Evaluation of a Variable Thickness Hybrid Composite Bull Gear

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ABSTRACT

For several years, NASA Glenn Research Center and the U.S. Army Research Laboratory have been investigating hybrid (composite/steel) gear technology for use in vertical lift drive systems. The hybrid gear concept replaces the structural portion of a gear between the shaft and the gear rim with a lightweight carbon fiber composite, in an effort to reduce the overall weight of a gear and increase the drive system power density. Past research includes both small-scale and large-scale hybrid gear concepts, all of which have a constant composite thickness throughout. The design described in this paper is of a variable thickness, such that the composite is thickest at the inner diameter and this thickness is gradually reduced toward the outer diameter. The resulting "stair stepped" design stems from dropping plies of the braided carbon fiber prepreg composite fabric gradually with increased radius. Additionally, the interlock pattern at the inner metallic adapter was adjusted slightly from previous designs to obtain a better stress distribution on the inner metallic adapter. The manufactured variable thickness web was tested both in static torsion tests and operationally in a relevant gearbox environment. The results of these experiments will be presented and compared to a baseline steel configuration.

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 and 2 for example). Composite materials have been considered for use in drive system components as a means of reducing the overall weight of the drive system, particularly for large components like drive shafts and housings (Ref. 3 and 4 for example). The use of composites was extended to gearing in a composite/steel "hybrid" gear concept, which replaces steel in the structural portion of a gear with a lightweight carbon fiber composite (Ref. 5). Past publications present experimental data from both small-scale and larger-scale gears, each of which utilized constant thickness web concepts with non-fastener interlocking features (Ref. 6, 7, 8).

Experiments performed on small-scale 3.5 inch (8.9 cm) gears in the past included static torsion testing, modal testing, and dynamic testing in a gear rig. Dynamic and endurance testing was performed to assess the vibration performance and durability. Additionally, experiments were performed under starved oil conditions (Ref. 9). To maximize the weight benefit of this technology, a series of feasibility experiments were performed using a much larger 17 inch (43 cm) transverse pitch bull gear (Ref. 8). Static torsion testing of these designs failed at a torque of approximately 140,000 in-lb (15,800 N-m), with yield starting in the range of 100,000 in-lb (11,300 N-m). As such, the dynamic testing performed was limited to approximately 40% of the yield torque.

In an effort to increase the strength of the design, both the prepreg layup and the interlock at the hub were redesigned. The study presented here outlines this variable thickness hybrid gear design and presents results from both static torsion and dynamic test rig data.

GEAR DESIGN

The hybrid composite gears used in this study are designed and manufactured as follows. The design of the test rig utilized for these experiments has a bolted gear configuration, which allowed for several hybrid gear web designs to be tested while utilizing the same gear rim. The hybrid web test

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article investigated here consisted of three main components: an outer steel adapter, an inner steel hub, and a composite portion that interfaces with both the inner and outer adapters (Figure 1). The composite web consists of 3 sections, each made up of multiple prepreg layers. The middle section of composite includes a mechanical interlock that mates with the adjacent metallic adapters. This center section is captured on either side with additional composite sections referred to as outer capture plies that contain the interlocking section axially and provide an additional bond surface at the steel/composite interfaces perpendicular to the axis of rotation.

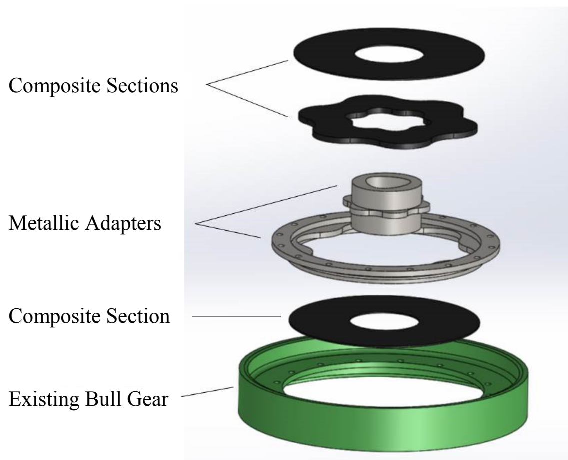


Figure 1. Exploded view of hybrid bull gear design.

The hybrid web test article used for this program was 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 0^0, +/- 60^0 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. After curing, the web was assembled on the shaft and final grinding was performed for the gear pilot and flange axial face to meet the runout tolerances required. After finish machining, the gear/shaft assembly was balanced for dynamic testing.

As mentioned previously, the design used for this study varies from that previously presented in Ref. 8, which consisted of a constant thickness composite section. To maximize strength and minimize weight the composite thickness at the inner hub is thicker than at the outer metallic adapter interface. This is performed by gradually reducing the number of plies with increased radius and results in a "stair-stepped" design as seen in Figure 2. The total composite thickness is 0.667 in (1.69 cm) at the center metallic adapter and 0.417 in (1.06 cm) at the outer metallic adapter. Additionally, after some analysis, the interlock pattern at the composite/inner adapter interface was altered to reduce maximum stress and create an improved stress distribution.

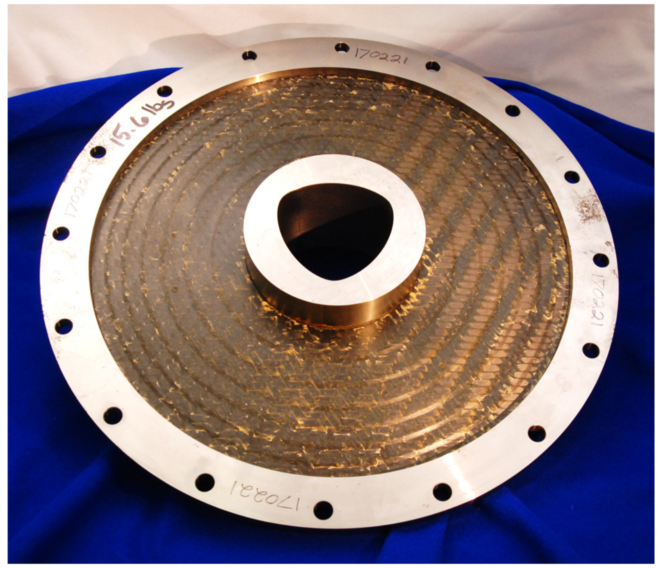


Figure 2. Variable thickness hybrid gear web.

A baseline web design was also tested and consisted of a constant thickness steel gear web. The steel web used had a web thickness of 0.573 in (14.6 mm). This thickness was chosen to match the plate bending stiffness of the previously presented constant thickness hybrid gear web with a thickness of 0.833 in. (21.2 mm).

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 weight optimized. Optimized configurations would likely remove the metallic adapters and have the composite mate directly with the shaft and/or gear rim, further reducing the weight of the assembly. Without optimizing for weight, the variable thickness gear web was 10 lbs (4.5 kg) lighter than the baseline.

EXPERIMENTAL SETUP AND PROCEDURE

Static Torsion Experimental Setup

Static torsion experiments were performed on the variable thickness hybrid gear web design using facilities at the University of Akron. The test frame has a 90° rotational range and a maximum torque capacity of 600,000 in-lb (67,800 N-m), however the installed load cell and requirements of the test limited the maximum torque to 240,000 in-lb (27,100 N-m). The torsion test frame was custom built to test composite components and further details of the design and operation are provided in Ref. 10. The outer rim of the web was bolted to a fixed platform, shown in the center of Figure 3, and a 0.2 degrees/minute rotational deformation rate was applied through a shaft driven by a hydraulic rack and pinion torsion actuator. A square polygon was used to mate this facility shaft with the hybrid web. Unlike the triangular polygon used for dynamic test articles, a square polygon interface feature was used for all static tests, since it was determined it would allow for easier removal of the shaft from the test article. Testing progressed until a failure of the test article or an exceedance in the torque meter range.

Digital image correlation (DIC) measurements were obtained using two GOM ARAMIS systems in order to monitor deformation during the test. A 5-megapixel DIC camera system was rotated to fully view the input loading shaft at the front of the test frame and a 6-megapixel DIC camera system was installed at the back of the test frame to observe the surface of the gear web (Figure 3).

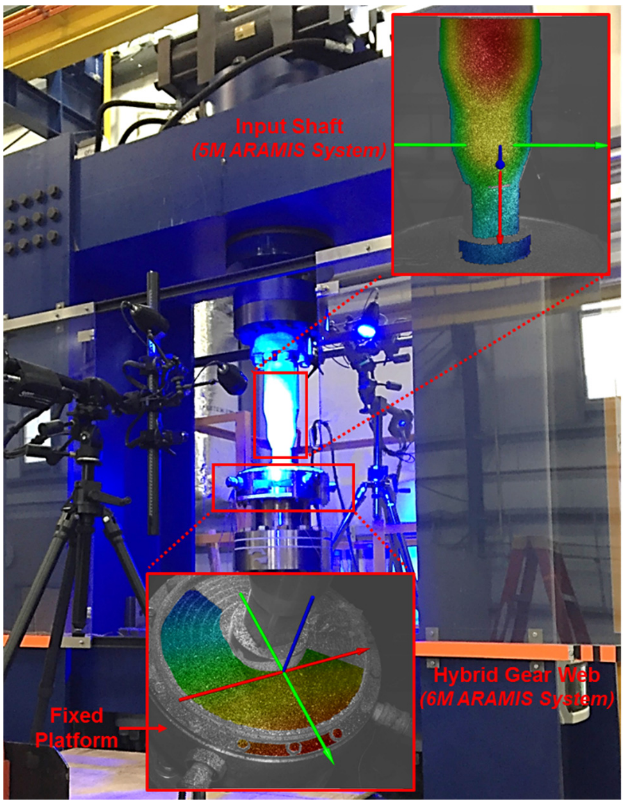


Figure 3. Static testing setup for the hybrid gear web including the two ARAMIS systems and the observable DIC measurement areas

Dynamic Gear Rig Experiment

Dynamic gear 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. It consists of back-to-back identical 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 4).

In this type of facility, only the closed-loop losses (frictional and windage 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 allows operators to adjust the loop torque during operation. The facility is powered by a 500 hp (373 kW) DC drive motor, through 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. Additional information about the rig can be found in Ref. 11.

Each gearbox has its own oil supply pump, scavenge pump and lubrication reservoir. 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 this study was a synthetic helicopter gearbox lubricant (DoD-PRF-85734), typically used in helicopter gearboxes in the field. For this study, an oil inlet temperature of 120°F (49°C) was utilized to ensure that the composite matrix remained well under its glass transition temperature.

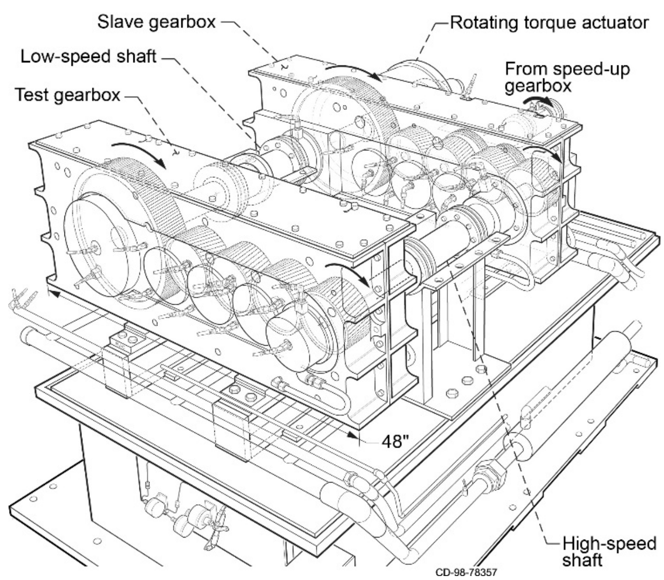


Figure 4. NASA Glenn Research Center High-Speed Helical Gear Train Rig.

The High-Speed Helical Gear Train 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 each gear onto its respective gear web or shaft. 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 utilizing the same gear rim, shafting and bearing races. To limit axial load on the test specimen, a double helical configuration was used for this study.

Several run conditions were planned for dynamic testing. The completion of each of these run conditions was dependent on the failure torque in static testing. Past designs with a failure torque of 140,000 in-lb (15,800 N-m) were only tested up to 3310 hp (2470 kW). A table of the nominal run conditions is shown in Table 1. Each run condition was performed until the rig reached approximately steady state. While at each run condition, data was recorded from facility instrumentation at 0.5 Hz including the low-speed shaft torque, the speeds of the high- and low-speed shafts, oil pressures and flow rates in each box, and several oil, bearing, and gearbox temperatures. Additionally, data was recorded in snapshots at 100 kHz from two research accelerometers on the bull gear bearing housing in both the axial and radial (vertical) direction. Data was also recorded from two proximity probes aimed at the space between the double helical gear teeth at 90° out of phase.

Table 1. Run conditions for dynamic testing.

Condition Number	**Speed** RPM	**Torque** in-lb (N-m)	**Power** hp (kW)
1	900	5000 (570)	70 (50)
2	900	10000 (1130)	140 (110)
3	900	15000 (1700)	210 (160)
4	1800	5000 (570)	140 (110)
5	1800	10000 (1130)	290 (210)
6	1800	15000 (1700)	430 (320)
7	2700	5000 (570)	210 (160)
8	2700	10000 (1130)	430 (320)
9	2700	15000 (1700)	640 (480)
10	3600	15000 (1700)	860 (640)
11	3600	19300 (2180)	1100 (820)
12	4500	19300 (2180)	1380 (1030)
13	4500	38600 (4360)	2760 (2060)
14	4500	58400 (6600)	4170 (3110)
15	5400	19300 (2180)	1650 (1230)
16	5400	38600 (4360)	3310 (2470)
17	5400	58400 (6600)	5000 (3730)

RESULTS

Static Torsion Results

Analysis of the torque and rotation provided by the facility software and the DIC deformation data was performed to determine if there was any noticeable compliance or failure of the hybrid gear web, specifically near the lobed interlocks. The torque response is shown in Figure 5. The initial negative torque stems from this being the second of two loading cycles performed, where the first loading cycle was performed to pre-load the test article and ensure it was properly set in the rig. The first cycle, which is not shown in Figure 5, increased the torque to 100,000 in-lbs (11,300 N-m) before suddenly releasing the load, resulting in a negative starting torque for the second loading cycle. The gear web endured a maximum torsional load of 240,000 in-lb (27,100 N-m), the maximum allowed by the apparatus, without experiencing a failure.

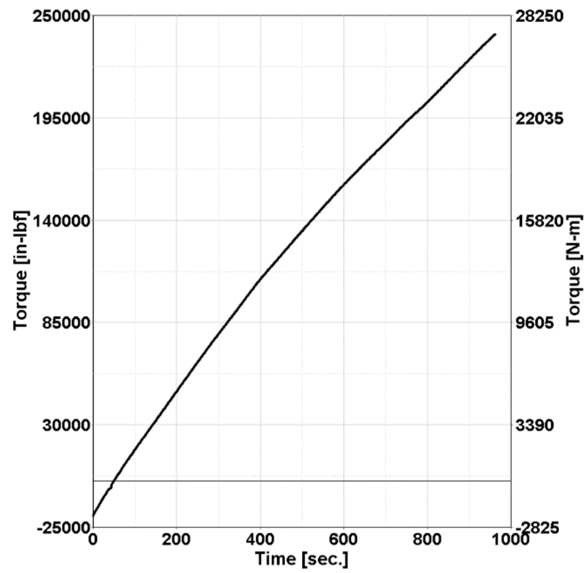
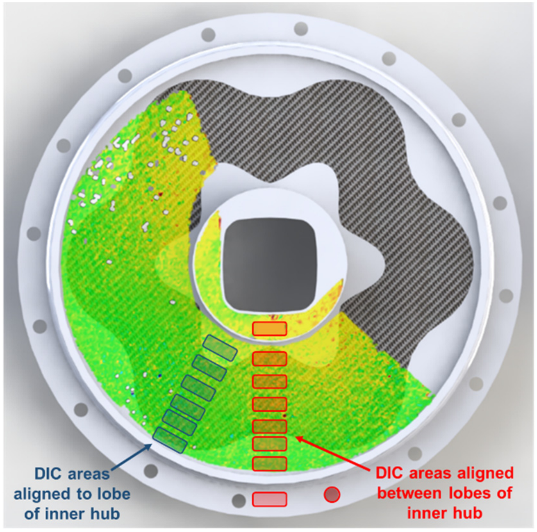
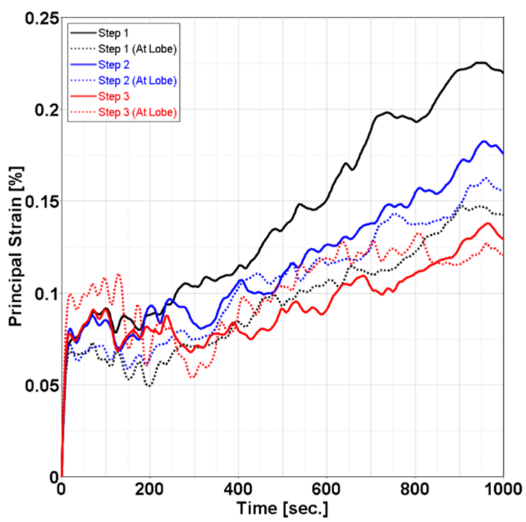


Figure 5. Torque response for static torsion test.

Analysis of the DIC results was performed by averaging data from specific measurement areas on the inner hub, composite, outer rim, and bolts as indicated by the red and blue outlined areas in Figure 6(a). Averaged measurements were obtained from each step of the composite, where a separate set of measurement areas were extracted approximately 30° from the first set in order to determine the effect of the lobed interlocks on the deformation results. The principal strain results are presented in Figure 6(b), where the "At Lobe" curves are measured from a section of composite over the lobe of the inner hub (blue outlined areas in Figure 6(a)) and the curves without this label represent the strain results from a section of the composite in between the lobes of the inner hub (red outlined areas in Figure 6(a)). Comparison of these results demonstrates a significant difference between the two sets of DIC areas, where the first step of the composite experienced approximately 50% more strain between the lobes than the strain from the step 1 area over the lobes. This strain gradient decreased in the steps of the composite that were farther away from the inner hub and inner lobed interlock, with the strain at the third step of the composite showing little difference between areas at the lobe and in between lobes. While these strain comparisons establish the effect of the gear web architecture, it is important to note that the maximum strain value was smaller than 0.25% which demonstrates that there was minimal compliance of the gear web. Additionally, the DIC contour of the loading shaft displayed in Figure 7 shows larger strains in the shaft indicating the stiffness of the gear web surpassed that of the test frame. The outcome of the test was the prevention of failure and compliance in the gear web, and these results provided beneficial information for designing the specifications for the dynamic experiments.



(a)



(b)

Figure 6. DIC analysis of the hybrid gear web from static torsion testing, where (a) identifies areas of interest for principal strain calculations shown in (b).

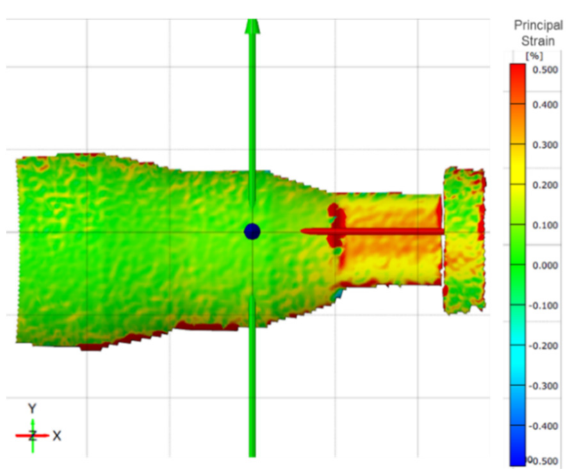


Figure 7. Principal strain contour of the input shaft.

Based on the results from this static torsion test as well as an additional static torsion test on the same design, which also extended to 240,000 in-lb (27,100 N-m), it was determined that the variable thickness hybrid gear web design was suitable for dynamic testing at the maximum power condition of 5000 hp (3730 kW).

Dynamic Results

Dynamic experiments with the baseline and variable thickness hybrid gear web were performed. Throughout the various test conditions, RMS vibration levels (measured at the bull gear bearing housing) are well matched between the two experiments with the exception of around 1380 hp (1030 kW) and 1650 hp (1230 kW), which demonstrate higher vibration levels for the hybrid test when looking at the radial vibration (Figure 8 (a) and 8 (b)). A time synchronous average was also taken at each condition, to provide a repeatable vibration signature specific to the gear's rotation. The magnitude of the vibration at the mesh frequency was compared at each condition in Figures 9 (a) and (b) for the axial and radial directions respectively according to the primary meshing frequency. Hybrid gear vibration in the axial direction dominates the baseline signal at the maximum speed (5400 RPM or 12.5 kHz primary mesh) for all load conditions. Similarly, the hybrid gear vibration dominates the radial vibration at the 1800 RPM (4170 kHz primary mesh frequency).

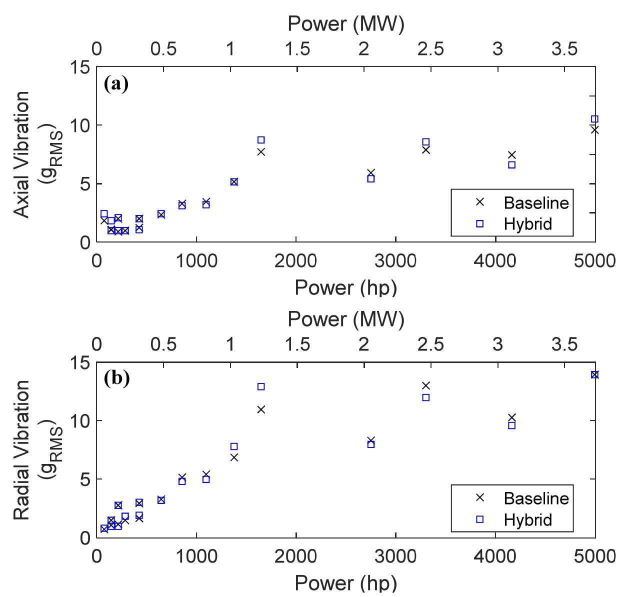


Figure 8. Vibration level in the (a) axial and (b) radial directions for both a baseline steel web and variable thickness hybrid.

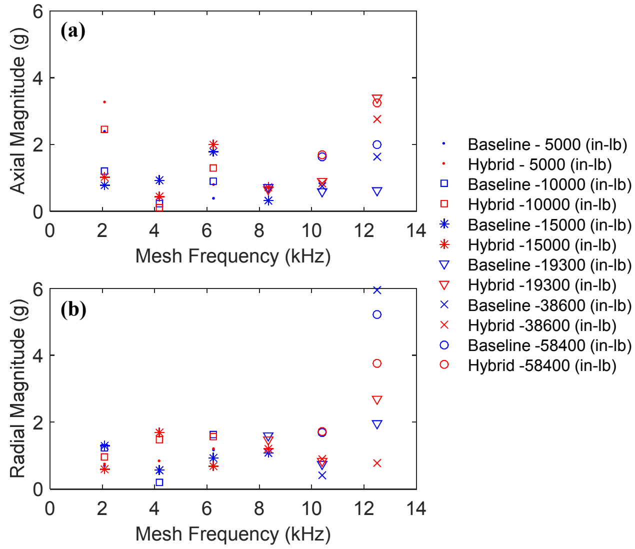


Figure 9. TSA vibration magnitude at the mesh frequency in the (a) axial and (b) radial directions.

Temperatures were also compared at each condition after steady state was reached. When comparing the fling off temperature at each condition, it was noticed that there was an increase in the bull gear mesh oil fling off temperature for the case of the variable thickness hybrid. While not shown here, data from prior hybrid gear tests were also compared and are almost exactly the same as the baseline data shown. Figure 10 shows the temperature differential between the bull gear fling off and the oil inlet to ensure that small increases in inlet temperature were not influencing the data. Above 1400 hp, temperature differentials between fling off and oil inlet is 4-9°F (2-5°C) higher for the hybrid gear than baseline test article.

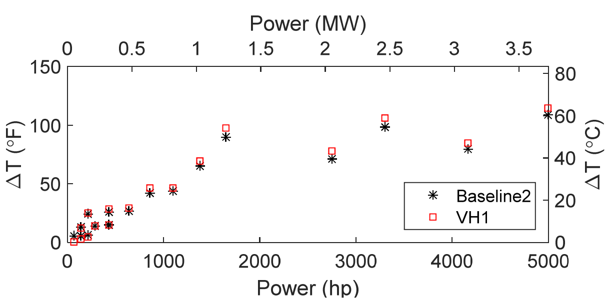


Figure 10. Temperature differential between the bull gear oil fling off temperature and the oil inlet temperature.

Endurance Experiment

After the completion of dynamic testing, an additional endurance test was performed. This test was meant to evaluate the endurance of the variable thickness hybrid gear at 5000 hp (3730 kW). The goal was to complete one million cycles at this condition if possible. Testing was uneventful until shortly after halfway through the test, when the center of the gear orbit started to shift and then became suddenly erratic. The test was discontinued at this time and a change in the axial stiffness of the bull gear was observed. The gearbox was disassembled and the shaft and gear were removed from the hybrid web.

After disassembly, the outer metallic adapter could be moved slightly axially and movement between the composite and the inner hub was visible. A post-test through-thickness ultrasound of the hybrid web was performed as shown in Figure 11. A large air bubble is visible in the top portion of the web indicating extensive delamination. Successive ultrasound measurements images, where the gear was rotated in the bath between scans, all look similar and include a similar air bubble in the top portion of the image. While the air bubble is only shown in the top portion of any single scan image, its presence regardless of orientation suggests the damage likely extends around the circumference of the gear web. Sectioning of the gear is planned, though it was not completed prior to this paper.

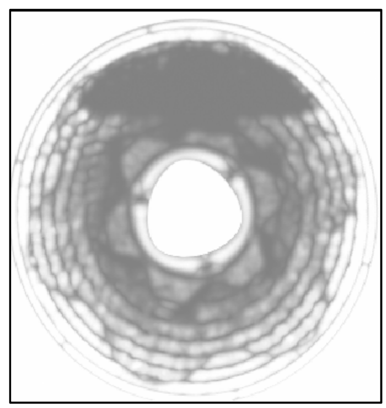


Figure 11. Post-test through-thickness ultrasound inspection of the variable thickness hybrid web.

While a failure of the gear was experienced during endurance testing, it is important to note that the failure was benign in nature and was detected from the proximity probe signal prior to damage to other components within the gearbox. The failure may have been related to a design flaw in the provided test article. The gear web was originally received with an improper axial placement of the bolted gear web flange for the test article used in the described dynamic experiments. While researchers thought they had accounted for this in the assembly, the first time the two halves of the gearbox were joined and bolted together resulted in a gearbox that had no backlash and was difficult to rotate by hand. With the gear placement being fixed, the axial offset was taken up by the splined shaft advancing slightly further into the mating splined shaft. Unfortunately, the shaft hit the end stop of the bore on the mating shaft, which resulted in an axial load on the bull gear. The problem was addressed by grinding down the end of the shaft slightly and the gearbox was reassembled.

As discussed previously, there was an increase in the differential temperature between the bull gear oil fling off and the oil inlet for the variable thickness hybrid gear in previous dynamic testing. This could be an indicator that there was still some axial loading on the bull gear in the final assembly.

CONCLUSIONS

A new variable thickness hybrid composite gear was designed and manufactured and results of static torsion, dynamic, and endurance experiments are presented. The variable thickness hybrid gear design presented greatly exceeded the performance of previous designs, and the capacity of the available static torsion rig, with a torque capacity of more than 240,000 in-lb (27,100 N-m). Dynamic and endurance testing showed that, while there are limitations to this particular test article, the use of hybrid gearing in high-power applications up to 5000 hp (3730 kW) is feasible.

Endurance testing of this particular test article did result in a delamination, though this was likely do to overloading of the gear axially. It is important to note that, while a failure occurred, the failure was rather benign in nature and detected by personnel using the available proximity probe signal. No damage was incurred by other components in the gearbox due to the failure and, most importantly, the gear continued to transmit torque after the failure was experienced.

FUTURE WORK

An additional test article of the same design described here, but with the correct positioning of the bolted flange has been acquired. The authors plan to rerun the dynamic tests discussed here and show that the full endurance test can be completed.

Additional ongoing work includes further processing of the DIC data obtained during static torsion testing. The authors hope to use this to validate a finite element model of the variable thickness web. Authors are also investigating the possibilities of being able to mate the composite directly to the polygon shaft and gear without the use of the metallic adapters. This has the potential to greatly decrease the weight of the full assembly.

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