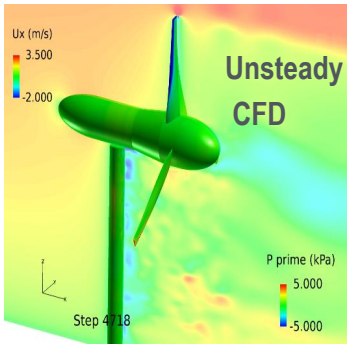
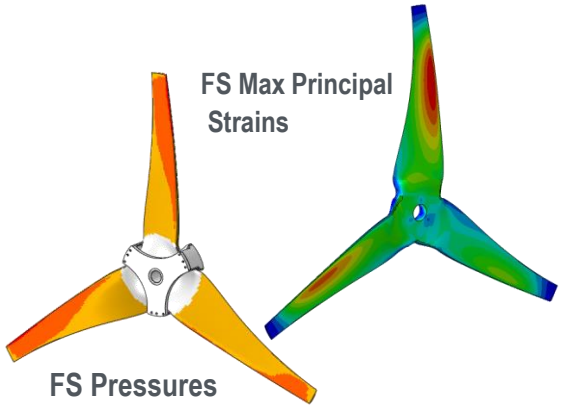
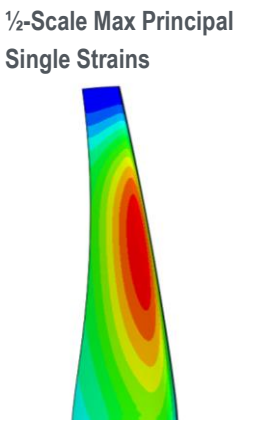
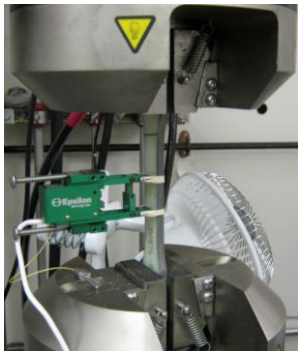
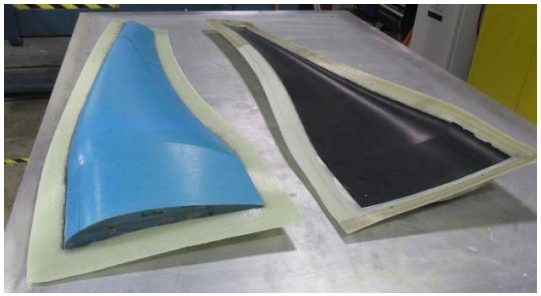


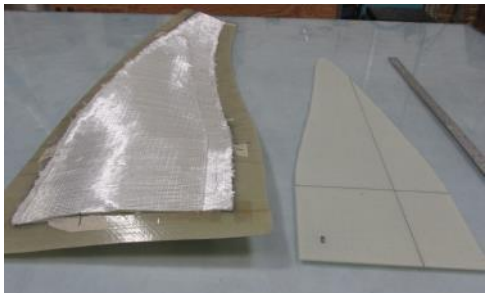


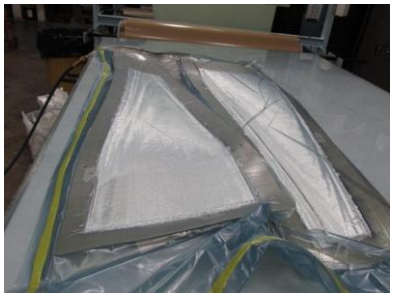




Full-Scale three-blade rotor and ½-scale single blade design methodology and material characterization







½-Scale Single Blade Net Shape Fabrication Process

Successful Single Blade Net Shape Fabrication

Net Shape Fabricated Low Cost MHK Pass-Through-The-Hub Turbine Blades with Integrated Health Management Technology

Dr. Kevin L. Koudela

The Applied Research Laboratory (ARL) - The Pennsylvania State University

klk121@arl.psu.edu; 814.863.4351

February 13-17, 2017

Project Overview

Net Shape Fabricated Low Cost MHK Pass-Through-The-Hub Turbine Blades with Integrated Health Management Technology

- Project Description: Develop and demonstrate via design, analysis, fabrication and test a novel ½ -scale low cost, net shape fabricated single piece three-blade pass-though-the-hub marine and hydrokinetic (MHK) composite rotor to demonstrate significant Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) cost reductions due to implementation of novel design and manufacturing processes
- Challenges: Demonstrating 1) manufacturing processes and quality control protocol to net shape fabricate a single piece composite rotor and 2) threshold fatigue strain allowable required for MHK rotor operational life
- Partner: Verdant Power Inc. to provide MHK rotor geometry and summary loading; support composite rotor design and manufacturability; evolve CAPEX and OPEX estimates and develop technology transition plan for Verdant Power Inc. Kinetic Hydropower System (KHPS) full-scale rotor

Increase MHK deployment in opportune markets

Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- **Conduct R&D for innovative MHK components**
- Develop tools to optimize device and array performance and reliability
- Develop and apply quantitative metrics to advance MHK technologies

Deployment Barriers

- Identify potential improvements to regulatory processes and requirements
- Support research focused on retiring or mitigating environmental risks and reducing costs
- Build awareness of MHK technologies
- Ensure MHK interests are considered in coastal and marine planning processes
- Evaluate deployment infrastructure needs and possible approaches to bridge gaps

Market Development

- Support project demonstrations to reduce risk and build investor confidence
- Assess and communicate potential MHK market opportunities, including off-grid and non-electric
- Inform incentives and policy measures
- Develop, maintain and communicate our national strategy
- Support development of standards
- Expand MHK technical and research community

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- Improve resource characterization to optimize technologies, reduce deployment risks and identify promising markets
- Exchange of data information and expertise

Increase MHK deployment in opportune markets

Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- **Conduct R&D for innovative MHK components**
- Develop tools to optimize device and array performance and reliability
- Develop and apply quantitative metrics to advance MHK technologies

The Impact

- Net shape manufacturing technology is applicable for fabrication of MHK or conventional hydropower rotors and potentially applicable to other MHK composite components
- Mature composite MHK rotor Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) from TRL/MRL equal to 3 to TRL/MRL equal to 6
- Generate fabrication, assembly, and operational performance data to enable robust CAPEX and OPEX reduction projections to facilitate full-scale implementation of low-cost net shape fabricated single piece composite three-blade rotor
- Fabrication and fatigue testing of the Verdant Power Inc. KHPS ½-scale single piece three blade composite rotor

Technical Approach

The proposed project is divided into three major tasks:

1. Single Piece Three-blade KHPS Rotor Full-Scale and ½-Scale Design to include composite rotor structural design and analysis using computational fluid dynamics and finite element analysis in conjunction with predefined design for manufacturability constraints to ensure ease and quality of rotor fabrication

Issue: *Design for manufacturability for MHK rotor* - Mitigation: Implement composite rotor concurrent engineering development protocol, threshold fatigue strain allowable and legacy KHPS rotor lessons learned

2. Composite Manufacturing Trials and ½-Scale Prototype Rotor Fabrica*tion* to include design and fabrication of single blade and three-blade clam shell molds; net shape fabricate prototype single blades to evolve high quality manufacturing methods; implement single blade process lessons learned to fabricate a prototype net shape three-blade composite rotor

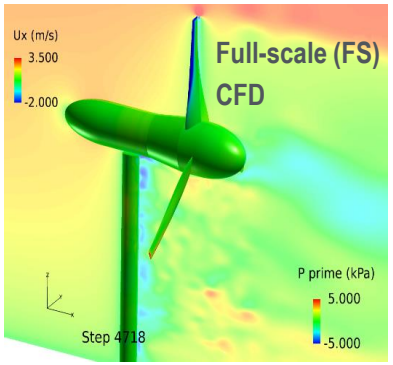
Issue: *Mold fill variability after pressure and suction side hot de-bulks.* Mitigation: Conduct manufacturing trials using ½-scale single blades to evolve de-bulk protocol to ensure 100% consolidation during rotor final cure

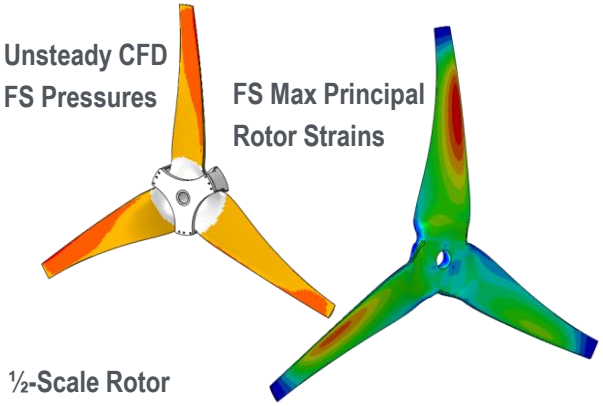
Technical Approach (Continued)

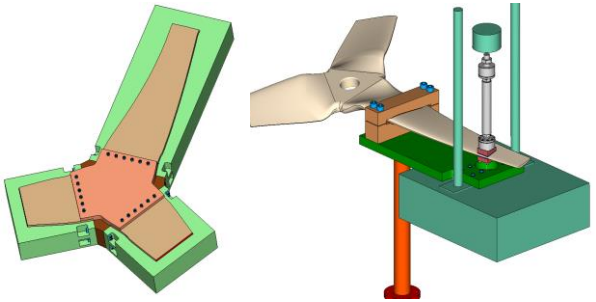
3. Material Characterization and ½ -Scale Prototype Rotor Test and Evaluation to generate 10M cycle threshold fatigue strain allowable for rotor design; design and fabrication of rotor test fixture and conduct 10M cycle fatigue testing to correlate analysis and demonstrate rotor fatigue robustness

Issue: *Fatigue failure of the three-blade rotor* – Mitigation: Develop 10M cycle threshold fatigue strain allowable and limit full-scale and ½-scale rotor design maximum principal strains to ≤ threshold fatigue strain allowable

Unique Contributions: Demonstrated composite propeller concurrent design methods for MHK rotor; single piece net shape fabricated pass-through-the-hub rotor (no secondary machining and ready to install); implementation of threshold fatigue strains for long-term life; and implementation of Fiber Bragg Grating optical fibers for structural health monitoring







Accomplishments and Progress

Important Technical Accomplishments from project initiation, May 2016, through November 2016 include the following:

- Completed design and analysis of full-scale and ½-scale single blade net shape fabricated rotor
- Completed net-shape fabrication of two ½-scale single blades using composite molds
- Completed design of ½-scale aluminum three blade rotor clam shell mold
- Completed initial 10M cycle tension-tension and compression-compression threshold fatigue strain coupon tests
- Completed design of ½-scale rotor test fixture

Project Plan & Schedule

- Project started on 01 May 2016 and will be completed on 30 June 2017
- Technical progress is commensurate with proposed schedule
- Successfully achieved critical milestone to net shape fabricate multiple ½-scale rotor blades
- Results to date indicate that net shape fabrication of a pass-through-the-hub composite three-blade rotor is feasible

Project Budget

Budget History	
FY2016	
DOE	Cost-share
$879.012k	$219.753k

- Cost of ½-scale aluminum rotor clam shell mold is 20% more expensive than the originally proposed ¼-scale molds. This cost growth was off-set by in-house fabrication of soft (composite) single blade clam shell molds.
- As of 15 November 2016, 41% of the proposed federal budget has been expended.

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

Verdant Power Inc.

Communications and Technology Transfer:

- Communications and technology exchange occur during quarterly reviews with DOE
- Manufacturing technology will be transitioned to Verdant Power Inc. after successful demonstration of our ½-scale net shape pass-through-the-hub three-blade composite rotor
- Net shape fabrication technology is agnostic and is applicable for fabrication of MHK or conventional hydropower rotors and potentially applicable to other MHK composite components

Next Steps and Future Research

FY17/Current research: Continue 10M cycle threshold fatigue strain data generation; fabricate ½-scale three blade rotor clam shell molds and ½ -scale prototype net shape composite three blade rotor; fabricate composite rotor fatigue test fixture and conduct 10M cycle composite rotor fatigue testing

Remaining Technical Challenges: Successfully demonstrate agnostic high-quality fabrication processes for the three blade pass-through-the-hub composite rotor and determine the full-scale rotor CAPEX/OPEX estimates from ½-scale rotor fabrication and fatigue test data

Proposed future research: This project will be completed in June 2017. The next step is to secure follow-on funding to scale up our net shape manufacturing process to facilitate fabrication of a prototype full-scale single piece rotor for in water evaluation.