaluation techniques are being investigated to allow researchers to get a better before and after look into the integrity of the composite.

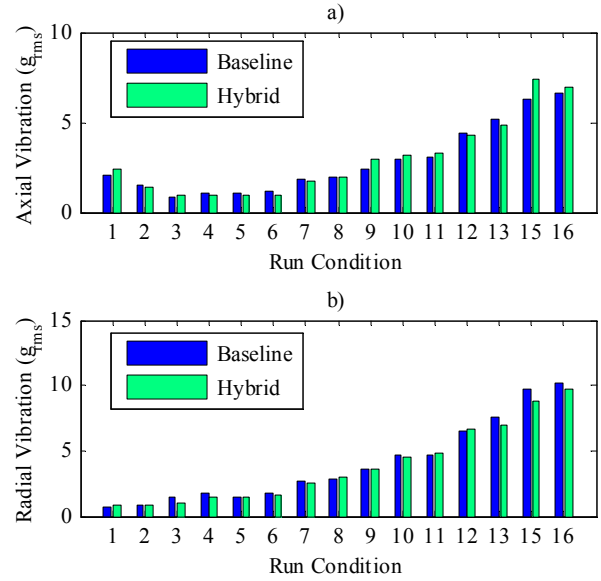


**Figure 8: Frequency response functions from (a) a well manufactured hybrid web and (b) a flawed hybrid web.**

## RESULTS

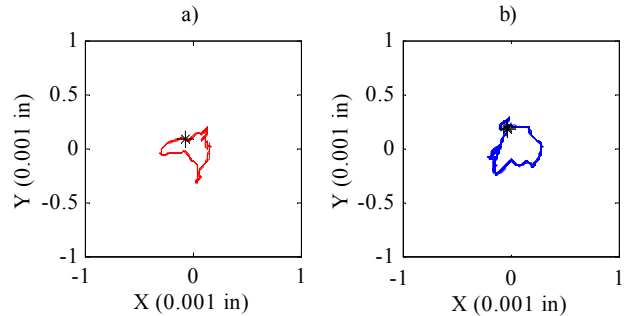
Experiments were performed, as discussed in the Test Procedure section, on both a baseline steel web and a hybrid web. While experiments were run at more than one oil inlet temperature, the experiments run at an oil inlet of 120°F will only be discussed here. As expected, no issues were experienced with the baseline steel web configuration during testing. A general root-mean-squared (RMS) comparison of the overall vibration level at each run condition for each of these tests is shown in Figure 9 (excluding conditions 14 and 17 as hybrid testing was not performed at these conditions). The hybrid gear performed well with an orbit and vibration magnitude comparable to the baseline configuration. The biggest deviations between the hybrid and baseline test occurred at conditions 15 and 16, where the hybrid gear demonstrated slightly increased axial vibration levels and

slightly decreased radial vibration in comparison to baseline tests.

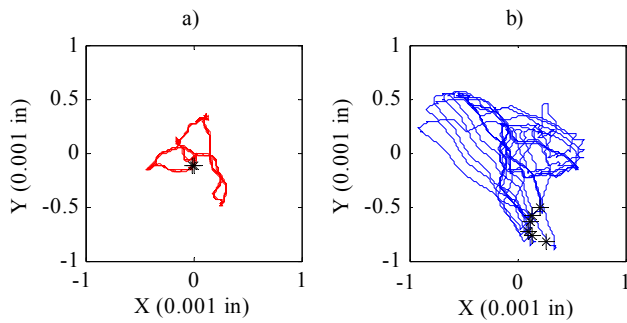


**Figure 9: Average (a) axial and (b) radial vibration levels for baseline and hybrid bull gear testing.**

Proximity data, taken at the double helical gap region on the bull gear, was averaged giving a single orbit average for each one second data packet. The data was filtered to remove the distortion caused by the teeth passing by the proximity probe. Data packets taken at a single condition were compared to investigate the repeatability of the orbit. Figure 10 shows an example of the orbit at run condition 6. During the hybrid gear test, the orbit of the gear started to both increase in amplitude and change shape while running at condition 16. When this occurred, the speed and torque were reduced. This behavior was visible in looking at the post-processed orbit data shown in Figure 11. The first few orbits recorded are repeatable and then they start to change shape and increase in magnitude.

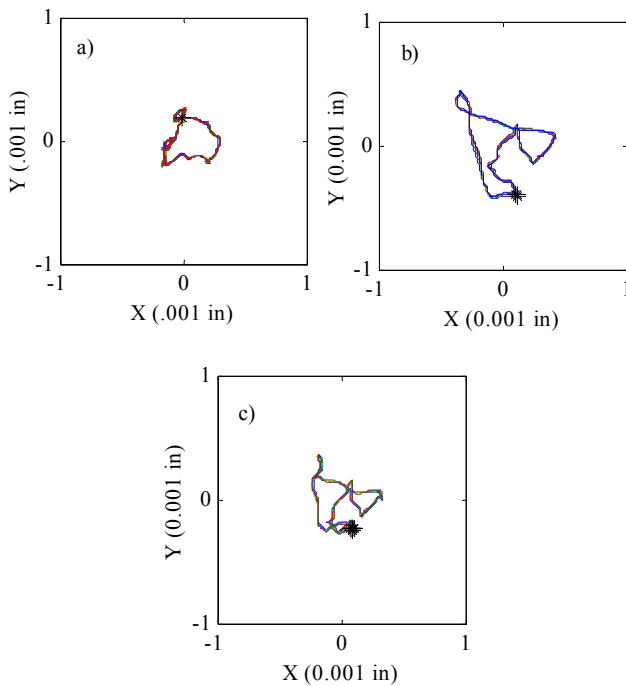


**Figure 10: Averaged orbits for the (a) baseline and (b) hybrid bull gear at 2700 RPM and 15,000 in-lb.**



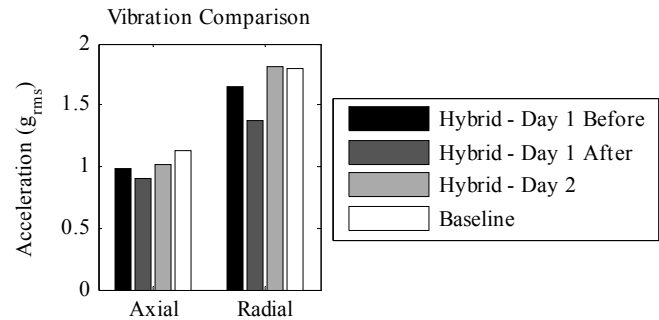
**Figure 11: Orbit comparison between the (a) baseline and (b) hybrid bull gear at 5400 RPM and 38,600 in-lb.**

After running at condition 16 during the hybrid gear test, condition 6 was repeated prior to rig shutdown. Additionally, several run conditions up to condition 10 were repeated the following day for comparison. The orbit data recorded after running at the most extreme condition resumed the repeatability seen in run conditions prior to the anomalous behavior. Figure 12 shows the hybrid gear filtered orbit at condition 6 for day 1, both before and after running condition 16, as well as day 2. The orbits for day 1 after condition 16 and day 2 are similar and both are very different from the orbit recorded on day 1 prior to the maximum run condition.



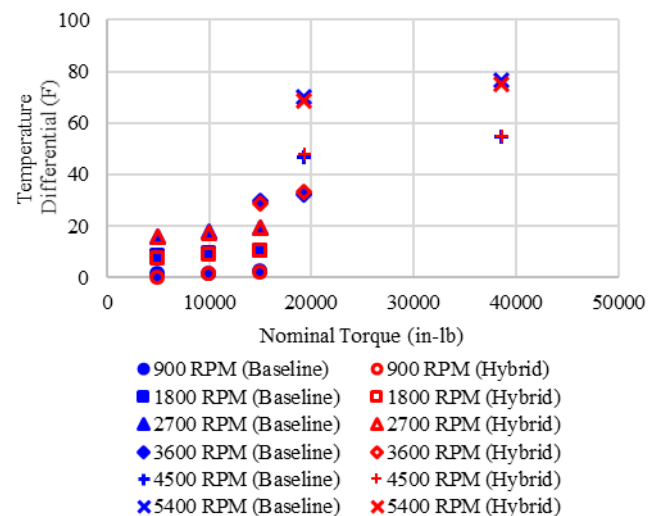
**Figure 12: Filtered orbit at 1800 RPM and 15,000 in-lb on (a) day 1 prior to running at the highest speed and load condition, (b) day 1 after running at the highest speed and load condition, and (c) on day 2.**

Similarly, the vibration levels at these three conditions were compared to each other as well as to baseline vibration levels. Figure 13 shows a comparison between general vibration levels for condition 6. Of the vibration levels taken from hybrid gear tests, the lowest of the vibration levels at condition 6 was taken on day 1 after the maximum run condition.



**Figure 13: Axial and radial vibration level at run condition 6 for hybrid and baseline tests.**

Along with the vibration and proximity probe data, the steady state thermal behavior of the bull gear and gearbox were compared between the two configurations. There was concern over how the addition of the composite webbed bull gear would affect the thermal behavior of the test rig. Fifteen of the run conditions are shown in Figure 14. The change in oil temperature from inlet to exit from the gearbox is shown for the six different speed and five different levels of applied torque. From this figure, it is evident that the hybrid bull gear did not affect the thermal behavior of the overall gearbox. A similar comparison of the axial fling off and bull gear bearing temperatures were made with the same net result.



**Figure 14: Temperature differential between oil inlet and outlet at each run condition by torque (oil inlet temperature ~120°F).**

## CONCLUSIONS

A hybrid bull gear design is presented. The hybrid gear was manufactured and tested along with a baseline steel configuration. The hybrid bull gear was successfully tested up to 3,300 hp (2,460 kW). This is the most power ever passed through a hybrid composite gear to date. Overall vibration levels were comparable between the hybrid and baseline tests, showing at least that there is no increase in vibration when transitioning to a hybrid design. Gear orbits at most run conditions displayed repeatability for both the baseline and hybrid cases. Additionally, the overall thermal effect of replacing the all steel bull gear with a hybrid bull gear was explored. The results found in this study indicated that the hybrid bull gear did not affect the thermal performance based on the amount of heat exchanged to the lubricant.

A modal test procedure is described here that should identify the presence of large voids and inconsistencies in the composite. However, similar modal tests were not performed prior to assembly and testing of the gear, so it is not possible to identify changes in the composite incurred during testing. Higher fidelity means of non-destructive evaluation for hybrid gears are being investigated.

Some anomalous behavior was experienced during hybrid bull gear testing while running at condition 16, forcing researchers to reduce the load and speed. Data collected before and after running at this condition demonstrated a repeatable orbit at any single condition, however, there was a change in orbit shape when comparing data collected before and after this condition. No appreciable increase in vibration level was recorded after testing at condition 16.

Without further destructive or non-destructive evaluation, it is difficult to say what caused the change in the hybrid gear orbit at run condition 16. One possibility is that the adhesive bond at the steel/composite interface degraded at this condition allowing for some degree of shift between composite and steel components. That being said, it is important to note that the hybrid gear never lost the ability to transmit torque and continued to run within set vibration and orbit amplitude limits after testing at the maximum run condition.

Future testing is planned for this project, including two additional hybrid web designs, one of which has a variable thickness web. While the current hybrid web configuration is shown to have promise in reducing component weight, the greatest opportunity for weight reduction would be to implement a blended web-shaft arrangement. This would eliminate the shaft-web interface and further decrease the weight of the component.

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