EE0007248 - The Design and Development of a Composite Hydropower Turbine Runner

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and
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Project Overview

### Project Summary

- **DOE objective:** Design and test new and innovative conventional hydropower powertrain components
- **Project goal:** Verify that composite materials are a reliable and economic alternative to traditional metallic runners to reduce costs and increase energy capture.
- **Develop cavitation-resistant coatings**
- **Prototype and test a composite runner system under real-world hydropower turbine operating conditions.**

### Intended Outcomes

- **Prototype a weight-efficient, fatigue resistant, low-maintenance turbine runner using composite materials to reduce mass and extend service life**
- **Improve runner reliability by developing a high-performance coating system that resists cavitation and sediment erosion**
- **Provide performance test data of the composite runner/coating in true hydropower turbine operating conditions**

### Project Information

- **Principal Investigator(s)**
  - Mr. Paul E. Fabian
  - Composite Technology Development, Inc., Lafayette, CO

- **Project Partners/Subs**
  - Penn State University – ARL
  - Sandia National Laboratory
  - Tribologix Inc.
  - Voith Hydro, Inc.

### Project Status

- **Completed**

### Project Duration

- **July 1, 2016**
- **April 30, 2022**

### Total Costed (FY19–FY21)

- **$698,247**
Project Objectives: Relevance

Relevance to Program Goals:
• This program addresses WPTO’s mission of enabling research, development, testing and commercialization of new technologies to advance marine energy as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid through the following:
  – Leverages new composite manufacturing and materials to dramatically lower costs of components and systems
    • Design and manufacture of composite hydroturbine runner
    • Developed new, higher performing liquid polymer resin system for runners as well as a cavitation resistant coating to increase longevity in operation
    • Both reduce costs through increased durability and expected lifetimes
  – Supports testing of new technologies (composite runners), including development of necessary testing infrastructure
    • Testing of composite runners in real-world environment
    • Fabrication of simulated hydroturbine inside ARL's water tunnel for advanced hydropower testing of components
  – Supports goal of utilizing advanced manufacturing and materials to reduce overall cost of energy/electricity
Project Objectives: Approach

Phased Program Approach

• Phase I
  – Develop system requirements
  – Perform materials assessment and cavitation coating development
  – Design a composite turbine runner

• Phase II
  – Fabricate composite hydroturbine blades
  – Perform composite blade mechanical testing to align
  – Fabricate composite hydroturbine runner set with cavitation coating
  – Perform scaled hydroturbine runner testing in ARL water tunnel

• Incorporated input from leaders in hydroturbine materials & testing
  – ARL/PSU
  – Sandia National Laboratories
  – Voith Hydro
Project Objectives: Expected Outputs and Intended Outcomes

Outputs:
- Prototyped a weight-efficient, fatigue resistant, low-maintenance turbine runner using composite materials to reduce mass and extend service life
- Improved runner reliability by developing a high-performance coating system that resists cavitation and sediment erosion
- Provided performance test data of the composite runner/coating in true hydropower turbine operating conditions

Outcomes:
- Further interest by Hydropower community in using advanced composite materials
- Commercial sales of new materials for use in hydropower applications
- Prototype production and field trials by major hydropower commercial partner
- Commercial large-scale production and use of design and materials in hydro applications resulting in lower cost electricity
Project Budget

<table>
<thead>
<tr>
<th>DOE</th>
<th>Cost-share</th>
<th>Total</th>
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<tbody>
<tr>
<td>$1,124.4K</td>
<td>$499.5K</td>
<td>$1,623.9K</td>
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<table>
<thead>
<tr>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>Total Actual Costs FY19–FY21</th>
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<tbody>
<tr>
<td>Costed</td>
<td>Costed</td>
<td>Costed</td>
<td>Total Costed</td>
</tr>
<tr>
<td>$223.5K</td>
<td>$179.5K</td>
<td>$295.2K</td>
<td>$698.2K</td>
</tr>
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</table>

- Phase I (Year 1) started in late 2016
- Phase II (Year 2) work was extended into FY19 due to delays in blade production and water tunnel modification work delays
- Phase II work was further delayed by COVID and resulting shutdown of facilities and availability of personnel. Work was restarted in FY21.
- Additional funding by DOE was provided in FY20 due to increased costs for fabricating water tunnel hardware and performing testing at ARL
End-User Engagement and Dissemination

- Program was initiated with a commercial stakeholder, Voith Hydro, as a partner in design and development
  - Proprietary blade design was supplied by Voith as a baseline
    - Allowed direct comparison to stainless steel material properties
    - Provided operational parameters used to set metrics for testing of composite blades
    - All information was proprietary so could not be shared with outside parties
  - Sandia National Laboratory (SNL), PSU/ARL, and Voith personnel were involved throughout the project and attended monthly program review meetings
    - Allowed regular advisement and input on program
    - Program team also participated in milestone meetings such as Requirements Review, Test Readiness Reviews, and Manufacturing Readiness Reviews
  - Voith included since they were our commercial manufacturing partner that allowed a direct path to the commercial market
  - PSU/ARL were the cavitation testing and water tunnel test experts who could enable simulated real-world test results
  - SNL acted as material coating experts
- Results have been shared with Voith Hydro for evaluation of next steps
Performance: Accomplishments and Progress

• Materials
  – Prior evaluation and screening tests in Year 1 identified materials to be used for water tunnel testing in Year 2
  – CTD-K08/K13916 high modulus carbon fiber provided necessary stiffness and performance to achieve mechanical properties desired for blade
  – CTD-133 coating was found to offer the best cavitation resistance in accelerated cavitation erosion testing conducted at PSU/ARL

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Material</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub interface</td>
<td>410 Stainless Steel</td>
<td>Various</td>
</tr>
<tr>
<td>Composite blade matrix</td>
<td>CTD-K08 resin</td>
<td>CTD</td>
</tr>
<tr>
<td>Composite blade fiber</td>
<td>K13916 carbon fiber</td>
<td>Mitsubishi</td>
</tr>
<tr>
<td>Hub to blade adhesive</td>
<td>EA9394</td>
<td>Loctite Hysol</td>
</tr>
<tr>
<td>Anti-cavitation coating</td>
<td>CTD-133</td>
<td>CTD</td>
</tr>
</tbody>
</table>
• **Composite Blade Fabrication**
  – Blades fabricated using Vacuum Assisted Resin Transfer Molding (VARTM) process
  – Post fabrication machining to achieve exact blade dimensions

**Performance: Accomplishments and Progress (cont.)**
Performance: Accomplishments and Progress (cont.)

- **Blade Prototype Testing Set-up**
  - Blades tested in bending in fatigue and to failure
  - Point loading in servo-hydraulic test machine at room temperature in air
  - Test results matched to FEA results to validate composite blade performs as designed

![Test Machine Actuator and Load Cell](image)

![Blade Prototype Testing](image)

200 rpm + Max Power

3pt Load (Scaled) BendTwist9

LVDTS (to measure displacement)

LVDT Reaction Plate

CASE: BendTwist9
TOTAL LOAD = 3 x 230 = 690 lbf
Performance: Accomplishments and Progress (cont.)

- **Blade Prototype Testing Results**
  - Deflection near tip of blade during operation biggest concern
  - Quasi-static test results matched FEM results
  - Fatigue testing at operating loads showed no degradation after $10^6$ cycles
  - Failure loads averaged over 4,000 lb.
  - Factor of Safety of over 4 from loads for Maximum Power

Maximum Power Operating Condition

<table>
<thead>
<tr>
<th>CASE</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST: Raw LVDT Measurement</td>
<td>0.089</td>
<td>0.093</td>
<td>0.097</td>
</tr>
<tr>
<td>TEST: Compensated for Failure Rotation</td>
<td>0.036</td>
<td>0.039</td>
<td>0.043</td>
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<tr>
<td>FEM: $E_1=67$MSI</td>
<td>0.022</td>
<td>0.020</td>
<td>0.023</td>
</tr>
<tr>
<td>FEM: $E_1=52$MSI &amp; Modified Load Points</td>
<td>0.033</td>
<td>0.030</td>
<td>0.035</td>
</tr>
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</table>
Performance: Accomplishments and Progress (cont.)

• Runner Set Fabrication
  – Runner set of 3 blades + 1 extra fabricated
  – Blades bonded and pinned to SS hub interface
  – CTD-133 anti-cavitation coating applied to outside surface of blade
  – Runner set shipped to PSU/ARL
Performance: Accomplishments and Progress (cont.)

• Turbine Runner Testing
  – Testing performed inside the Garfield Thomas Water Tunnel (GTWT) at PSU/ARL
  – A scaled (76%) version of the Voith Bulb Turbine system was fabricated and installed inside the water tunnel
  – Parts fabricated and installed in water tunnel
Performance: Accomplishments and Progress (cont.)

• Turbine Runner Testing
  – Installation of scaled Voith Bulb Turbine in GTWT
• Turbine Runner Testing
  – Test Plan
    1. Windage test - Remove rotor blades and vary rpm to measure drivetrain windage losses
    2. Hydrodynamic performance sweep - Hold flowrate constant and vary rpm
    3. Reynolds sweep - Vary flowrate and rpm by constant ratio
    4. Condition Based Maintenance (CBM) test - Simulate fault condition by removing IGV blade

![Graph showing Tip Clearance](image)

- Tip clearance of tallest composite blade

![Graph showing Bare Hub Windage Test](image)

- Measured torque from bare hub windage test used to correct the raw torque data from the other tests
Performance: Accomplishments and Progress (cont.)

- **Turbine Runner Testing**
  - The key measurements required for the validation test were:
    - Flowrate, \( Q \)
    - Stagnation pressure change across turbine, \( \Delta P_t = P_{t1} - P_{t2} \)
    - Turbine rotor rotational speed, \( N \)
    - Turbine rotor torque, \( \tau \)

- **Hydrodynamic Performance Sweep Results**

<table>
<thead>
<tr>
<th>Impeller RPM (Estimate)</th>
<th>Flowrate (m³/s)</th>
<th>Turbine RPM</th>
<th>Maximum Power</th>
<th>On Design</th>
<th>Maximum Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.175</td>
<td>0.75</td>
<td>35.42500221</td>
<td>69.69209822</td>
<td>60.20844907</td>
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<td>21.55</td>
<td>0.75</td>
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<td>26.725</td>
<td>1</td>
<td>70.83702024</td>
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<td>113.13802189</td>
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<tr>
<td>31.9</td>
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<td>83.32502627</td>
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<td>37.075</td>
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<td>129.38705642</td>
<td>184.1700401</td>
<td>184.1700401</td>
<td>212.58901754</td>
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</table>

**Test matrix for correct RPM and speed for safe operating conditions**
Performance: Accomplishments and Progress (cont.)

• Turbine Runner Testing
  – Reynolds Sensitivity Sweep Results
    • Reynolds number based on blade chord and relative velocity at tip
    • Hydrodynamic performance insensitive to changes in Reynolds number

<table>
<thead>
<tr>
<th>Variable</th>
<th>Full Scale</th>
<th>CFD</th>
<th>Tunnel Test</th>
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<tbody>
<tr>
<td>Rotor Pitch (°)</td>
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<td>19</td>
<td>19</td>
</tr>
<tr>
<td>IGV Pitch (°)</td>
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<td>63</td>
<td>63</td>
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<tr>
<td>D (m)</td>
<td>1.155</td>
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<td>0.887</td>
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<tr>
<td>N (rpm)</td>
<td>375</td>
<td>350</td>
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</tr>
<tr>
<td>Q (m^3/s)</td>
<td>6.03</td>
<td>2.47</td>
<td>1.5</td>
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<tr>
<td>Reynolds Number</td>
<td>11,000,000</td>
<td>5,900,000</td>
<td>1,500,000</td>
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Performance: Accomplishments and Progress (cont.)

- **Turbine Runner Testing**
  - **Condition Based Maintenance Test Results**
    - Generating simulated fault condition to evaluate if sensors in turbine system can be used to detect changes in operation
    - Would allow monitoring of system health
    - Fault condition simulated by removing two Inlet Guide Vanes

- Overall spectra of the torque sensor timeseries indicating no instability
- Minor differences in frequencies, but not significant enough to be indicators for system health monitoring
- Shows that the composite runner system is a robust system hydrodynamically
Summary & Conclusions

• Materials selected in Phase I proven in real-world simulated testing
• Composite runner turbine blades successfully fabricated using VARTM process
• Mechanical laboratory testing showed good correlation between predicted FEA performance and actual blade performance
• Scaled Voith Bulb hydroturbine successfully designed, fabricated, and deployed in PSU/ARL water tunnel
• Composite runner set successfully tested under simulated hydroturbine operational conditions
  – Hydrodynamic performance similar to stainless steel runners
  – Surface roughness and tolerances for the composite runner blades did not have a significant impact on performance parameters
  – No indication of cavitation was experienced, audibly or after visual inspection of the blades, indicating that the anti-cavitation coating performed as expected
• Proved that advanced manufacturing methods and materials used in the composite turbine blades are viable candidates for use in hydroturbines