Final Report

Award Number:	N00421-19-1-0004
Title of Proposal:	Swept-Tip Blades for Mach-Scaled High-Speed Tiltrotor Tests
Prime Applicant:	University of Maryland
Type of organization:	Other Educational
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Award type requested:	Grant
Proposal validity period:	120 days
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14. ABSTRACT

The Year-2 effort fabricated, measured properties, and spun the blades upto 2400 RPM in the Glenn L Martin Tunnel. The blades have 2.375-ft radius, 3.1-in chord, -37 degrees twist, 20 deg sweep back 0.8-1.0R, VR-7 airfoil profiles, D-spar, all composite +/-45 deg weave of IM7/8552. Three sets of blades were built-straight, twisted, and twisted-swept. Year- 2 (this proposal) completed the swept blades. The tunnel spin-up was carried out using the twisted blades since a set of 3 identical blades were needed for spin-up whereas only 2 swept blades could be fabricated by the tunnel entry date. The third and

15. SUBJECT TERMS

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Executive Summary:

The objective of this proposal was to design, fabricate, and characterize, highly twisted (-30° to -45°) and swept (20° back) composite tilt rotor blades. The swept tip is the novel and new basic research component. Comprehensive analysis performed by the US Government and Academia in the last decade have shown the potential of swept tip blades in extending whirl flutter boundary. Swept tip blades can be also contribute positively to DoD's vision of 2X speed of Future Vertical Lift (FVL). The intent is to follow-up this seed program with wind-tunnel testing of the blades at Maryland Tiltrotor Rig (MTR) at the Glenn L Martin wind tunnel. The project tracked all its milestones and completed all deliverables. The blades were designed, fabricated, characterized, integrated on the MTR, and spun-up for loads check-out on Sep-Oct 2019 a few months before the campus and the facilities shut down due to covid-19.

Planned Project Schedule and Milestones:

The planned schedule and milestones in the original proposal are copied below for reference. Both 2018 and 2019 plans were completed.

2018: Design, fabrication, property characterization of **twisted blades**
2019: Design, fabrication, property characterization of **twisted and swept blades**
2020-2022: Wind-tunnel tests on UMD tilt rotor rig for performance, loads, and whirl flutter. Note that this is part of our over-all roadmap, not part of this proposal.

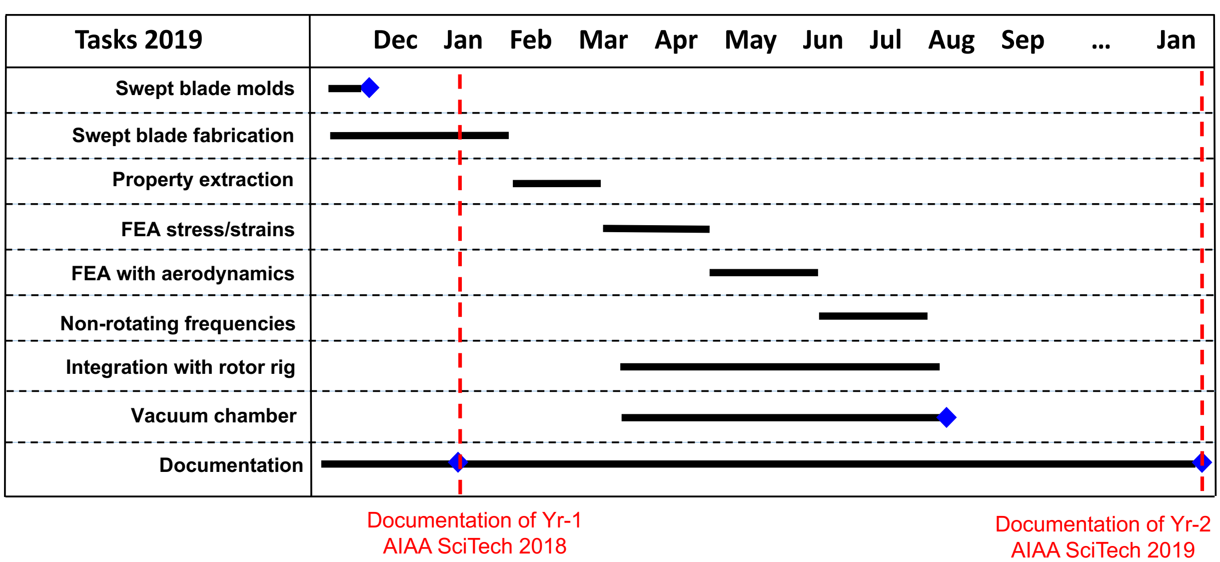
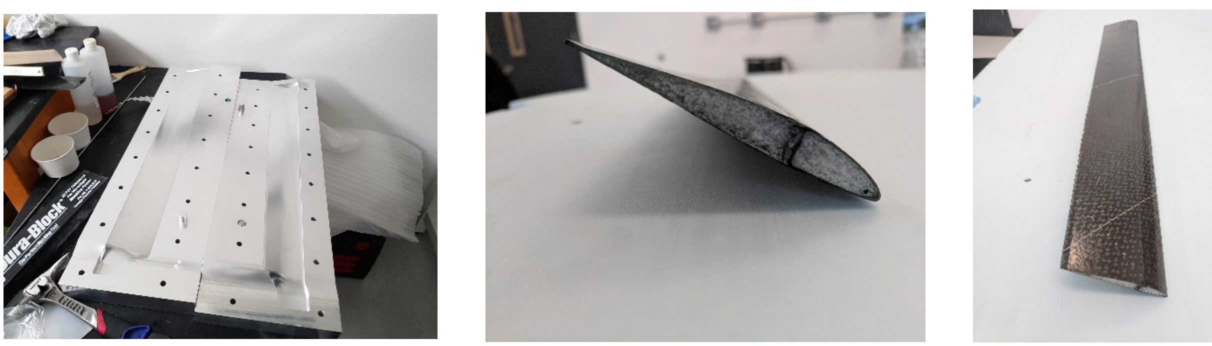


Table 1 Project schedule for 2019

Year 1 Accomplishments:

The Year-1 effort (10/01/2017 – 09/30/2018) tracked its milestones. The student took 6 graduate classes – 3 on rotorcraft: Aerodynamics, Dynamics I, Stability & control; and 3 on Composite Structures, Structural Dynamics, and Computational Methods. The research conducted and principal results were documented in AIAA Conference Paper at SciTech 2019 Dynamics Specialists Conference Session on Next-Generation Tiltrotors [1]. Figures 1 and 2 summarize its final products. Figure 1 shows the baseline composite D-spar twisted blade (-40° from root cut-out to the tip) built in-house as part of this project. Figure 2 shows a new gimballed hub being developed as part of ONR DURIP. The two parts are now being prepared for integration. Thus this NAWC-AD project is in perfect sync within the over-all tiltrotor research program. Characterization of the blades (3-blades built so far) for stiffness, inertial and modal properties, and validation with in-house CAD/meshing/FEA analysis is on-going. The swept-tip blade effort is also on-going. Figure 1c shows a 4-axis Tormach milling machine procured as part of this project. It will be essential for fabricating blade molds, root inserts, swept tip spars, and embedded sensor decks, all in-house, by the graduate student – an important long term investment for cost reduction and hands-on student training.



(a) Twisted mold **(b) D-spar section view** **(c) twisted blade**

Figure 1: Composite tiltrotor blade; twist -45°, radius 2.5 feet, profile VR-7, D-spar.

(a) isolated blade **(b) blade and gimbal hub** **(c) 4-axis Tormach mill**

Figure 2. Tiltrotor blade shown with parts of the new gimballed hub.

Year 2 Accomplishments:

The approach followed the task break down shown earlier in Table 1. The swept tip blade molds were fabricated and a strategy formulated to construct the swept tip spar. The composite skin can be overlaid in two different ways in the swept section in order to prevent (at least minimize) ply drop out at the junction. These methods are consistently evaluated (same weight and sectional properties) for strength and structural integrity. The better of the two was used to proceed to blade fabrication. This was **Step-1** in Year 2. Figure 3 shows the two methods. Figure 4 shows the implementation of the chord-wise cut method. The overall procedure is then summarized in Figure 5. Figure 6 shows the fabricated blades – straight, twisted, and twisted swept.

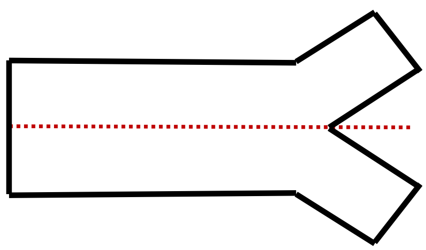


Figure 3 Swept-tip blade fabrication; choice of ply lay-ups on the swept section; the chordwise cut method (right) was decided.

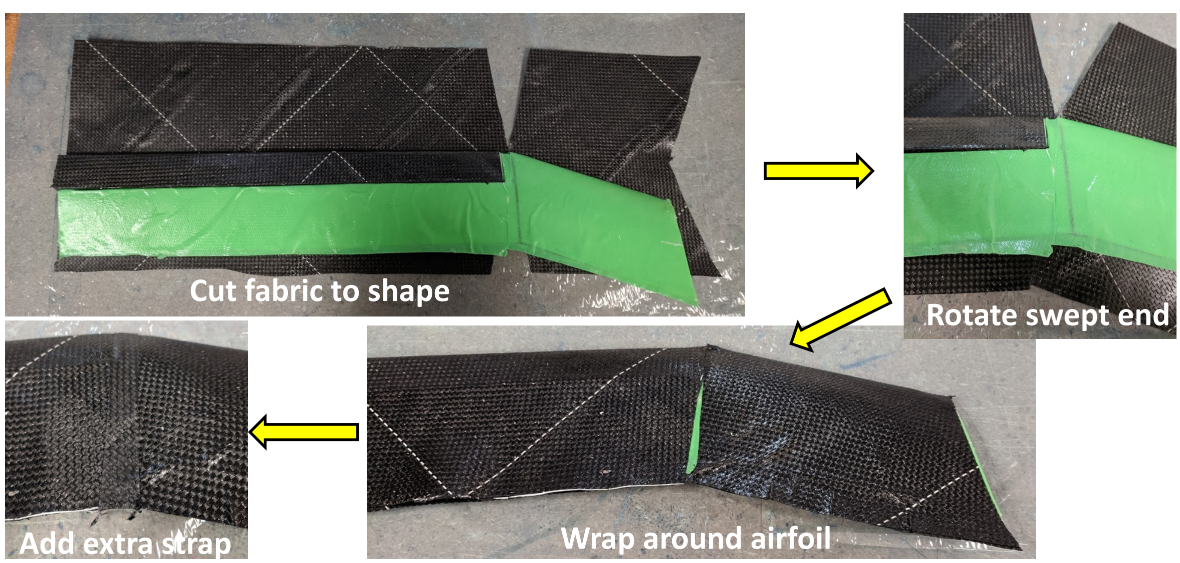


Figure 4 Ply lay-up on the swept tip section using the chord-wise cut method; integration/assembly with inboard main blade lay-up. This step is before curing in the oven.

Figure 5 Fabrication steps.

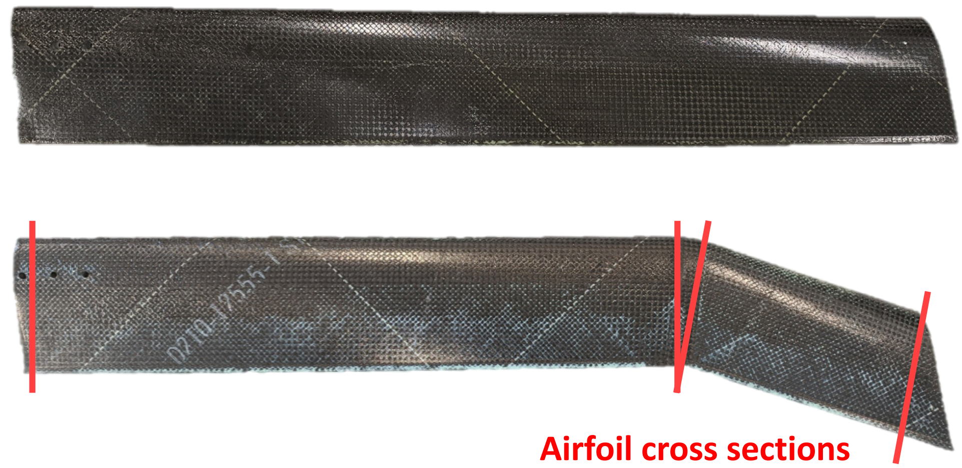


Figure 6 Finished twisted and twisted-swept tiltrotor blades.

In **Step-2**, the blade was tested for stiffness and inertial properties. Stiffness properties included sectional EI and GJ as well as measured frequencies from rap tests. The sectional property extraction was complicated due to the twist (flap-lag coupling) and sweep (swept elastic axis) and was a major emphasis of this work. In order to verify the sanctity of the measurements an additional set of molds were built and blades fabricated. These surrogate blades had the same airfoil profile internal construction, but un-twisted and un-swept. The composite ply was also coupon tested to verify and correct manufacturer provided properties. Figures 7 and 8 shows the measured properties compared to targets (as well as predicted properties, which resulted from Step-3). In **Step-3**, the blade CAD was meshed, control links inserted, and a full structural analysis carried out using the in-house tool X3D (X3D is an UMD-US Army NextGen code for Integrated-3D Aeromechanics predictions). The predicted blade properties were verified with measured values. Measurements and modeling were refined and de-bugged until a close match was obtained. It was observed that the chord-bending predictions were still very complicated and had more than 50% errors in stiffness (Figure 8). Figure 9 shows the CATIA and CUBIT models used in the analysis. In **Step-4**, the blades were stress tested in the wind tunnel systematically at 900, 1200, 1600, 2000, and 2400 revolutions per minute (r.p.m.) for structural integrity and performance. Figure 10 shows the twisted blade integrated on the Maryland Tiltrotor Rig and installed in the Glenn L Martin wind-tunnel. At the time of first (and last, due to covid-19) testing, only two swept blades could be fabricated, hence the strength testing was performed only on the twisted blades (twisted blades were result of Yr-1 effort). Since the internal construction, dimensions, and profile of the blades are identical it is expected that the swept blades will also pass. This will be confirmed in 2020 as soon as the tunnel opens. Finally, in **Step-5**, the methodology and models were documented partially in the VFS Forum 2019 [2]. Due to covid-19 caused wind-tunnel shutdown, as well as deferment of the Vertical Flight Society Annual Forum 2020 (the premier conference in vertical lift), we have deferred full documentation to the next year.

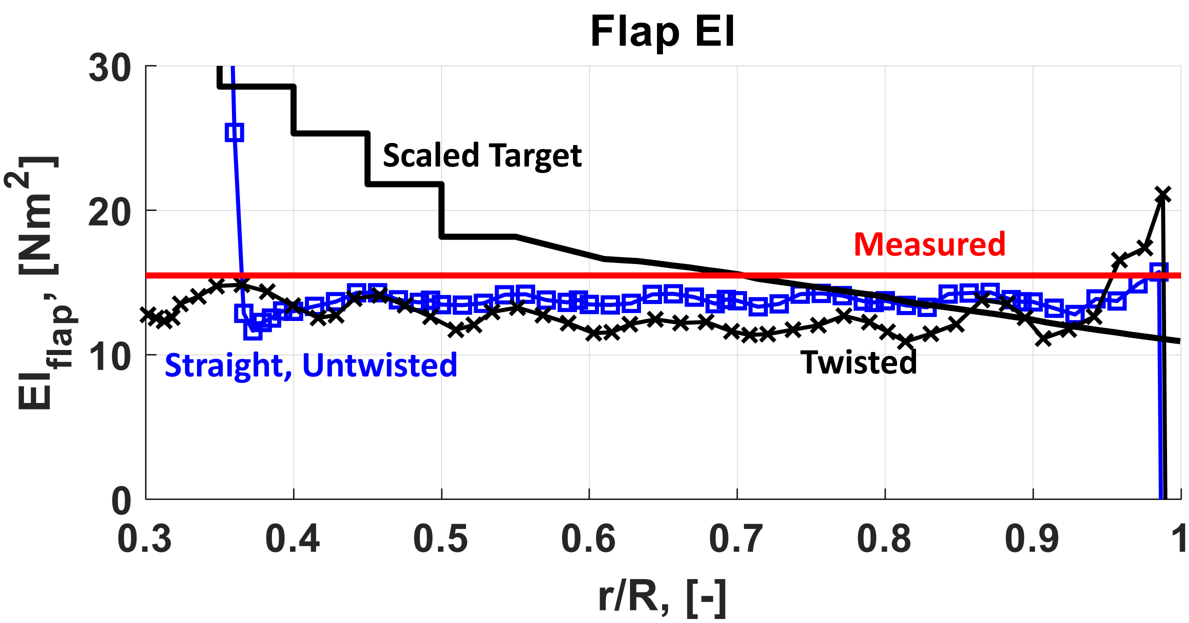


Figure 7 Measured and predicted blade normal bending stiffness; target is NASA-Bell XV-15 properties.

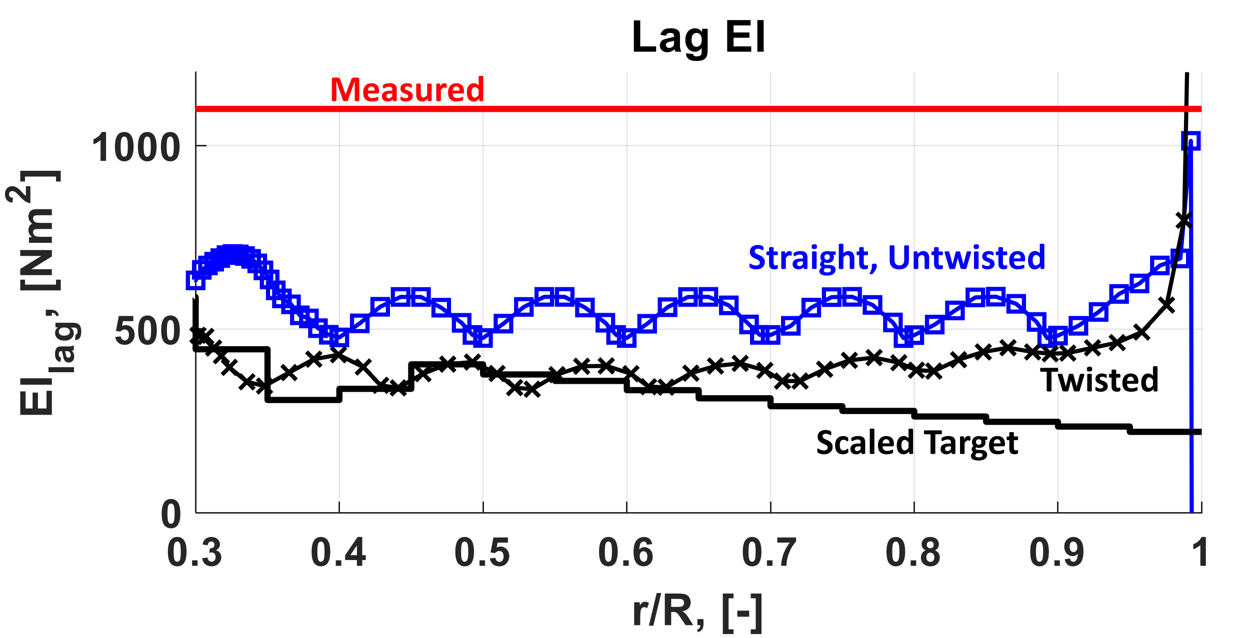


Figure 8 Measured and predicted chord bending stiffness; target is NASA-Bell XV-15 properties; large errors in predicted values.

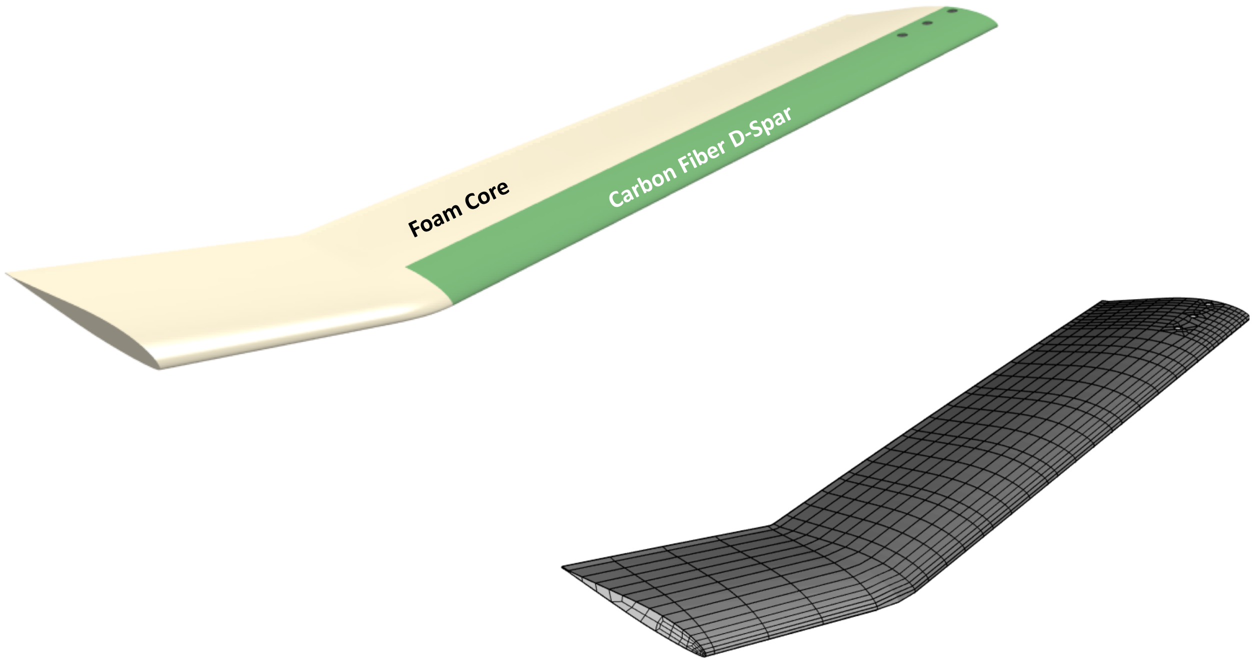


Figure 9 CAD (CATIA v5) and 3D solid hexahedral meshing (CUBIT software from Sandia Labs); example shown is the twisted and swept blade.

Figure 10 Blades installed (twisted blades shown) and stress tested from 900-2400 RPM on the Maryland Tiltrotor Rig at the Glenn L Martin Wind Tunnel in September 2019; wind-off conditions; 2400 RPM equals tip Mach number of 0.6; at the time, only 2 identical swept blades could be fabricated, hence these were not tested on MTR.

Papers & Productivity:

Two papers were published in refereed conferences.

1. Tsai, F., Sutherland-Foggio, J., and Datta, A., "Design of a New Tiltrotor Test Facility at the University of Maryland," abstract submitted to AIAA SciTech 2019, DSC Session on Next-Generation Flutter-Free Tiltrotors, 7-11 January, San Diego, CA, 2019.

1. Tsai, F., Sutherland-Foggio, J., Datta, A., Privett, D., "The Maryland Tiltrotor Rig (MTR): The Baseline Gimballed Hub," Vertical Flight Society's 75^{th} Annual Forum, Philadelphia, PA, May 13-16, 2019.

The student James Sutherland will continue toward his PhD based on the support of this project.

Lessons learned were transitioned to Navair (Mark Silva), US Army ARL (Rajneesh Singh) and Bell Helicopter (Jeff Bosworth) who are continuing to the monitor the larger tiltrotor program. The most important and creative component of any advanced rotor testing is the blade set. This project allowed us to design, fabricate, and this important component.