Rotor Blades with Insight

With the help of a powerful computer design tool, NASA and the US Army get heavily instrumented composite rotor blades to validate airflow simulations and measure rotor noise.

By Frank Colucci

Extensively instrumented rotor blades promise NASA and Army researchers high-fidelity hover performance and forward-flight acoustic data from future wind tunnel tests. The Hover Verification Acoustic Baseline (HVAB) blade set delivered in August to NASA Langley Research Center in Virginia is meant first to improve the accuracy of computational fluid dynamics (CFD) simulations and better predict rotor figures of merit early in design. Subsequent tests will characterize rotor noise generated by blade interactions.

The scaled, six-blade set is 11 ft (3.4 m) in diameter and uses NASA airfoils developed in the early 1990s. Research scientist Austin Overmeyer at the Army Combat Capabilities Development Command (CCDC) Aviation & Missile Center (AvMC) Technology Development Directorate (TDD) at NASA Ames Research Center in California explained, "The objective was to have a blade set with open source data, such that the research community could share information freely."

HVAB blade design was driven by weight and center-of-gravity considerations rather than rotor performance, and buried sensors posed challenges for blade designer and fabricator Advanced Technologies Inc. (ATI) in Newport News, Virginia. "It's the internals that are notably different," observed ATI engineering manager David Pullman. "You've got almost 200 pressure sensors, temperature detectors and strain gauges. We had to undersize the spar to provide space for sensors." ATI used the Variational Asymptotic Beam Sectional Analysis (VABS) design software from AnalySwift in West Jordan, Utah, to turn the complicated composite structure into a manageable engineering beam model.

The VABS code computes properties of long, slender composite parts such as rotorcraft blades with accurate prediction of ply-level stresses and strains. Details of composite ply buildups can be modeled quickly. Pullman said, "We would evaluate the blade outside mold line and any unique properties. We basically developed a series of spar laminates, skin laminates, and iteratively evaluated the design to come up with spar and blade sections to meet customer requirements."

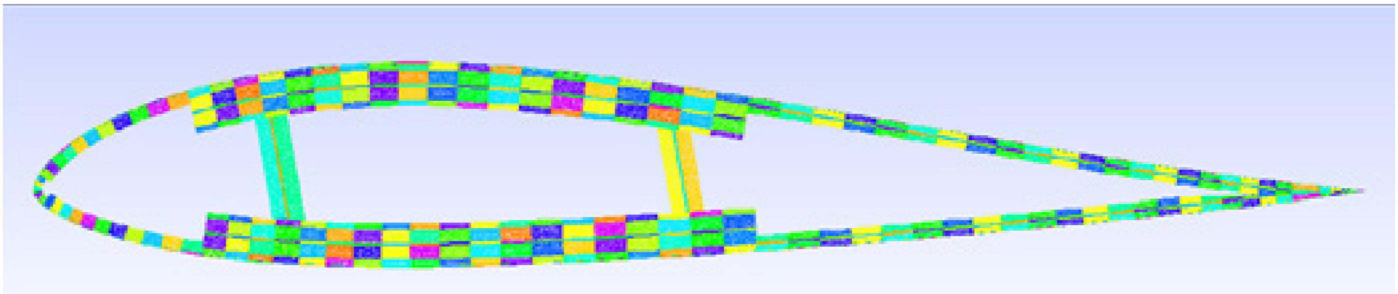
The customers for the six HVAB blades are the Revolutionary Vertical Lift Technology (RVLT) project at NASA Langley aand Army TDD at Ames. The Army paid about half the cost of the research blade set and will lead initial hover checkout testing on the Army Rotor Test Stand (ARTS) in the Langley rotor test cell. The ARTS makes it possible to measure rotor thrust and torque in hover and forward flight. Following checkout, the blades and stand will be shipped to Ames for tests in the National Full-Scale Aerodynamic Complex (NFAC).

Hover testing of the HVAB blade set will be done in the NFAC 80-by-120 ft (24.4-by-36.6 m) wind tunnel with the rotor turning 40 ft (12.2 m) above the tunnel floor to minimize recirculation and wall effects. RVLT leader Susan Gorton explained, "The data that will be collected will allow detailed comparisons between experimental measurements and computational analysis tools, specifically looking at transition location on the blades, hover air loads and performance." Pre-pandemic plans called for HVAB checkout/functional test at Langley in late summer followed by shipment to Ames for testing from October to December 2020. Actual schedules depend on when the NASA centers reopen, but NFAC hover testing should run eight to 12 weeks and conclude in early 2021.

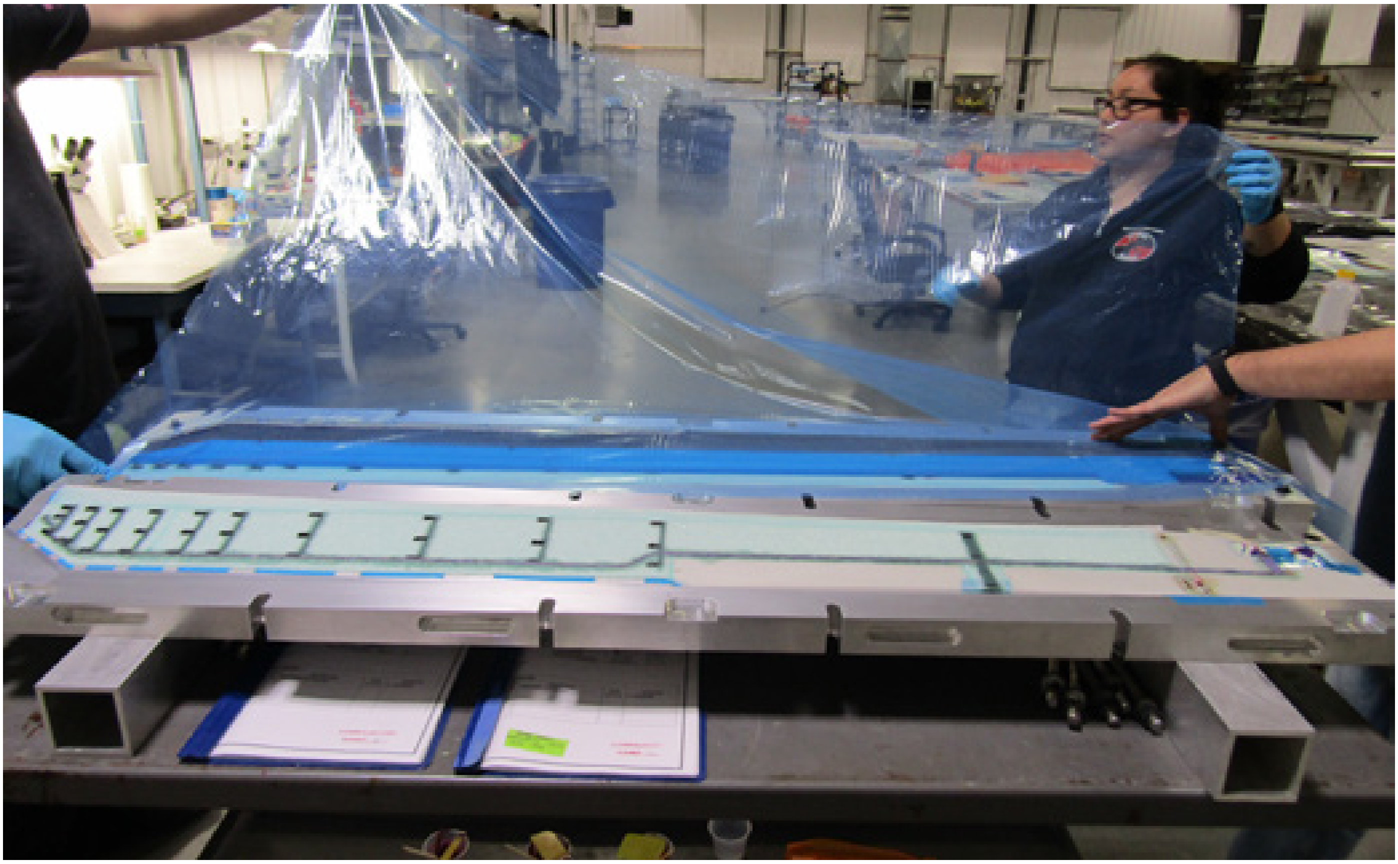
Making Blades

Up to four HVAB blades will be used at a time to generate high-fidelity CFD validation data in hover and provide an acoustic baseline for a representative rotor in forward flight. According to research scientist Dr. Norman Schaeffler in the flow physics and control branch at NASA Langley, "The large number of transducers required the development of a very unique and innovative blade design and fabrication technique. We went through many design iterations to ensure that the pressure transducers are sufficiently isolated from the mechanical strain in the blade itself. This even included the testing of a number of small instrumented specimens in my lab at NASA Langley."

The HVAB blade design repeats the radius, twist and triple airfoils of pressure-sensitive paint (PSP) blades first tested in the Langley wind tunnel in 2008. Blades with PSP were laser-illuminated to help visualize and measure global pressure distributions rather than measure spot pressures with individual transducers. The HVAB miniature pressure sensors are made by Kulite Semiconductor Products.



AnalySwift VABS code works with other tools to automate the blade design and optimization process. Here, a blade cross section with members generated by the PreVABS input tool is visualized by Gmsh three-dimensional finite element mesh generator.



The HVAB blades use Rohacell foam spar cores and pre-cured instrumentation covers and leading-edge skins. ATI bonded the carbon-epoxy HVAB spars and instrumented fiberglass skins. (ATI photo)

The HVAB blades have different transducer arrays feeding a hub-mounted data acquisition system. Tests will combine sensor outputs to generate usable data. Ames researcher Tom Norman explained, "These data will include highly accurate measurements of the rotor performance, blade airloads, blade transition location, rotor wake, and blade deformations. The new HVAB blades are key to the success of this test, providing measurements of the airloads — derived from the pressure transducers — and blade bending moments. In addition, the close-tolerance requirements for these blades will ensure the minimal blade-to-blade differences necessary for benchmark quality data."

The HVAB hover blade has 187 miniature pressure transducers at 11 stations along its length. The acoustic blade has 52 pressure transducers arranged to define pressure signatures created by flow interactions between the blades. One HVAB blade has multiple strain gauge bridges along its length to measure blade bending. To the pressure and strain sensors are added resistance temperature detectors and tip-tracking light-emitting diodes (LEDs). Three blades have minimal instrumentation, but all-told, about 490 conductors carry power and data through the HVAB blades to flush-mounted end connectors.

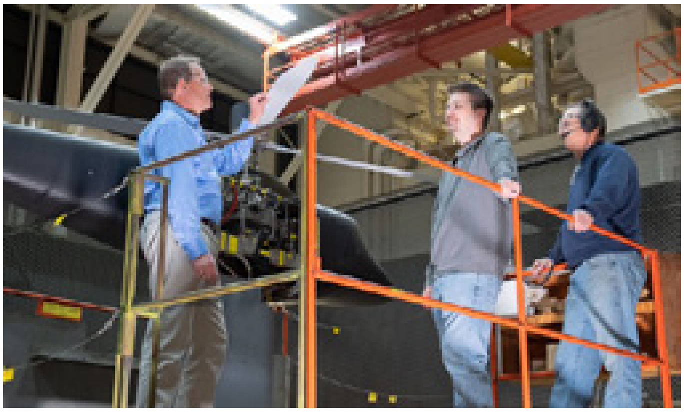
The HVAB pressure transducers are arranged so airloads can be calculated at the collected sensor stations. Previous instrumented blade sets distributed pressure transducers over all four blades. "With this solution, there is always an assumption that all the blades fly exactly the same," said Schaeffler. "By putting all of the transducers on one blade, this uncertainty can be eliminated, but the complexity of the design of the blade increases dramatically."

All six HVAB blades were designed and fabricated with the same mass distribution. "We had to replace the equivalent mass in the highly instrumented blade with dummy wires, dummy sensors to provide the same mass and inertial properties," said Pullman at ATI.

Prototyping house ATI has long built wind tunnel models, large-scale mockups and full-scale flight hardware for the rotorcraft industry. It produced full-size composite blades later certified by Erickson for its S-64 Air Cranes and Carson for the Sikorsky S-61 helicopters. The HVAB outside mold line was provided by NASA, and ATI was tasked to provide internal structure and install instruments to meet test load requirements.

To reduce risk, the blade maker chose familiar IM7 carbon fiber epoxy prepreg for the spar and fiberglass cloth for the skins. "Design wise, as we built the blade, it's actually very conventional," acknowledged Pullman. "In order to get all of that instrumentation into the blades, there were numerous additional steps to get all of that installed." ATI, for example, made the pre-cured skins separately and mated them with pre-wired, leading-edge sub-assemblies containing the highest concentration of sensors.

Composite rotors made up of hundreds of thin plies are difficult to model. Three-dimensional finite element analysis (FEA) of the complex structures becomes prohibitive in terms of computational resources. Engineers typically "smear" properties over stacked laminates and sacrifice accuracy. Pullman explained, "VABS can compute ply-level stress field without such approximations, achieving the accuracy as if 3-D FEA modeled all the ply-level details."



NASA and the Army have a long history of instrumented rotor wind tunnel research, including the scaled research blade set shown here. A new Hover Validation Acoustic Baseline (HVAB) blade set and Army Rotor Test Stand will begin testing later this year. (US Army)

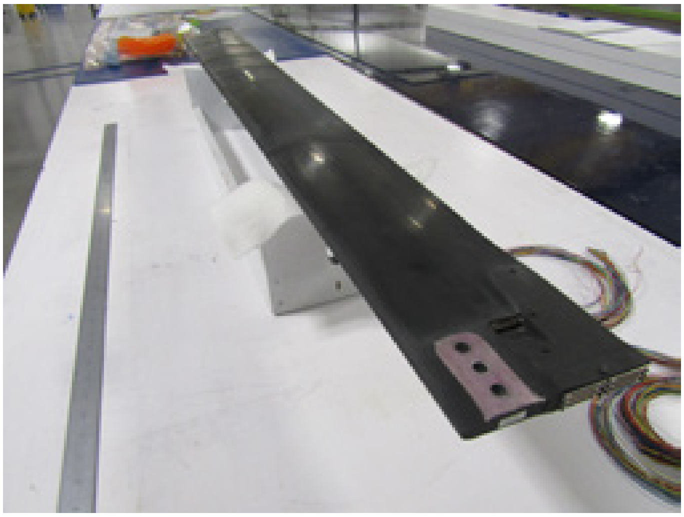
The general-purpose code integrates a finite element mesh of the cross section with details of material and geometry to calculate structural properties such as torsional and bending stiffness. VABS can also be used to maximize torsional stiffness while maintaining a desired center of gravity. The tool calculates accurate ply-level details for static or dynamic analysis and generates accurate 3-D displacement/strain/stress parameters needed for predicting failure, strength and fatigue life. The result includes all inertial properties including center of gravity and mass distribution based on given blade section. VABS enabled ATI engineers to decouple the complex 3-D analysis into a 2-D cross-sectional analysis with structural and inertial properties plus a one-dimensional beam analysis.

VABS analytical code emerged from Army research in the 1990s on computer tools to predict rotor performance. AnalySwift chief technical officer Wenbin Yu worked on VABS for his PhD thesis at Georgia Tech in 1998, under the direction of Professor Dewey Hodges, and continued to refine the code as a professor at Utah State University and later at Purdue. AnalySwift began in 2011 as a university spinout and today offers a portfolio of multi-scale, multi-physics modeling codes for composites. AnalySwift president Allan Wood noted, "The high level of efficiency without sacrificing accuracy makes our software appealing for these types of projects."

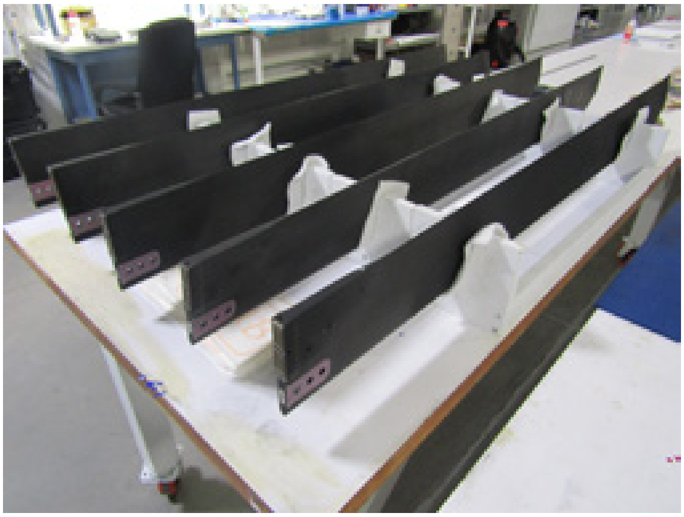
ATI first used VABS in 2008 for the Erickson blades and has relied on it through more than 20 advanced rotor projects. Pullman recalled, "Previously, we had been using in-house developed codes which, while being very efficient, did not accurately predict the torsional stiffness and shear center." VABS provides complete elastic and inertial blade definition and 3-D stress and strain fields within complex laminates, he noted.

VABS is commonly used with other design tools to complete the structural analysis. According to Pullman at ATI, "Right now, the idea of VABS is to take an incredibly complicated blade structure and boil it down to a one-dimensional, numerical presentation that can be used for dynamic analysis." Pullman noted engineers need user-friendly graphic interfaces now in development to build the model and get it back out, but he acknowledged the power of the VABS code for projects like the HVAB blade set. "Analytically, functionally, it pretty much does everything you could possibly want."

The HVAB blade with primer coat shows pressure sensors before trimming. The blade is a bonded assembly with integrated sensors and conductors. (ATI photo)



The HVAB hover blade has 187 miniature pressure transducers at 11 stations along its length. (ATI photo)



ATI fabricated the HVAB blade set for NASA and Army researchers using VABS design and analysis software. (ATI photo)