Testing the Digital Gearbox

Computational testing tools promise to save designers of rotorcraft transmissions physical testing time and money, and make Health and Usage Monitoring Systems more reliable

By Frank Colucci

Computational testing has already helped develop Condition Indicators for Health and Usage Monitoring. The Army Aviation Applied Technology Directorate plans flight tests with an AH-64E in 2017 to validate CIs for ASTRO (Autonomous Sustainment Technologies for Rotorcraft Operations) program. (US Army)

Complex, costly and flight-critical gearboxes and related drivetrain components are key to rotorcraft performance and safety. Computational testing — running high-fidelity transmission models in a digital environment — promises to shorten the time needed to test the real thing. "The potential payoff, if it works, is to allow the rotorcraft industry to implement new gearbox technology more quickly," explains Dr. Timothy Krantz, drive systems technical lead at the NASA Glenn Research Center." Experimental work has such a long lead-time, if you can back that up with analytical work that allows you to understand why the thing works, it puts more confidence in things sooner."

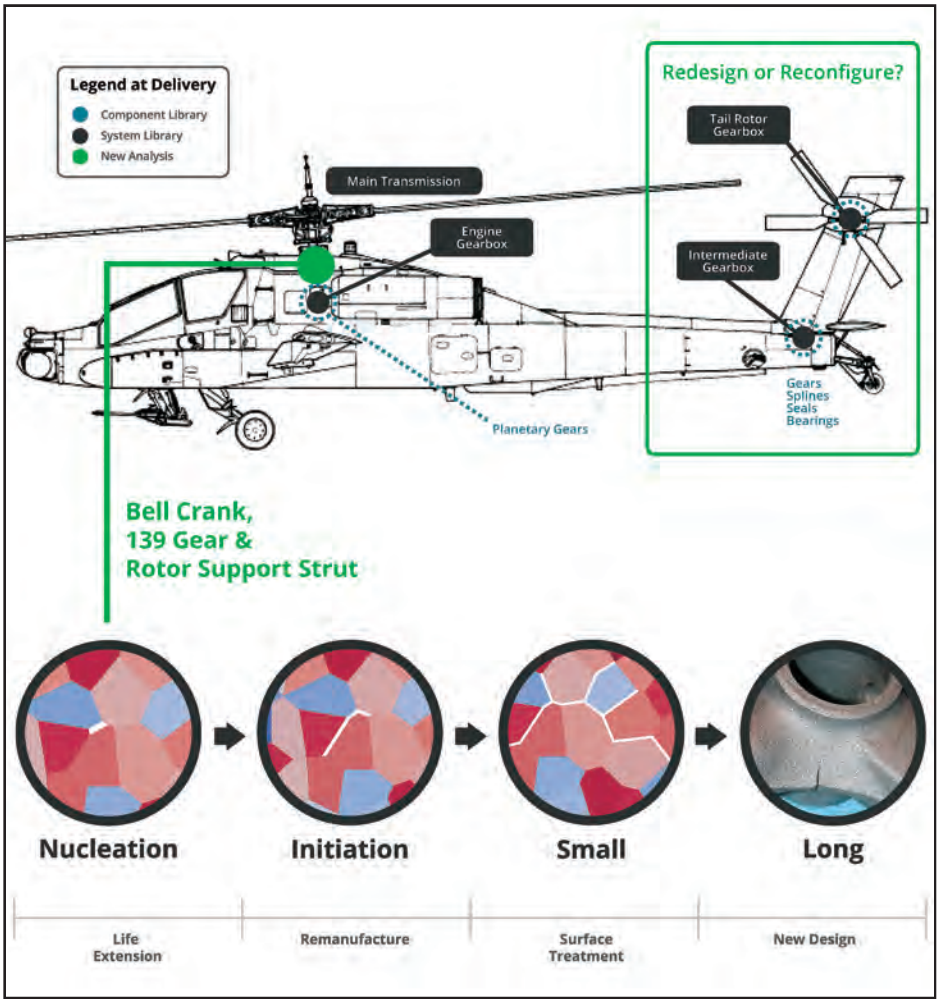
The same understanding can fine-tune Condition Indicators (CIs) generated by rotorcraft Health and Usage Monitoring Systems (HUMS). "We use a lot of physics-based models to feed into our HUMS and Condition-Based Maintenance (CBM) systems," notes aerospace engineer Chris Lyman in the sustainment technical area of the US Army Aviation Applied Technology Directorate (AATD). Under the Autonomous Sustainment Technologies for Rotorcraft Operations (ASTRO) program, AATD at Joint Base Langley-Eustis, Virginia plans a real flight demonstration to validate power assurance CIs refined by computational testing. More reliable CIs transitioned from laboratory to flightline could someday cut unnecessary engine removals. "We're trying to reduce the risk of transitioning technologies like that."

> **"We're more accurate than physical tests now. The physical tests are important but we can provide more information. "**
>
> **Ward Thomas**
> **Sentient Science**

How much risk Army, NASA and industry engineers ultimately accept will determine how and where computational testing is applied to Future Vertical Lift (FVL) and other drivetrain developments. Both the Sikorsky-Boeing Defiant compound helicopter and Bell Valor tiltrotor Joint Multi-Role (JMR) technology demonstrators rely on innovative transmissions to advance different FVL solutions. Sikorsky management has acknowledged in the media that errors were made modeling the huge CH-53K main gearbox, but declined any comment on computational testing for this article. Bell has done research and development work with VEXTEC on behalf of the Vertical Lift Consortium. VEXTEC in Brentwood, Tennessee offers Virtual Life Management engineering software that integrates material micrograin structure into component life predictions. The company has, for example, modeled crack growth in helicopter tail rotor drive shafts for the Naval Air Systems Command.

Advanced Numerical Solutions (ANSOL) in Hilliard, Ohio, has built computational models of planetary and spiral bevel gear sets since 1989, and today works for most big aircraft and engine makers. According to company president Sandeep Vijayakar, "The geometry is very complicated in helicopters.... Development of a new helicopter gearbox could take 7 to 10 years. We try to help them cut that down." ANSOL models predict gear stresses and vibrations and estimate sensitivity to manufacturing errors. "We predict the actual contact pressures on the gear. Once you know that, you can estimate the wear." The analysis now even figures in models of the machines that cut the gears and the behavior of lubricants. "It's gotten possible to do a more complete model," says Mr. Vijayakar. "Previously, we could only do a small part of the gearbox. As time goes on, it becomes more realistic."

DigitalClone software developer



Sentient Science DigitalClone models include material and lubricant properties to predict wear in helicopter gearboxes. (Sentient Science)

Sentient Science in Buffalo, New York, offers high-fidelity gearbox models that perform like the real thing as an attractive way to cut physical testing costs at the design stage. Sentient Science president Ward Thomas offers, "We're more accurate than physical tests now. The physical tests are important, but we can provide more information." The DigitalClone software builds material, component and systems models. An Apache gearbox model, for example, reproduces the entire system and its individual components, including their materials and lubrication. It draws on multi-body dynamics from the gaming industry to predict fluid movements and allows for lubricant changes with altitude. The model shows what components will fail and the effect of a new material or change in operation in the drivetrain, including the ability to handle the increased horsepower of new engines. "It's not just one point," says Mr. Thomas. "It's the complete system that we're able to look at including structure for rigidity."

Computational testing also plays a role in HUMS development. Under the Army Aviation and Missile Research, Development and Engineering Center (AMRDEC) at Redstone Arsenal, Alabama, ADD and AATD started the ASTRO drive, propulsion, structures and rotor program in 2013. (An ASTRO electrical effort is scheduled to start this October.) The S&T effort aims to develop and demonstrate monitoring technologies that may reduce weight, stretch component life, optimize performance and cut the maintenance burden on current and future vertical lift platforms.

A computational testing model can predict the durability and reliability of the Apache main transmission, tail rotor drive planetary gear and bearing system. It predicts overload and over-torque conditions and can be integrated with the real AH-64 HUMS to provide Condition Indicators. Boeing wants to advance ASTRO sustainment technologies for the Apache and other products. Applied testing with a real transmission in a representative environment could lead to further maturation and an operational TRL-9 solution. However, Boeing Mesa engineering cautions, "Until successfully completed, the selected technologies are not, and have not been demonstrated, at a maturity level necessary for supporting production platforms."

ASTRO drive technologies will be physically tested on a real AH-64E Apache Guardian transmission in Fiscal 2017. In the meantime, Boeing chose Sentient Science to build DigitalClone life prediction models of the Apache gearbox. The prognostic models are used to evaluate reliability and performance trade-offs and can integrate data from CBM sensors in real-world environments to show how manufacturing changes impact component life.

Sentient Science is also working with the Army and Original Equipment Manufacturers to develop computational testing guidelines and procedures for gear qualification testing. Paul Panetelis, AATD technical area lead for sustainment says, "We've had some success, but not the success you would want to use as far as qualifying the part. …The data has come out generally where the spalling [destructive pitting due to high contact pressures] starts, but some of the degree where it advances is not in synch with what actually happens to the gear or bearing."

The Army Research Laboratory forecasted a totally digital testing environment back in the early 1990s. "We're still not there, but I think we're getting closer," says aerospace engineer and Aviation Sustainment Science and Technology Focus Area lead Bradley Miller at the Aviation Development Directorate (ADD) in Huntsville, Alabama. "Our intent is to have a DigitalClone [like] process built into FVL at some point. But I think we still have some way to go."

Computational testing figures in Army and NASA research into variable speed transmissions by NASA and the US Army, providing starting points and some analysis prior to building real gearboxes. According to Mr. Miller, "Under the current paradigm, every system is so unique that going through the qualification process is costly. Computational testing holds promise to reduce the costs, but there are still many uncertainties. Eventually, we'll get there."

Build Better Models

Physical gearbox testing for helicopters and tiltrotors uses gears seeded with faults. However, running "iron bird" transmissions backed by dynamometers and material testing machines is costly and time-consuming. "We're talking millions of dollars and years of time," notes Mr. Thomas at Sentient Science. The time and cost of physical testing also limits how many operating conditions can be tested. "In the end, after all that time and money, you wind up with only three or four data points.... We need a way to test all the possible variations, even it if funnels down to a final physical test."

Computer-based FEA introduced in the 1980s identified gear stresses, but still had limitations. "It turned out you could not get from stress to life without a physical test," says Mr. Thomas. Sensor and software integrator Sentient Science uses collected tribology data — gear contact pressures, material characteristics, surface roughness, lubricant properties and contaminants — to model gear wear and predict life. "We've been building up a library," explains Mr. Thomas. "You can't afford to build a gearbox or a helicopter. It forced us to build relationships with the manufacturers to give us time on their test rigs."

Sentient Science began its computational testing development under a DARPA contract in 2001 to predict machine component life. Subsequent DigitalClone models focused mostly on aircraft engines. "We started with gas turbine engines at GE and Pratt & Whitney," explains Mr. Thomas. "Then came the drivetrains, because drivetrains have been the most difficult components." Future turboshafts with about twice the horsepower of today's engines further tax transmission development. "They don't know the effect on the drivetrains because we haven't built them yet."

The DigitalClone maker has a physical testing lab in Idaho Falls, Idaho, that cuts up gears, shafts and splines to analyze real flaws and varies common foundry and milling techniques to build material variability into its computer models. "We're looking at the grain structure, the grain disruption, grain boundaries, the sub-boundaries within the grain in between molecules.... Now we have enough characterization."

Modeling Apache and Black Hawk drivetrains began in 2006. "We started with the tail rotors on the aircraft because they were more difficult," recalls Mr. Thomas. "Then we worked our way forward to the main gearboxes, the nose gearboxes." In October 2010, a Small Business Innovative Research contract enabled Sentient engineers to use physical gear tooth pitting data from NASA Glenn to validate DigitalClone predictions.

Sentient Science used NASA data generated by an aerospace-quality test gear to validate its DigitalClone wear predictions. (NASA)

NASA researchers provided data collected over nearly 25 years from tests of a generic aerospace-quality spur gear. Sentient Science engineers showed a close correlation between their models and a physical data set of 20 to 30 points. NASA researchers routinely measure pitting in accelerated life tests. According to Dr. Krantz at NASA Glenn, "We try to speed it up by a factor of 10. Even with that, it's a long time to get any one data set. If you could complement that with a computational testing data set, it would help."

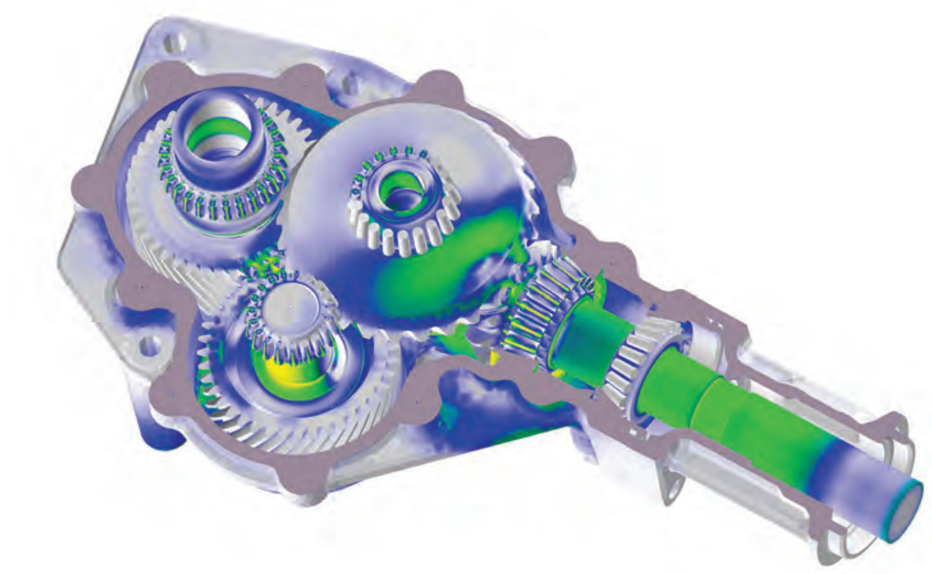
Successful data validation led Sentient to more tests with Boeing, Sikorsky and General Electric. According to Mr. Thomas, "The near-term opportunity is to run just millions of more tests because it's so inexpensive. In an hour's time, we can run 10,000 tests." DigitalClone models of the Apache and Black Hawk drivetrains have provided important insights into wear. Computational testing of Black Hawk spline threads, for example, led to a surface treatment that extends the life of the original design.

Helicopter rotors and control linkages are the next fertile area for computational testing especially with coaxial rotors like those on the Sikorsky Raider and Defiant. "We're able to look at all the tradeoffs," explains Mr. Thomas. "The use of clutching to slow down the rotor speed to speed up the aircraft — that's a perfect use of what we're doing and why we're working so hard on rotors currently."

NASA's Revolutionary Vertical Lift Technology (RVLT) project has ongoing efforts to validate computational models of gearbox windage (overall power required) through a Space Act Agreement with the Applied Research Laboratory at Penn State University (ARL/PSU). The work builds on research sponsored under previous NASA Research Announcements. The ARL/PSU is also modeling gearbox performance under loss-of-lubrication conditions for the joint Vertical Lift Research Center of Excellence. NASA this year also started some computational model development for Condition Based Maintenance with ANSOL to support research in HUMS Condition Indicators and fault detection.

Help With HUMS

Computational testing promises to reduce diagnostic false alarms and enhance prognostics. Sentient Science markets its DigitalClone Live tools for operational equipment. The company has found commercial success in the last two years, improving the reliability and reducing the operating costs of wind turbines and looks to extend the technology to rotorcraft. "We



ANSOL builds detailed computational models of helicopter gear sets that identify contact pressure. The colors here represent stress levels — blue/gray for low stress and yellow/red for high. (Advanced Numerical Solutions)

see what the sensors see and what they can't see," explains Ward Thomas. "We look at the vibrations. The HUMS data helps us serialize it to that tail number. …Because we understand the initiation and propagation of failure …we're predicting what Condition Indicator is going to occur and when it's going to occur."

Honeywell Aerospace has used Sentient Science tools to help develop HUMS CIs aimed at CBM (see "Keeping The Guard Up," *Vertiflite*, May/June 2013). Jason Rios, Honeywell CBM business manager explains, "Our system is based on evaluating thresholds for failure modes. Over time, those are refined by seeded fault-analyses and field observation. If you add the computational testing into that, you can forecast what failure modes look like. …We're able to refine those thresholds earlier in the process with this kind of information."

Honeywell Advanced Technologies research scientist Andrew Vechart adds, "We better understand how that fault progresses and how severe it would be at a certain CI level." HUMS CIs are based on vibration generated as parts wear. "We may with the model understand fatigue in a gear tooth that leads to a gear tooth breaking. We might look at that underlying fatigue mechanism with the computational testing tools.

"The other way it could help is perhaps with some initial CI identification and threshold estimation. You may be able to target it better."

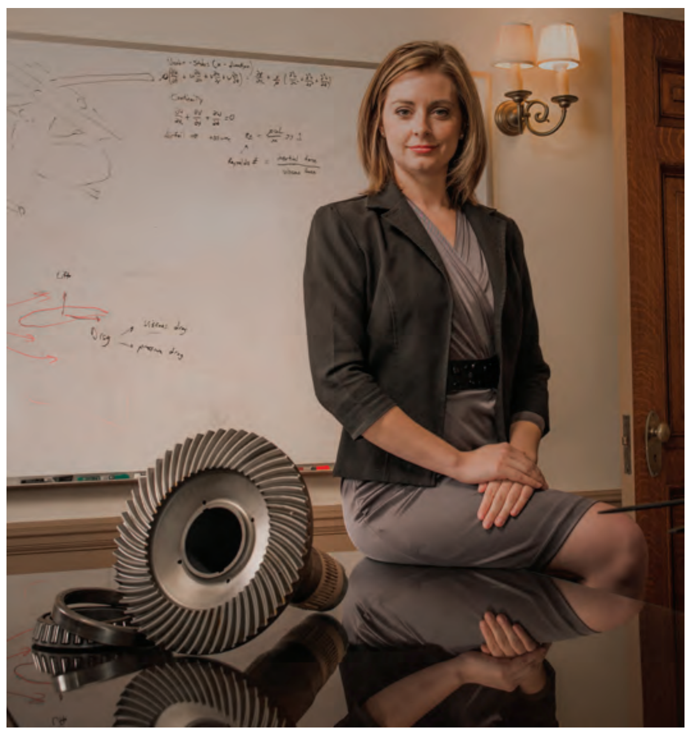
Where and how aircraft are flown meanwhile affects the way real parts wear. "Typically with computational models, you gain confidence with measured experimental data collected either in the field or the lab. …What's especially important in rotorcraft is capturing the operational environment accurately."

Like design applications, HUMS development with computational testing promises to save time and cost. "The approach and value in including computational testing in our HUMS solution is related to potentially reducing the seeded-fault testing burden that's an integral part of fully validating Condition Indicators," says Mr. Rios. "Computational Testing is a way to reduce some of that burden and still maintain that conservative engineering analysis that's necessary to making maintenance-related decisions."

How much physical validation testing is enough to prove HUMS Condition Indicators are accurate enough to support maintenance decisions is to be determined. Mr. Rios observes, "I think that a lot of that is dependent on the customer's opinion of the accuracy of the computational testing model, whether they believe the model they're using is sufficiently well-developed that they're willing to accept it instead of seeded-fault testing requirements. …We do a lot of our refinements and improvements to the system with some of our more advanced users, like the Army, for example. They have a great deal of expertise with regards to the failure modes seen with these aircraft."

About the Author

Senior contributing editor Frank Colucci has written for *Vertiflite* for the past 20 years on a range of subjects including rotorcraft design, civil and military operations, testing, advanced materials and systems integration. He can be emailed at **rotorfrank@aol.com**.



Sentient's Government Programs Manager, Dr. Jennifer Haggerty, is one of the company's "Computational Test Aerospace Engineers." Her expertise in the uncertainty of dynamical systems enhances DigitalClone prognostic models of gearboxes, engines and components, such as this spiral bevel gear for the Black Hawk tail rotor gearbox. (Sentient Science)