UNCLASSIFIED

Performance Investigation of a Full-Scale Hybrid Composite Bull Gear

Kelsen LaBerge (ARL), Robert Handschuh (NASA), Gary Roberts (NASA), and Scott Thorp (NASA ret.)

May 18th, 2016 – AHS Forum 72

Approved for public release:

Outline

- Motivation
- Past efforts
- Bull gear design
- Experimental setup
- Results
- Conclusions
- Future work

Motivation

- **Several past government programs aimed at increasing rotorcraft power density**
- **Advanced rotorcraft configurations require the ability to change rotor speed, which requires additional drive components further increasing drive system weight**
- **No suitable replacement for steel in durable high-stress contacts**

- **Hybrid composite gears are being investigated to replace the structural portion of a steel gear with lightweight composite material**

Past Efforts

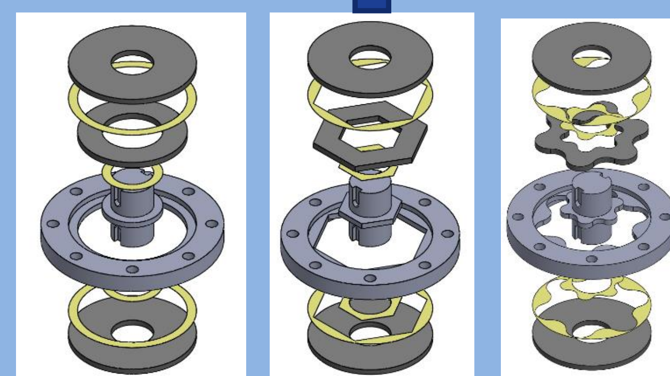
A&P Technology

Small-Scale Proof-of-Concept

Endurance testing of 3.5” pitch diameter coupon gears

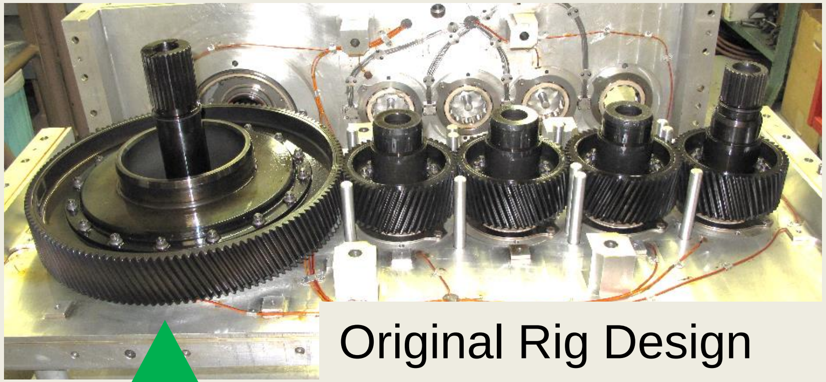
Static torque tests on coupon level gears

Full-Scale Bull Gear



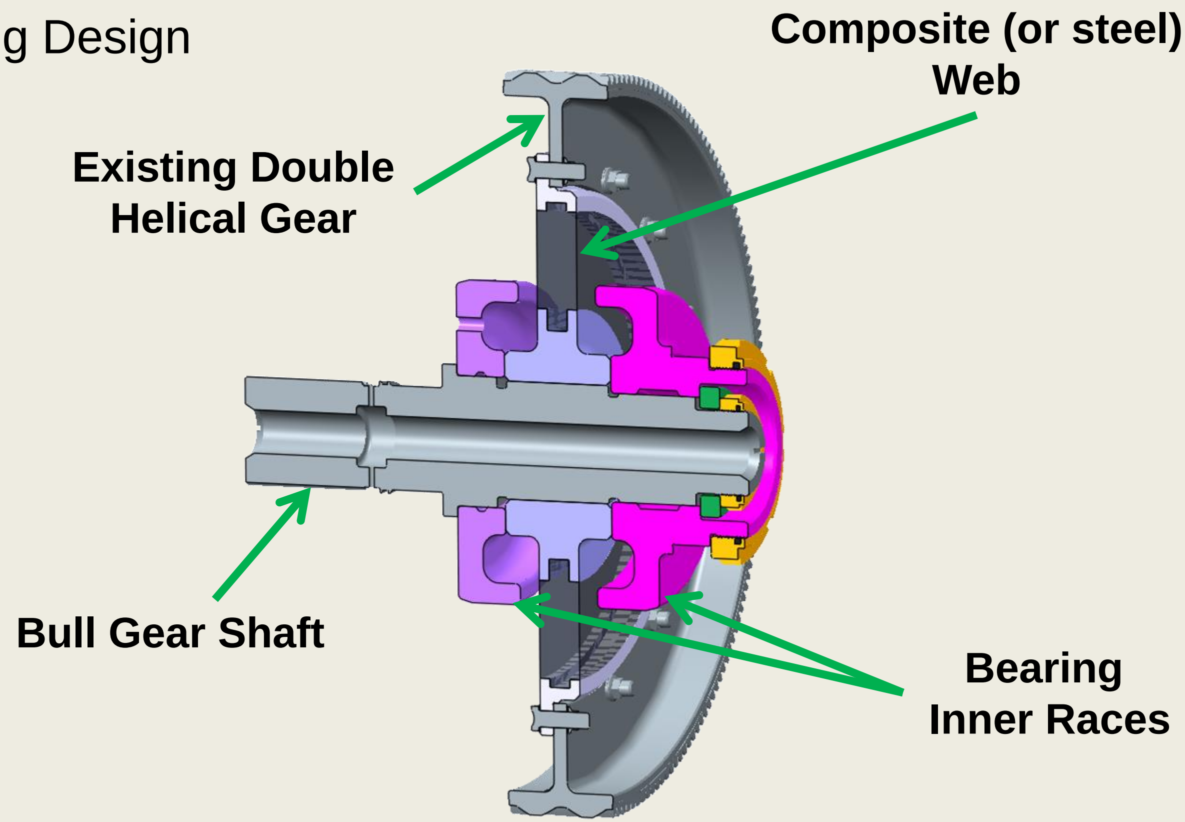
Mechanical interlock testing

Bull Gear Design



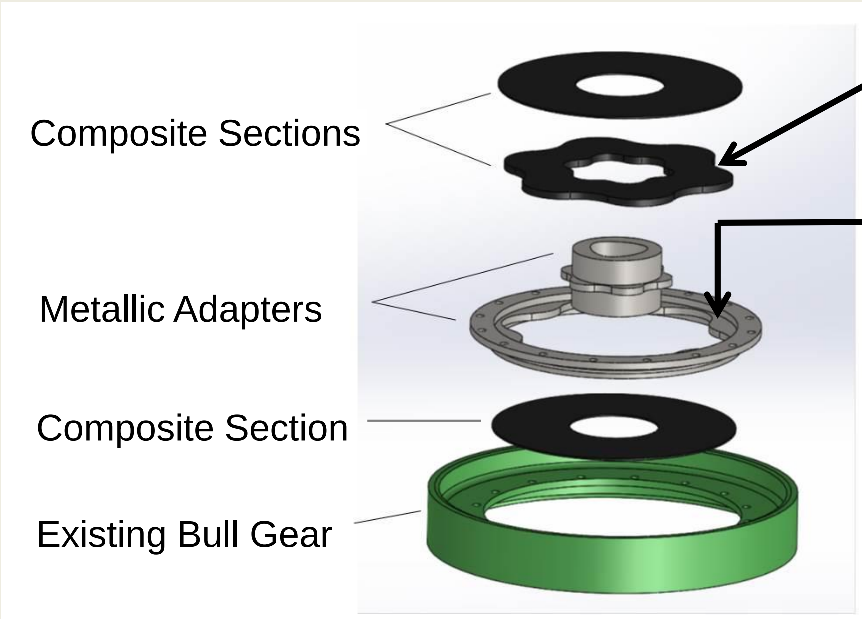
Original Rig Design

Modular hybrid bull gear design allows for several hybrid web designs to be evaluated with minimal additional cost.



Bull Gear Design

Exploded View of Hybrid Web

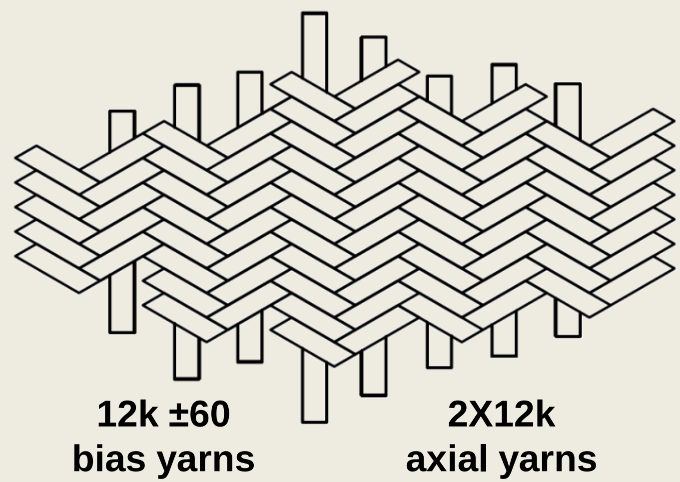


Torque Transfer Mechanisms

Mechanical interlock

Adhesive bond at axial steel/composite interface (Cytec MTA-241 film adhesive)

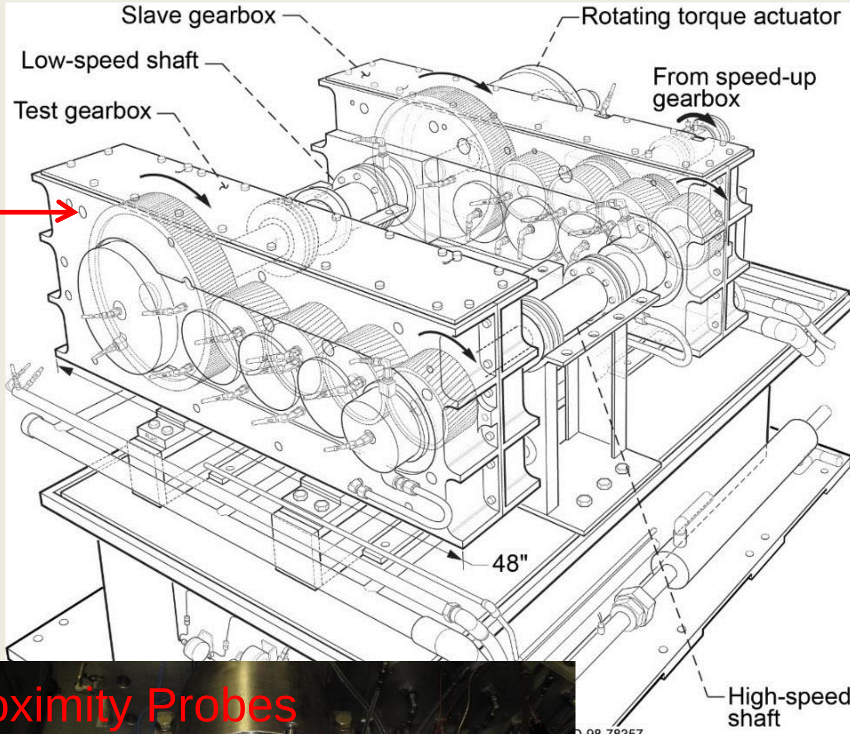
Triaxial Braid Architecture

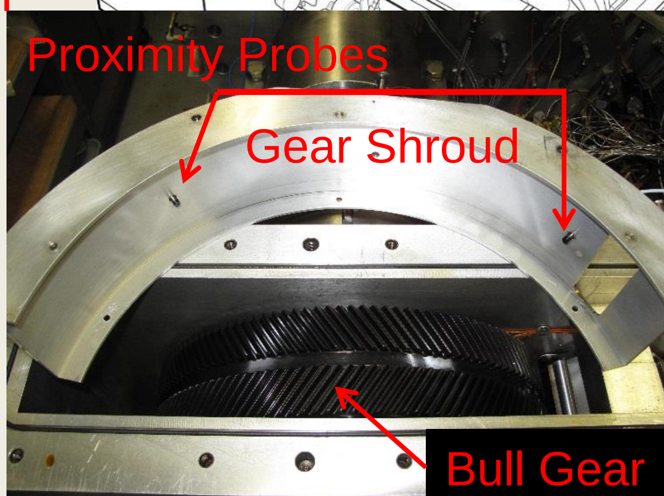


Braided composite information

- T-700 SC carbon fibers
- Prepreg 0^0, +/- 60^0 braided architecture
- Equal fiber volume in all directions
- Tencate TC-250 resin with 56% fiber volume

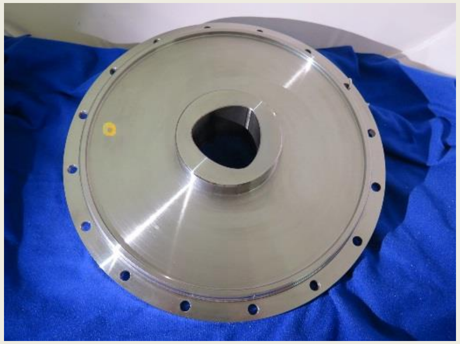
Experimental Setup

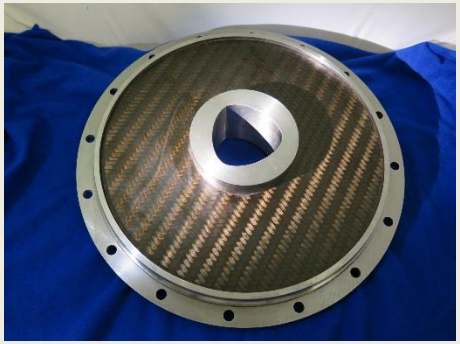




- **NASA Glenn Research Center High-Speed Helical Gear Rig**
- **Rig capable of running at aerospace conditions (5,000 HP)**
  - **Input Pinion: 15,000 RPM at 21,000 in-lbs**
  - **Bull Gear: 5475 RPM at 58,400 in-lbs**
  - **Up to 250°F oil inlet temperature**
- **Instrumentation**
  - **Axial and radial vibration monitoring at bull gear bearing housing**
  - **Proximity sensors for monitoring bull gear orbit**

Test Matrix





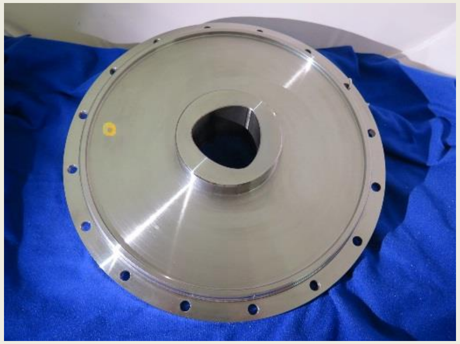
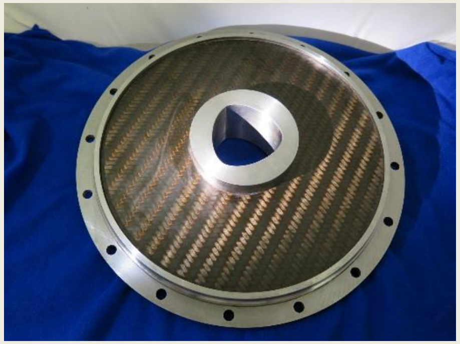
Run Condition	Shaft Speed (RPM)	Torque in-lb (N-m)		Power hp (kW)	
1	900	5,000	(560)	71	(53)
2	900	10,000	(1,130)	143	(106)
3	900	15,000	(1,690)	214	(160)
4	1,800	5,000	(560)	143	(106)
5	1,800	10,000	(1,130)	286	(213)
6	1,800	15,000	(1,690)	428	(319)
7	2,700	5,000	(560)	214	(160)
8	2,700	10,000	(1,130)	428	(319)
9	2,700	15,000	(1,690)	643	(479)
10	3,600	15,000	(1,690)	857	(639)
11	3,600	19,300	(2,180)	1,102	(822)
12	4,500	19,300	(2,180)	1,378	(1,028)
13	4,500	38,600	(4,360)	2,756	(2,055)
14	4,500	58,400	(6,600)	4,170	(3,109)
15	5,400	19,300	(2,180)	1,654	(1,233)
16	5,400	38,600	(4,360)	3,307	(2,466)
17	5,400	58,400	(6,600)	5,004	(3,731)

- **Tests were run with an oil inlet temperature of 120°F**
- **Test were run according to the test matrix**
- **Vibration level and orbit size were monitored during testing**

Note: Tabulated horsepower values in the paper are incorrect!

U.S. ARMY RDECOM

Test Matrix

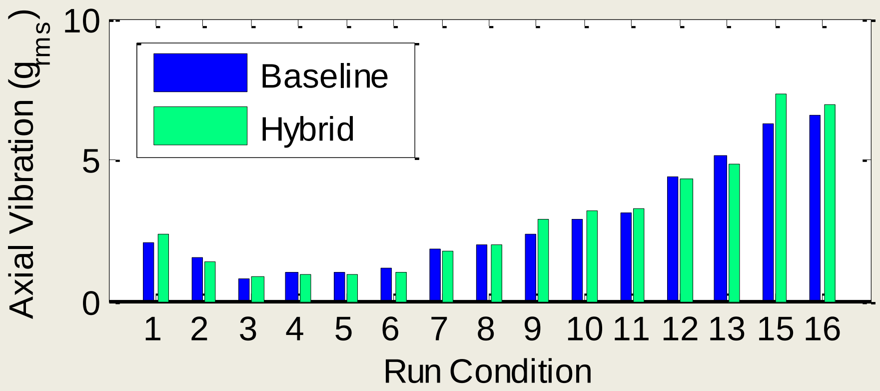
Run Condition	Shaft Speed (RPM)	Torque in-lb (N-m)		Power hp (kW)	
1	900	5,000	(560)	71	(53)
2	900	10,000	(1,130)	143	(106)
3	900	15,000	(1,690)	214	(160)
4	1,800	5,000	(560)	143	(106)
5	1,800	10,000	(1,130)	286	(213)
6	1,800	15,000	(1,690)	428	(319)
7	2,700	5,000	(560)	214	(160)
8	2,700	10,000	(1,130)	428	(319)
9	2,700	15,000	(1,690)	643	(479)
10	3,600	15,000	(1,690)	857	(639)
11	3,600	19,300	(2,180)	1,102	(822)
12	4,500	19,300	(2,180)	1,378	(1,028)
13	4,500	38,600	(4,360)	2,756	(2,055)
~~14~~	~~4,500~~	~~58,400~~	~~(6,600)~~	~~4,170~~	~~(3,109)~~
15	5,400	19,300	(2,180)	1,654	(1,233)
16	5,400	38,600	(4,360)	3,307	(2,466)
~~17~~	~~5,400~~	~~58,400~~	~~(6,600)~~	~~5,004~~	~~(3,731)~~

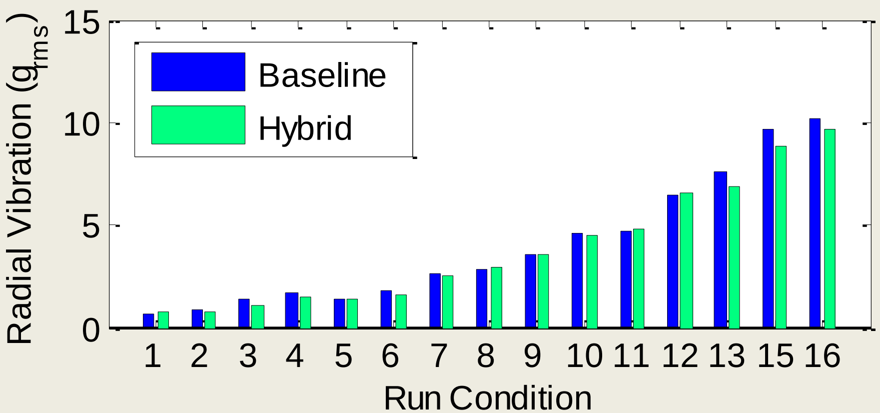
- **Tests were run with an oil inlet temperature of 120°F**
- **Test were run according to the test matrix**
- **Vibration level and orbit size were monitored during testing**
- **Hybrid bull gear tests were limited to 40% the static torque capacity of the web, eliminating conditions 14 and 17.**

U.S.ARMY U.S. ARMY RDECOM® NASA ARL

Results - Vibration

Averaged Vibration Level

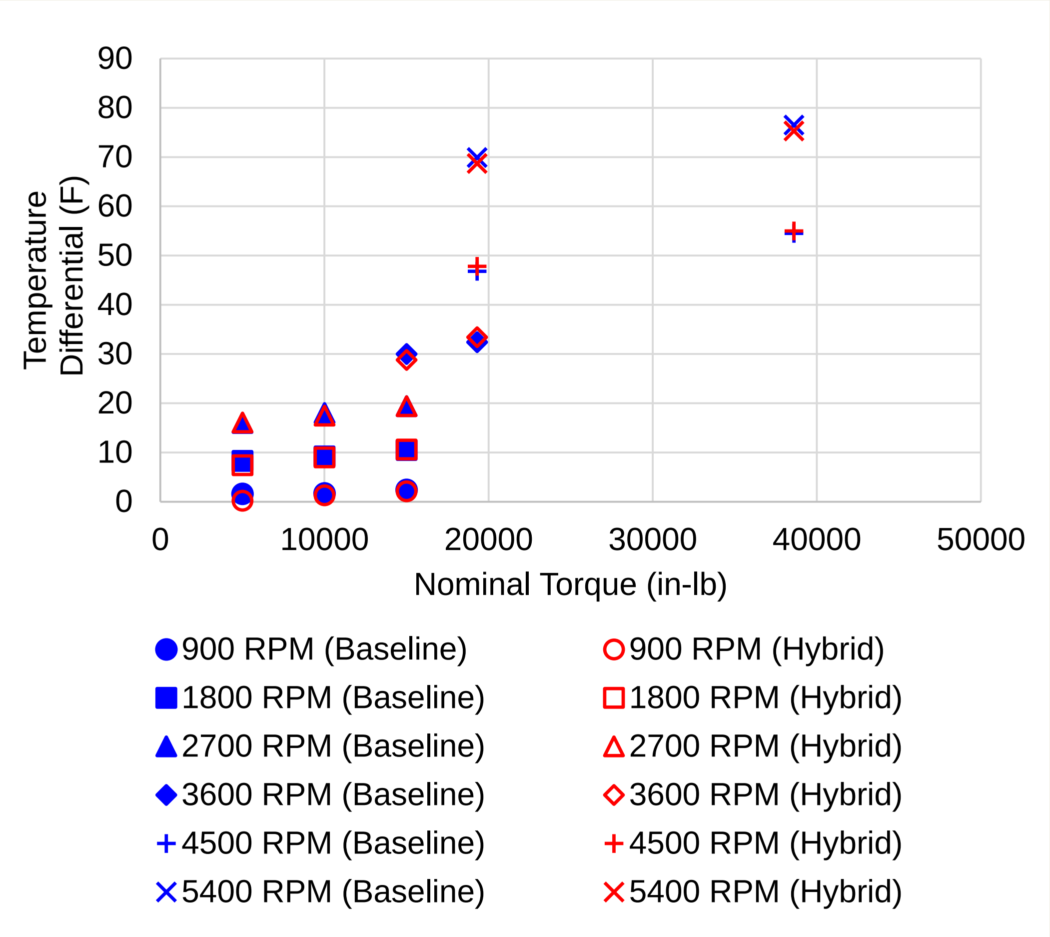




Run Condition	Shaft Speed (RPM)	Torque in-lb (N-m)
1	900	5,000 (560)
2	900	10,000 (1,130)
3	900	15,000 (1,690)
4	1,800	5,000 (560)
5	1,800	10,000 (1,130)
6	1,800	15,000 (1,690)
7	2,700	5,000 (560)
8	2,700	10,000 (1,130)
9	2,700	15,000 (1,690)
10	3,600	15,000 (1,690)
11	3,600	19,300 (2,180)
12	4,500	19,300 (2,180)
13	4,500	38,600 (4,360)
~~14~~	~~4,500~~	~~58,400 (6,600)~~
15	5,400	19,300 (2,180)
16	5,400	38,600 (4,360)
~~17~~	~~5,400~~	~~58,400 (6,600)~~

Results – Temperature

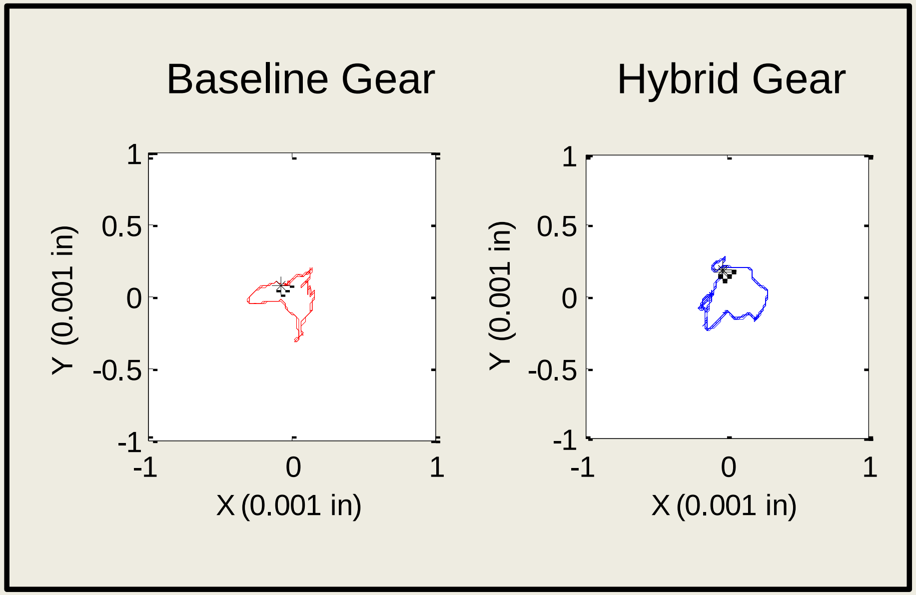
$$T_{diff} = T_{oil\text{-}outlet} - T_{oil\text{-}inlet}$$



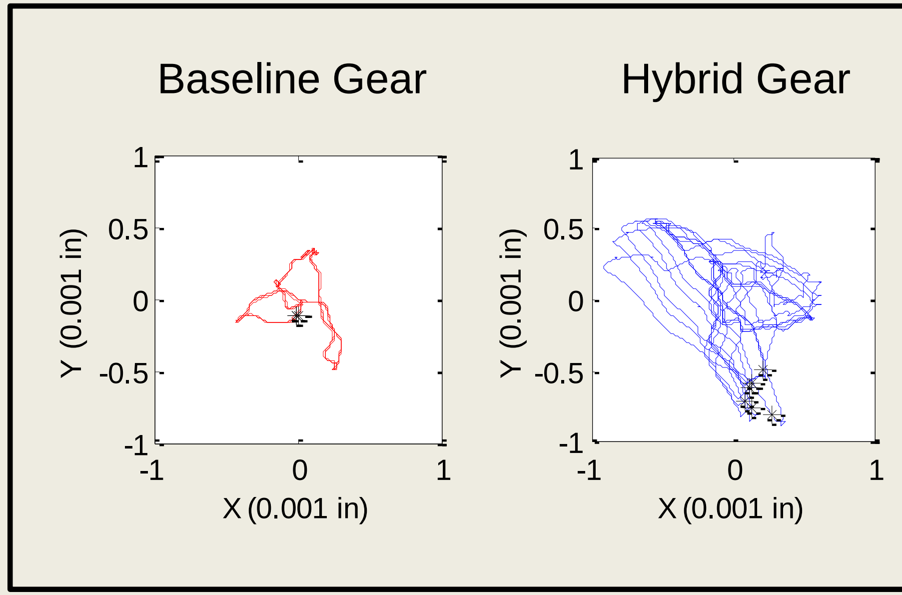
No increase in heat generation!

Results – Averaged Orbit

Run Condition 9:
2700 RPM
15,000 in-lbs



Run Condition 16:
5,400 RPM
38,600 in-lbs



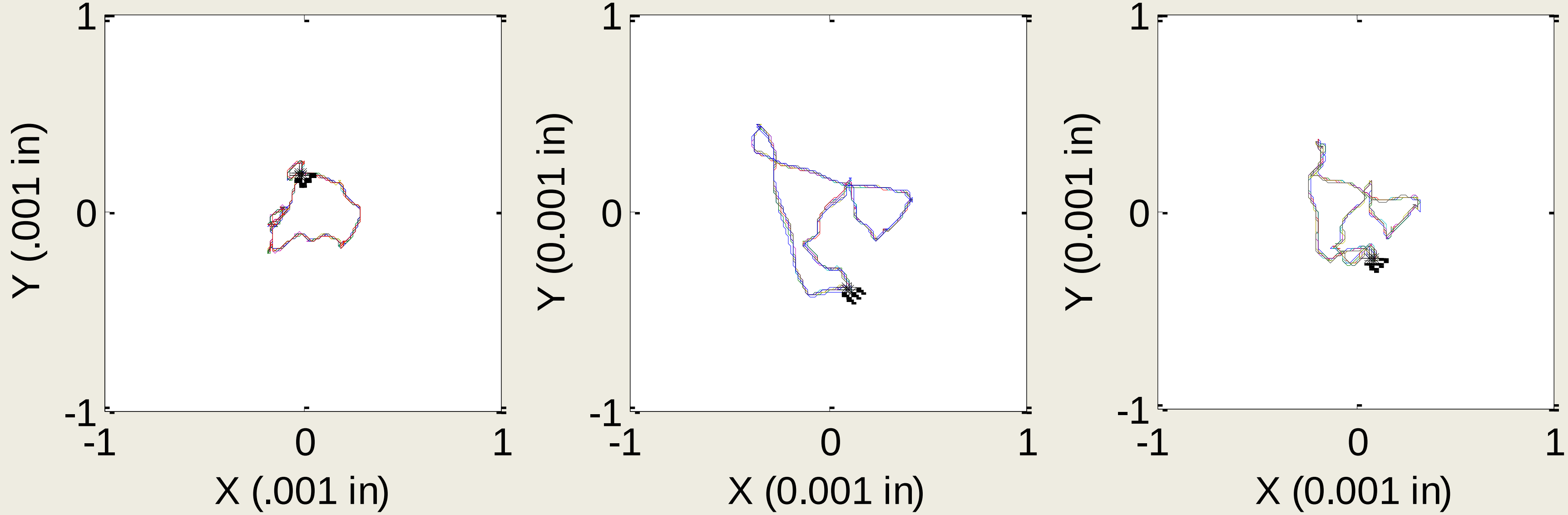
Hybrid gear orbit size starts to increase and change shape while at condition 16

Results – Averaged Orbit

Testing day 1
Condition 6 – Before max run condition

Testing day 1
Condition 6 – After max run condition

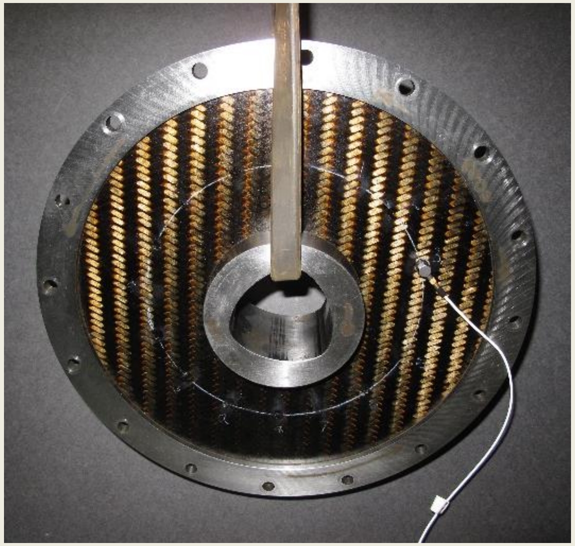
Testing day 2
Condition 6



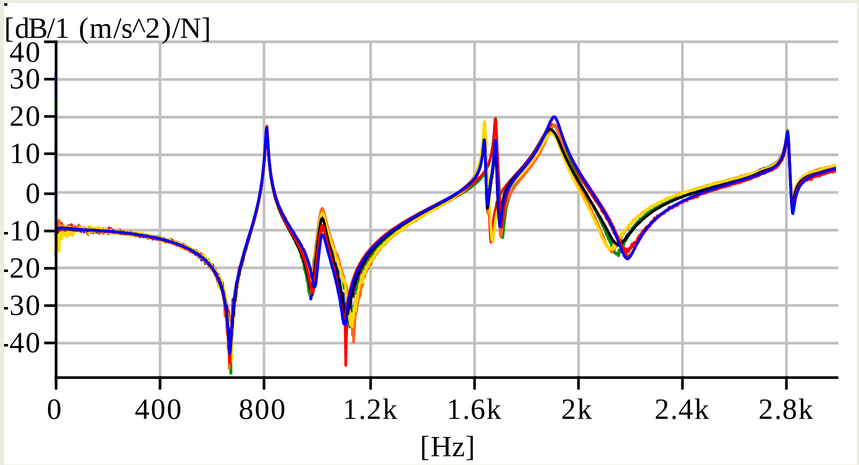
Change in shape after running at max 3300 HP condition

NDE

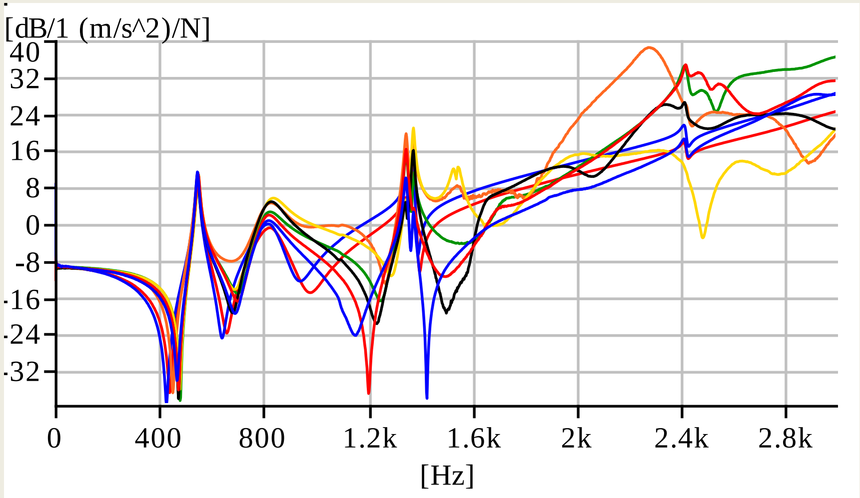
- Ultrasonic testing was unsuccessful
- Alternatives
  - Scanning acoustic microscope
  - X-ray
- Instrumented hammer tests



Driving Point FRF – Hybrid Web Tested



Driving Point FRF – Flawed Hybrid Web



Conclusions

- Successfully tested a hybrid composite bull gear up to 3300 HP
- Increase orbit size at 3300 HP resulted in discontinuation of test
  - <u>No loss of torque</u>
  - <u>Gear continued to perform at lower power conditions</u>
- No increase in overall vibration level over baseline configuration
- Composite material has no apparent effect on operating temperature
- Instrumented hammer tests give good indication of inconsistencies in the composite material

Future Work

- Continue hybrid bull gear testing with 2 additional web designs
  - Reduced number of capture plies
  - Variable thickness web
- Investigate direct mating of composite to the polygon drive eliminating the inner metallic adapter
- Complete and validate finite element model of hybrid gear
- Investigate additional NDE techniques
- Hot oil material testing
- System level testing in a production gearbox
- Static loading under combined loads

Questions?

Acknowledgements:

- **A&P Technology – NASA SBIR**
  - **Nathan Jessie**
  - **Mike Braley**

A&P Technology

Past Publications:

PATENT: R. F. Handschuh and G. Roberts, “Hybrid Gear,” US 9,296,157 B1, 29-Mar-2016.

R. F. Handschuh, K. E. LaBerge, S. DeLuca, and R. Pelagalli, “Vibration and Operational Characteristics of a Composite-Steel (Hybrid) Gear,” NASA/TM-2014-216646; ARL-TR-6973, Cleveland, OH, Jun. 2014.

R. F. Handschuh, G. Roberts, R. Sinnamon, D. B. Stringer, B. D. Dykas, and L. Kohlman, “Hybrid Gear Preliminary Results—Application of Composites to Dynamic Mechanical Components,” in American Helicopter Society 68th Annual Forum, Fort Worth, Texas, 2012.