Additive Manufacturing of Circumferentially Embedded Optical Sensor Modules for In Situ Monitoring of Coal-Fueled Steam Turbines

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NETL Sensors and Controls Project Review meeting, 5/4/2022
Objective
To design, additively manufacture, and test the circumferentially installed sensor modules for in-situ monitoring the temperature, pressure and blade tip-timing in turbines.

Background
❑ **Turbine blade failures**: a major cause of outages of turbomachinery and cost of millions to repair

❑ **Practice to minimize the turbine blade failures: Scheduled maintenance**
  - Millions spent on the parts, labors and more importantly, loss of service
  - Still cannot completely prevent the unexpected turbine failures and unplanned outages
Needs Condition-based monitoring (CBM) and Challenges

- Becomes a necessity to handle frequent load changes due to the increasing contributions of renewable energy sources
- Currently available sensors have low survival rate under harsh environment and too expensive to be widely deployed in existing turbines
- Relies on in situ monitoring
- Has long been identified as the “missing and mostly required to fill capability gap” due to the lack of effective monitoring tools

Technology Gaps

- **Gap #1**: the lack of robust harsh environment sensors
- **Gap #2**: the lack of effective methods to package and install the sensors into the turbines without degrading their performance
### CBM parameters for turbine blades

<table>
<thead>
<tr>
<th>Blade monitoring methods</th>
<th>Monitoring parameters</th>
<th>Characteristics and applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>Blade pass frequency (BPF)</td>
<td>(i) Easy to implement</td>
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<tr>
<td></td>
<td></td>
<td>(ii) Suitable for blade rubbing detection</td>
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<td></td>
<td></td>
<td>(iii) Not sensitive to detect minor faults such as blade geometry alterations</td>
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<tr>
<td>Pressure</td>
<td>Pressure distortion around blades</td>
<td>(i) Suitable for blade deformation and fouling detection</td>
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<td></td>
<td></td>
<td>(ii) Difficult to deploy under operating conditions</td>
</tr>
<tr>
<td>Acoustic</td>
<td>Acoustic signal</td>
<td>(i) Suitable for blade rubbing detection</td>
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<tr>
<td></td>
<td></td>
<td>(ii) Sensitive to noise</td>
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<tr>
<td>Debris</td>
<td>Particle in oil and charges</td>
<td>Suitable for blade rubbing and FOD detection</td>
</tr>
<tr>
<td>Strain gauge</td>
<td>Displacement</td>
<td>Suitable for blade deformation and blade fatigue detection</td>
</tr>
<tr>
<td>Temperature</td>
<td>Temperature</td>
<td>(i) Suitable for blade creep monitoring</td>
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<tr>
<td></td>
<td></td>
<td>(ii) Can provide early warning</td>
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<td></td>
<td></td>
<td>(iii) Embedded temperature sensors are required</td>
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<tr>
<td>Performance</td>
<td>Performance (efficiency, output, fuel consumption, etc.)</td>
<td>(i) Suitable for blade fouling and rotating stall detection</td>
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<td></td>
<td></td>
<td>(ii) Large number of sensors required</td>
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<td>(iii) Large number of data and calculation required</td>
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</table>

A Smart Ring circumferentially installed inside the turbine casing for in situ monitoring of temperature, pressure and tip-timing.

**Proposed Solution**

Three types of embedded sensor modules:

- Temperature sensor module
- Pressure sensor module
- Blade tip-timing sensor module
Project Tasks

Four Major Tasks

- **Design** optical temperature, pressure, and blade tip timing/clearance sensor modules
- Develop processes to **additively manufacture** the designed optical sensor modules
- **Test and validate** the optical sensor modules in laboratory simulated environments
- **Test and evaluate** performance of the optical sensor modules in an industrial scale test facility
Integrated Additive and Subtractive Manufacturing (IASM)

- 3D printing of glass and ceramics
- Laser melting and sintering
- Ultrafast laser micromachining
3D printing of Glass

3D print fused silica glass with excellent optical quality
Use picosecond laser to cut the shape of an optical component (e.g., a lens)
Keyence Sensor

Confocal displacement sensor:
- Range: ± 1.3 mm
- Resolution: 0.25 μm
- Spot size: 25 μm
Cascaded Intrinsic and Extrinsic Fabry-Perot Interferometers

Embed the sensor in a 3D printed glass housing
Blade Tip-Timing Sensing Requirements

- High time resolution (~ns)
- High signal-to-noise ratio
- Circumferentially positioned
- Low profile
Sensor design in raytracing software (Zemax)
Fiber-tube-lens assembly:
- A lens (D: 2mm) is welded on a tube (OD:2mm, IN:0.2mm) using a CO₂ laser.
- A fiber (D: 125 µm) is inserted into the tube and welded.

Laser welding procedures:
- (b) Welding on glass tube
- (c) Welding inside glass tube

Output beam profile
Fiber-tube-lens assembly:
- A cone-shaped opening is cut using a picosecond laser on one end of the tube to preserve the output beam’s shape.
9-degree tilted slant:
- The slant is cut by the picosecond laser layer by layer.
- One cutting layer is 25 µm.
9-degree tilted slant:

- CO2 resurfacing reduces the surface roughness and makes it transparent.
**Blade tip-timing sensor**

**Excitation path:**
- Fiber, tube and lens are fused together.
- Implement a fixture to align the component in-situ during fabrication.

![Diagram showing excitation path with fiber-tube-lens assembly, mirror, and prism in a tilted slot.](image)
Lens-prism assembly:
- A 3 mm lens and a 3 mm prism are welded together using a CO$_2$ laser.
Fabricate both slots in one step:
- Two tilted slots are cut and resurfaced.
- Collection efficiency is low because the tilting angle of the slots are not symmetric.
Stage alignment:

After alignment, tilt w.r.t the picosecond laser cutting plane:
- 40 μm per 10 mm in X direction.
- 16 μm per 10 mm in Y direction.
**Improved substrate fabrication:**

- After alignment, the slots are symmetric.
- The sensor prototype is assembled and tested.
- Reception is improved by 20 dB.
Prototype test with a blade model:
- Peak received power is -44.6 dBm, with 10 dBm input power.
- Signal-to-noise ratio is about 20 dB.
Budget Period I (01/2020-09/2022)

Scope of Work in Budget Period I
- Optical designs of the sensor module (Completed)
- Temperature sensor prototypes are fabricated and confirmed by laboratory tests (Completed)
- Pressure sensors prototypes are fabricated and confirmed by laboratory tests (Completed)
- Tip timing sensor module prototypes are fabricated, assembled and tested under laboratory conditions (09/30/2022, on schedule to complete).

Progresses of the project
- The technical progress of the project is on track.
- All the milestones have been met.
Plan

Fabrication & Testing of Sensor Modules

Remaining BP1 (09/30/2022):
- Continue to fabricate and package pressure and tip-timing sensor prototypes
- Test the sensor modules in the lab.

BP2 (10/01/2022 – 09/30/2023):
- Fabricate and package temperature, pressure, and tip-timing sensor modules.
- Install and test the sensor modules using a test rig.
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