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Ingenuity for life

Embedded sensors integrated into critical components for *in situ* health monitoring of steam turbines

Anand Kulkarni, Siemens Corporation

DOE Award: DE-FE-0031832
Review meeting: August 26th 2020

Acknowledgements: DOE Fossil Energy
Jessica Mullen– DOE NETL Project Manager

Outline

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Introduction

Project Objective

Project Approach to Meet Technical Targets

Task 2.0 - Demonstrate component scale up efforts for embedded sensors

Task 3.0 – RF Communications package development

Task 4.0 – Integration into Blade Health Monitoring and Power Diagnostics®

Task 5.0 - Define and Manufacturing Test Article for engine test

Task 6.0 - Conduct Engine testing of Instrumented Turbine blades

Project Schedule and Milestones

Project Objectives to Meeting FOA requirements

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Project information

PI: Anand Kulkarni

Funder: DOE Office of Fossil Energy (FE) – NETL Crosscutting

Strategic Partner: Siemens Gas and Power, RTRC

Total Project Funding: $1.25M ($1M Federal/$250K Cost share)

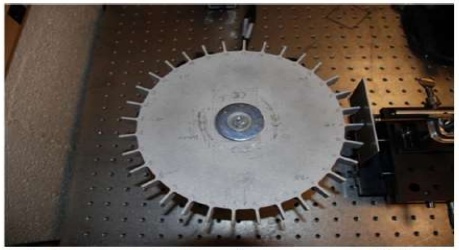
Project Details

- **Design and develop embedded elements and communication/sensing circuitry for blade health monitoring of steam turbine.**
- **Baseline the performance of RF sensor/ communication with current multi-probe blade vibration monitor utilized in service on a test rig.**
- **Integrate the novel RF-based blade vibration monitoring within Siemens Power Diagnostics ® for remote real-time monitoring of blade health.**
- **Technology validate an integrated blade with embedded sensor/wireless communications device in an extreme-environment steam turbine.**

Technical Highlights

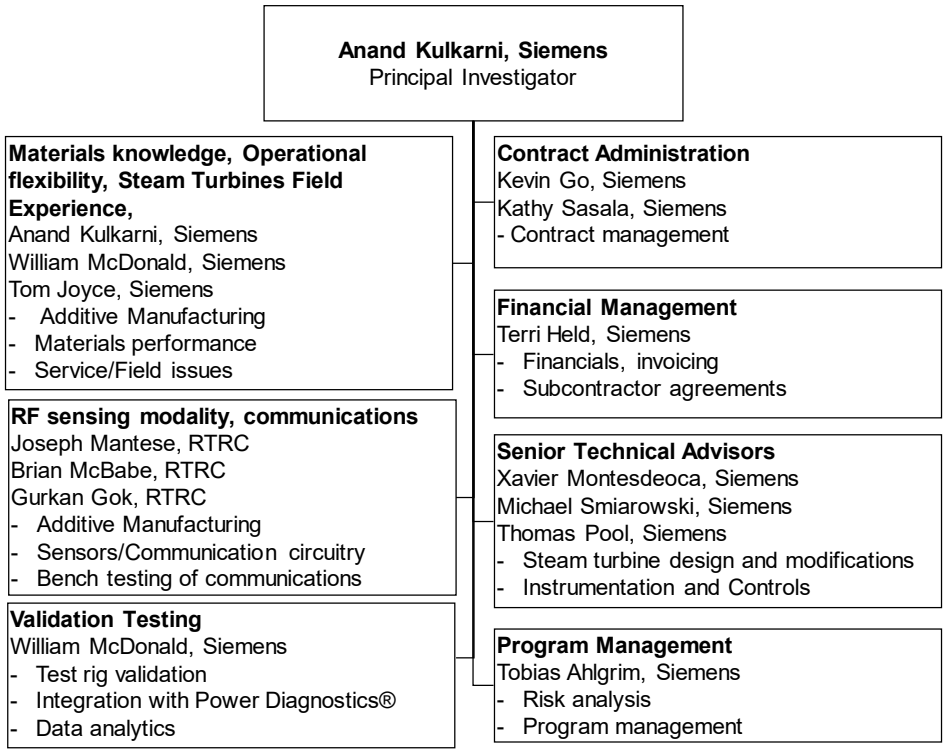
Funding Opportunity Objective	Objective of the proposed work
Fabricate and assemble a component with embedded sensor technology ⇨	Design and develop embedded elements utilizing additive manufacturing and RF communication/sensing circuitry for blade health monitoring of steam turbine
Develop methodologies that merge in-situ component health monitoring ⇨	Integrate the novel RF-based blade vibration monitoring within Siemens Power Diagnostics ® for remote real-time monitoring of blade health
Conduct testing and demonstration of a fully integrated 'smart' prototype applicable to a fossil-based energy system process ⇨	Technology validation of an integrated blade with embedded sensor/wireless communications device in an extreme-environment steam turbine.

NASA GRC high precision spin rig microwave sensor.



Blade tip clearance and timing testing on the sensor Calibration Rig

Project Team and Expertise



Team Member	Skill and expertise
Principal Investigator: Anand Kulkarni	Principal Key Expert; 25 years in research and technology in the area of materials/coatings/sensors for power systems, 10 years in materials needs for environmental and operational flexibility
Siemens Team: William McDonald (WM) Tom Joyce (TJ)	**WM**: Senior Engineer, Program Manager, 10 years' experience with service engineering and monitoring of steam turbines. **TJ**: Senior Engineer, 10 years' experience with design, and instrumentation/testing of steam turbines
UTRC Team: Joseph Mantese (JM) Brian McCabe (BM) Gurkan Gok (GG)	**JM:** Research Expert; 30 years of experience in electronic materials, components, sensors, and packaging, developing the additive manufacturing processes for sensors and RF sensing/communication circuitry **BM:** Research Expert, 30 years' experience of architecture and electronic systems for interfacing with the sensor suite at the system level and in test rig configurations **GG:** Research Expert, 10 years' experience in sensor and packaging, simulations and RF sensing/communications circuitry

The technical team is strong and has the capability for successful demonstration

Sensors Using RF as Sensing Modality

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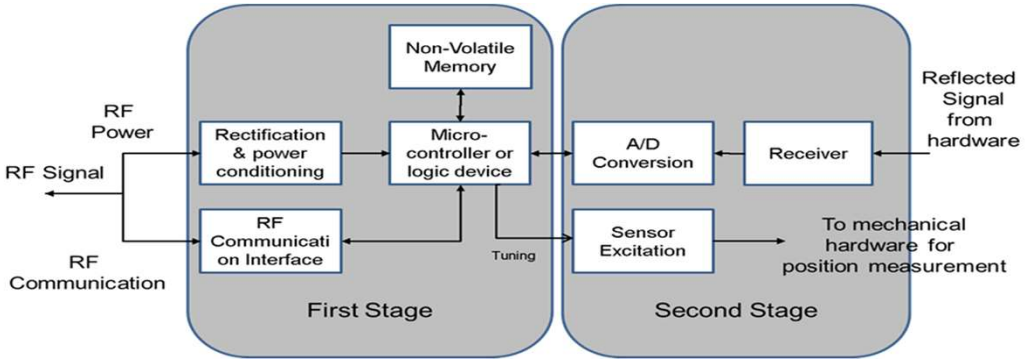
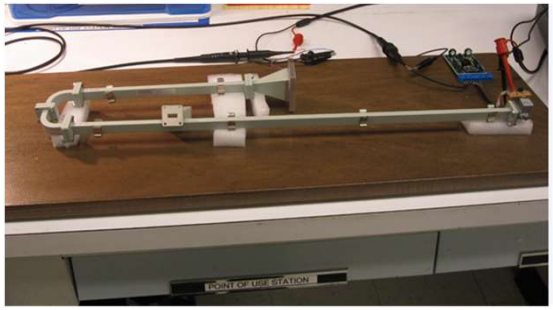
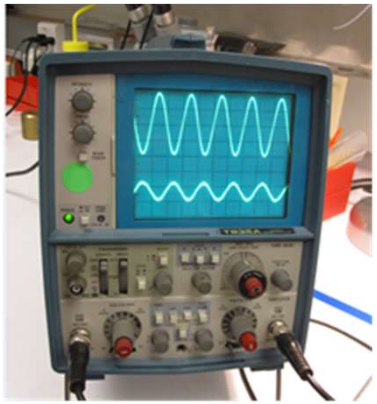
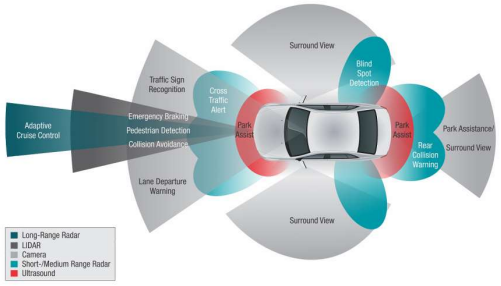
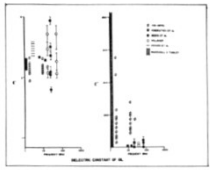
New Generation of Sensing Utilizing an RF Modality with Miniaturized High Efficiency Antenna Structures



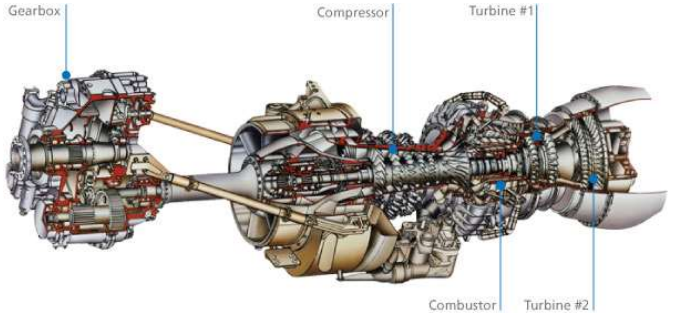








W band RF windows (chemical sensing)



New class of sensors (especially for extreme environments): position, velocity, acceleration for pressure, vibration, temperature, etc

Existing Blade Vibration Monitoring Approach

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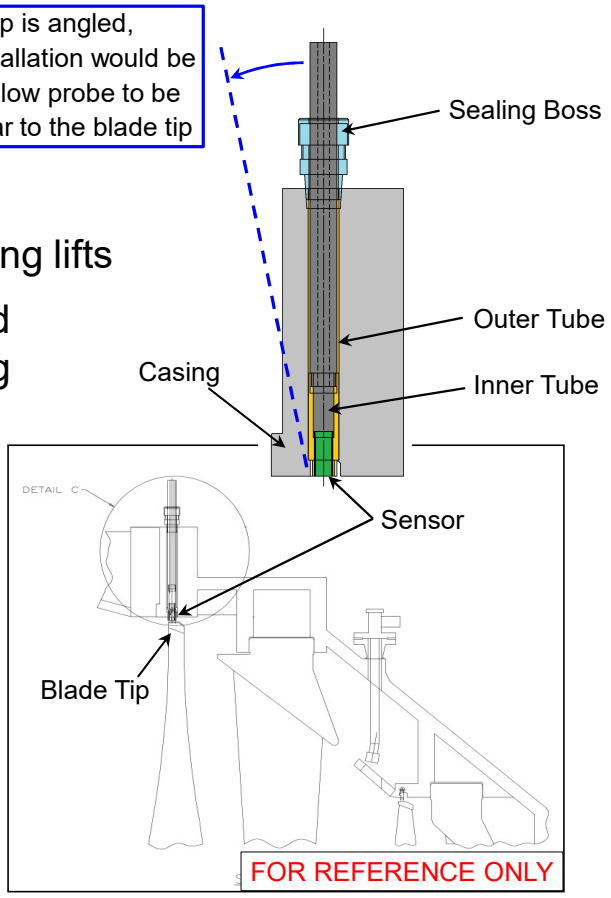
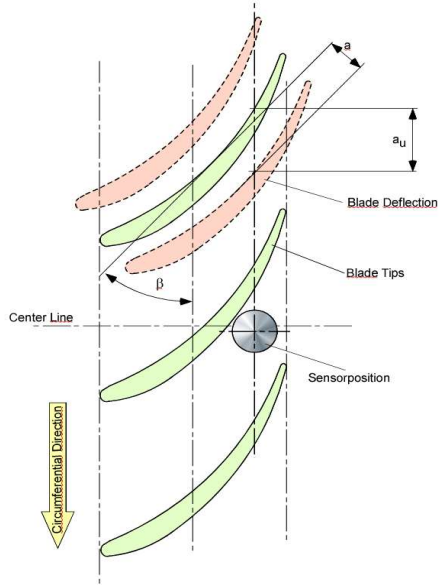
- Probe installation features
  - Ease of access for maintenance
  - Probes can be removed / replaced in-service
  - Probe(s) in upper half to be removed for casing lifts
- Recommend to install 3 probes, equally-spaced (120 deg apart) around circumference of casing



- Stationary pickups (magnetic sensors) sense time of arrival for each blade tip
- Difference between actual and expected times represents tip deflection (a_u)



Project Overview
Project Tasks

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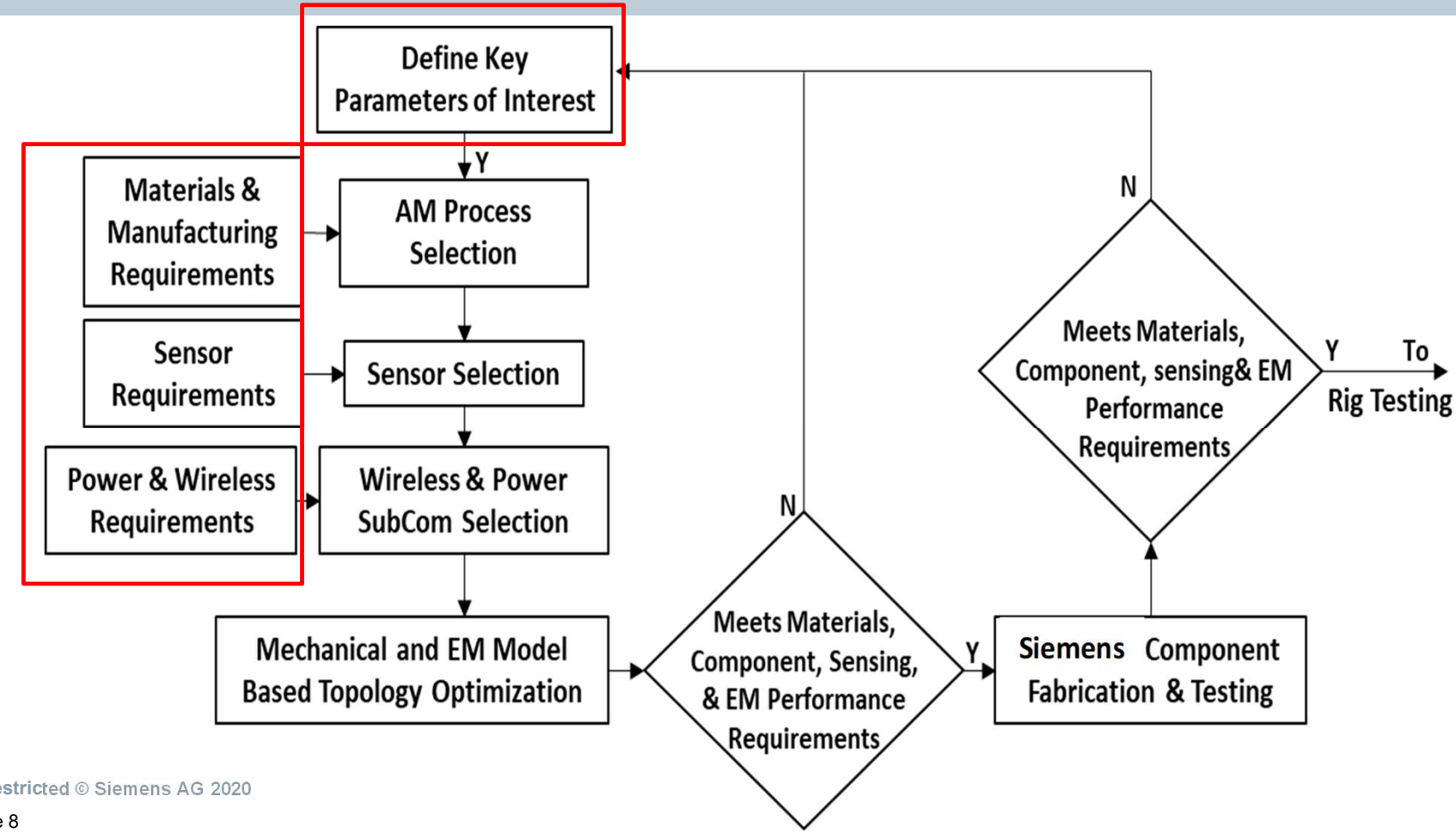
Task	Description	Responsible
Demonstrate component scale up efforts for embedded sensors	• Establish sensor specification • Sensor selection and localization • Sensor and circuitry design • Benchmark criteria selection	RTRC Siemens CT
RF Communications package development	• Communication requirements • Layout of communication circuitry • Assembly of test rig • Functional tests	RTRC Siemens CT
Integration into blade Health monitoring und power diagnostics	• Interface specification to Siemens Power Diagnostics • Calibration Model • Develop Observers	Siemens CT Siemens Energy
Define and manufacturing test article for engine test	• Define test scenario • Localization of sensor on steam turbine • Integration of sensor and steam turbine	Siemens Energy RTRC
Conduct engine testing of instrumented turbine blades	• Simulate Engine test to provide predictions • Run an engine test that follows the predictions • Evaluate the sensing	Siemens Energy

Task 2.0 – Demonstrate component scale up efforts for embedded sensors



RF-based Blade Tip Timing Sensor

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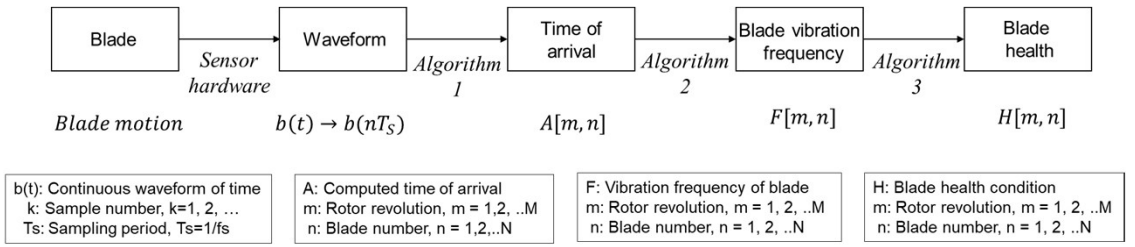
- Blade vibration monitoring system aims to assess changes in vibration frequency of blades over time.
- RF/MW based blade tip timing sensor hardware consists of a transceiver, a waveguide and sensor.
- Received signal waveform provides information about the position of the blade with respect to aperture.

Waveform

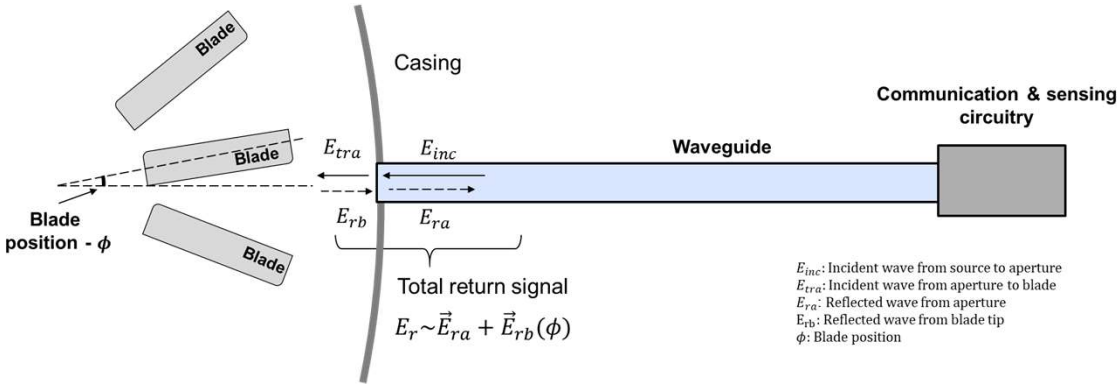
$$E_r \sim \vec{E}_{ra} + \underbrace{\vec{E}_{rb}(\phi)}$$

Carries blades position information

Functional block diagram of a generic blade vibration monitoring system



Schematic of an RF-based sensor for blade vibration monitoring



Simulation Model Development

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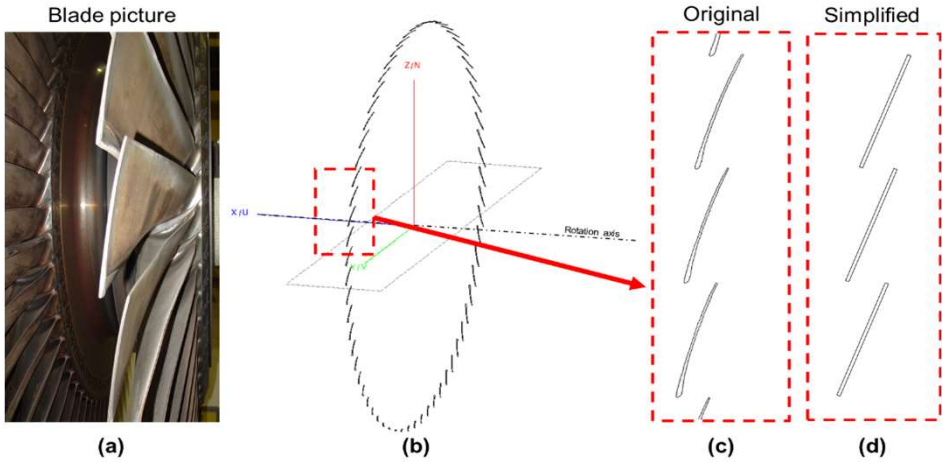
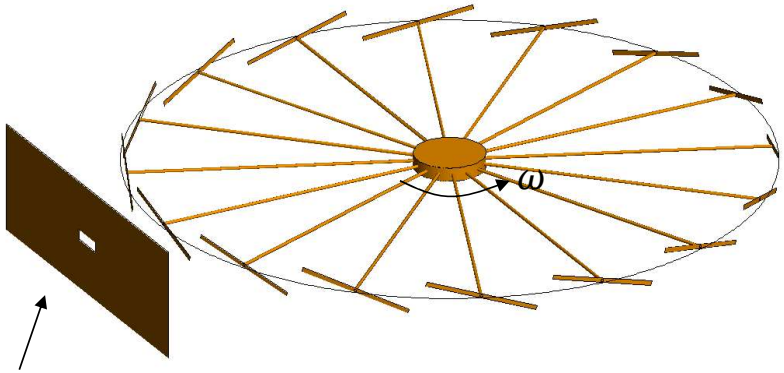
- To characterize the signal waveform from RF based sensors and the blade geometry of interest, a simulation model for the blade and sensor were developed.
- The blade tip dimensions were modelled based on the information provided by Siemens.
- A rectangular waveguide probe was chosen as sensor geometry at this stage of the investigation.

Blade geometry model





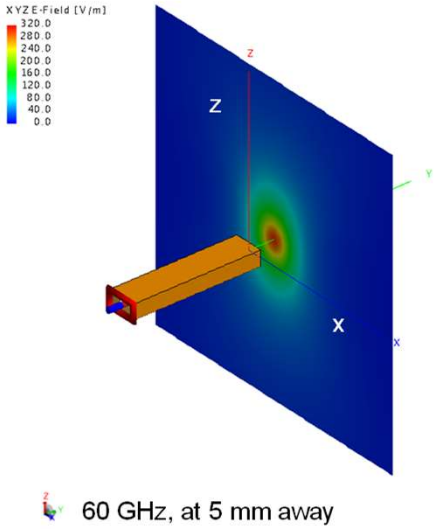
Sensor aperture and small representative rim

Blade cross sections – Aluminum

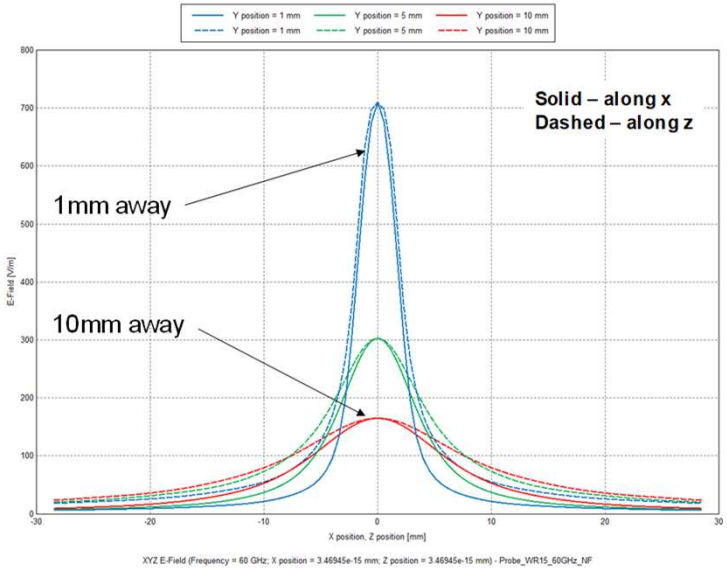
Rest of the structure will be made of relatively less reflective plastic material

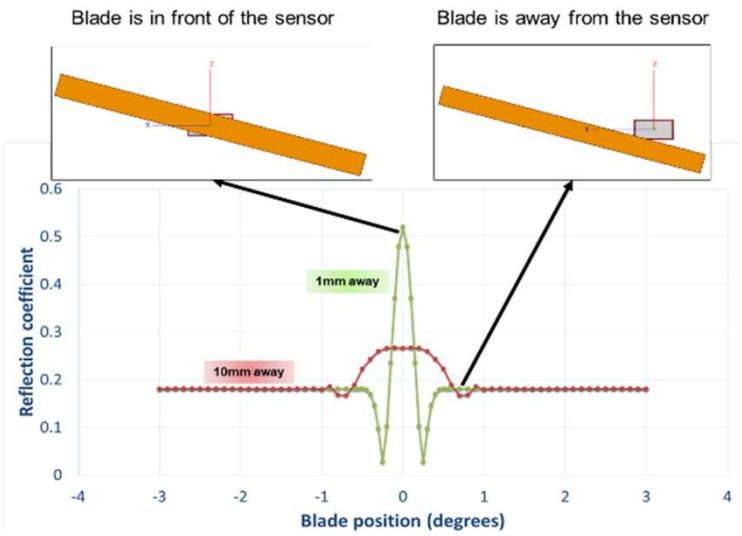
Simulated Sensor Performance

- A preliminary performance analysis of the RF/MW probe was investigated.
- Waveforms as blade sweeps across the aperture were simulated for two extreme clearances.
- The sensor was not optimized for best performance and does not include proper protective packaging/housing for its endurance in the turbine environment, yet.



60 GHz, at 5 mm away





Concepts Under Consideration

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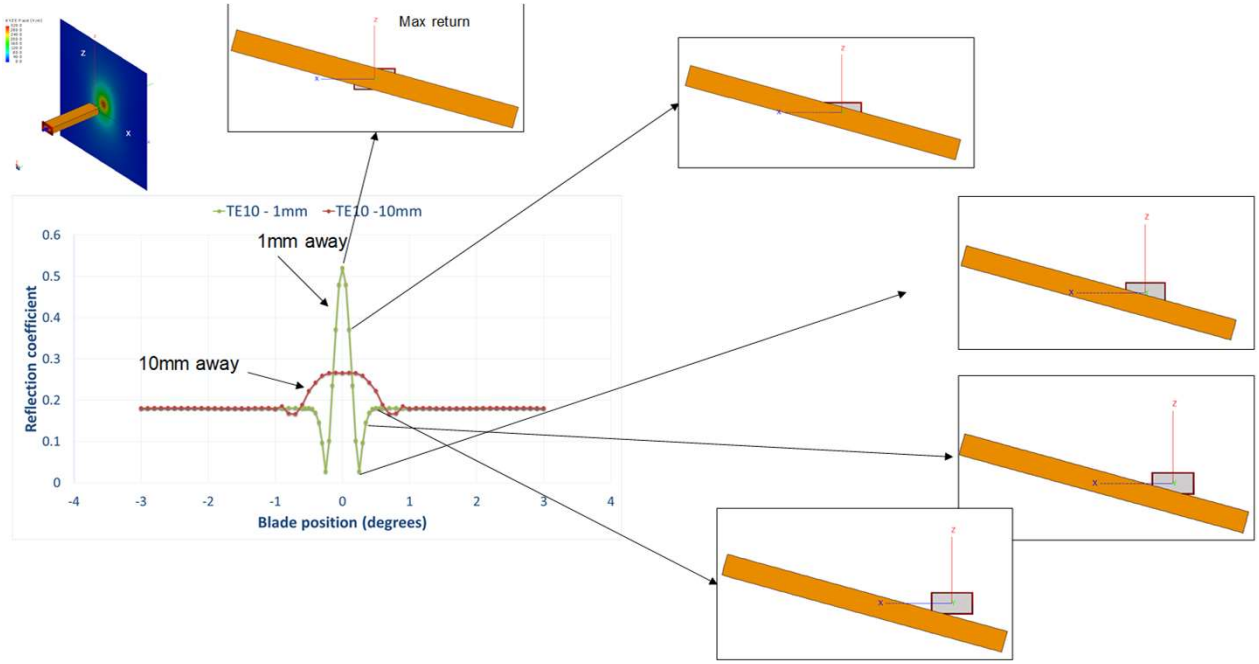
Concept investigation for optimum probe performance



Probe/beam shaping

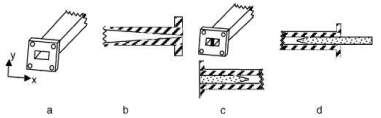
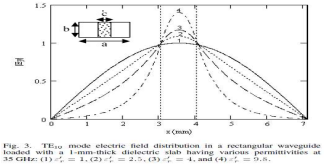
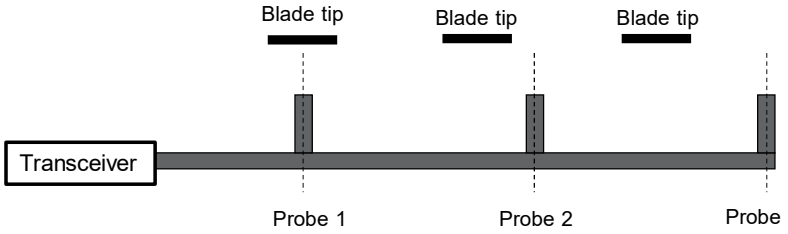


Fig. 2. Open-ended probes. (a) standard rectangular waveguide. (b) Tapered waveguide. (c) Dielectric slab-loaded waveguide. (d) Dielectric waveguide.

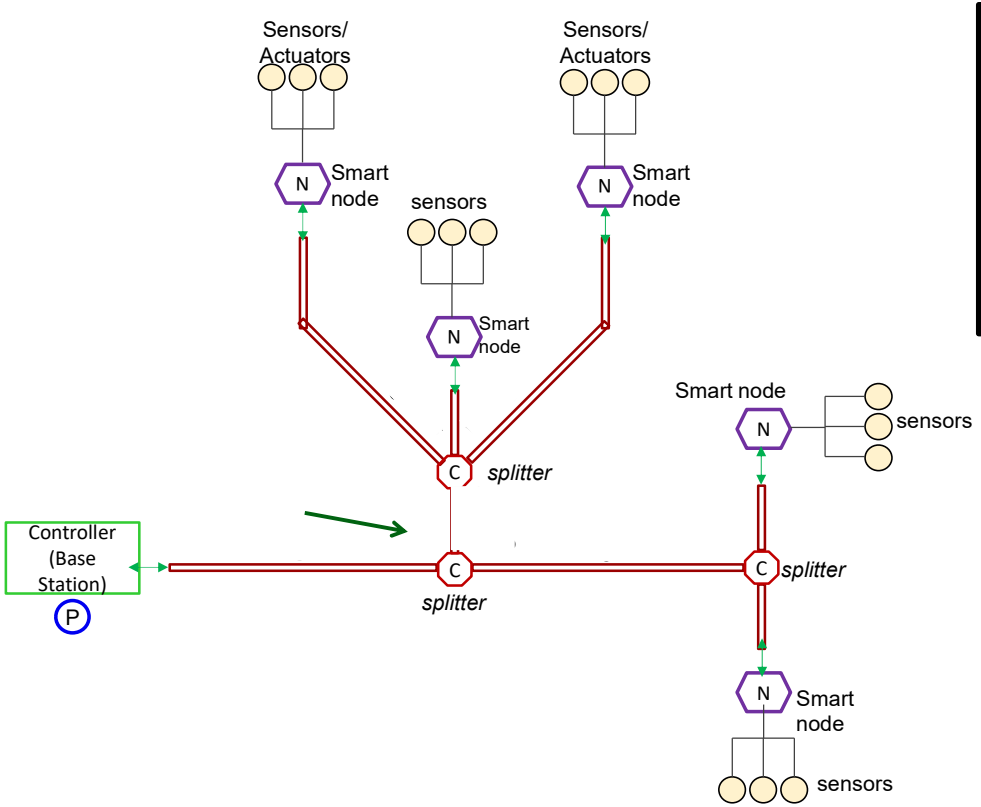


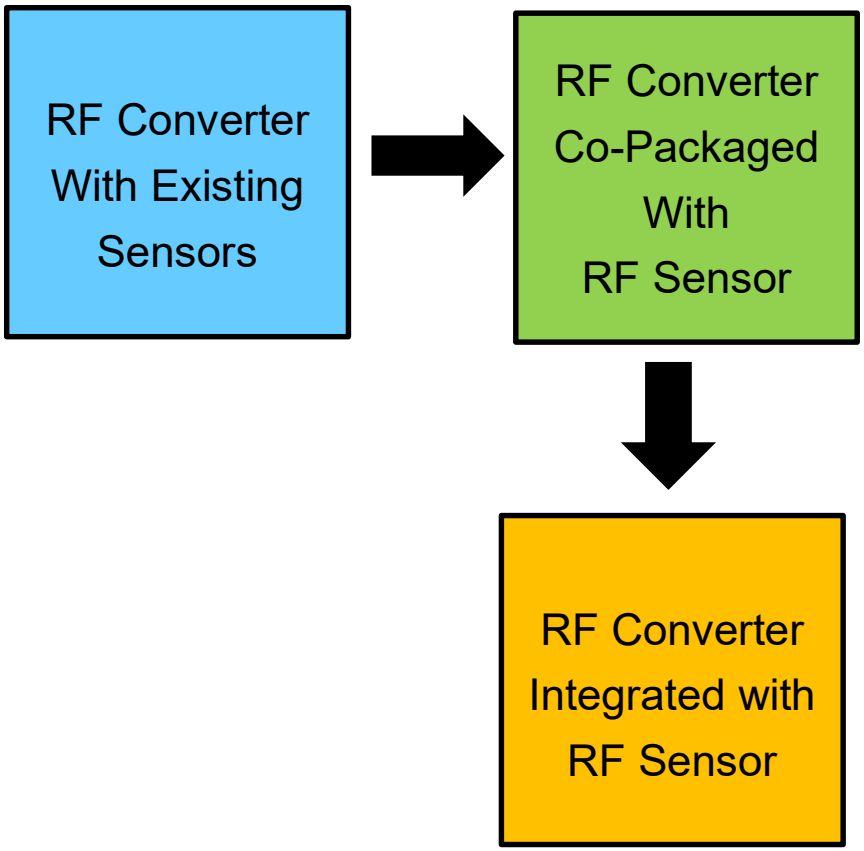
M. Ghasr et al. IEEE Trans. Instrumentation and Measurement 54.4 (2005)

Multiplexing



Task 3.0 – RF Communications package development





Benchtop Model and RF Communication Package Development

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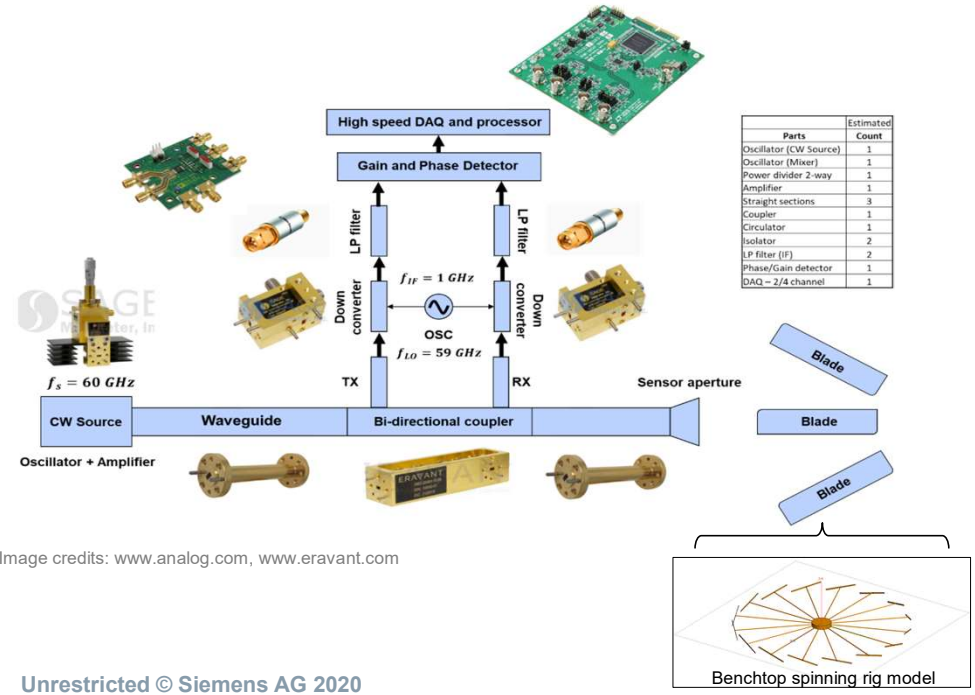
Preliminary design of bench-top model for testing sensor and communication/sensing circuitry

Communication/sensing circuitry for benchtop model



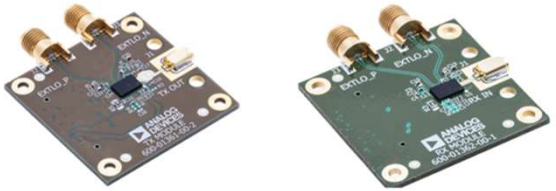
Parts	Estimated Count
Oscillator (CW Source)	1
Oscillator (Mixer)	1
Power divider 2-way	1
Amplifier	1
Straight sections	3
Coupler	1
Circulator	1
Isolator	2
LP filter (IF)	2
Phase/Gain detector	1
DAQ – 2/4 channel	1

Image credits: www.analog.com, www.eravant.com

Benchtop spinning rig model

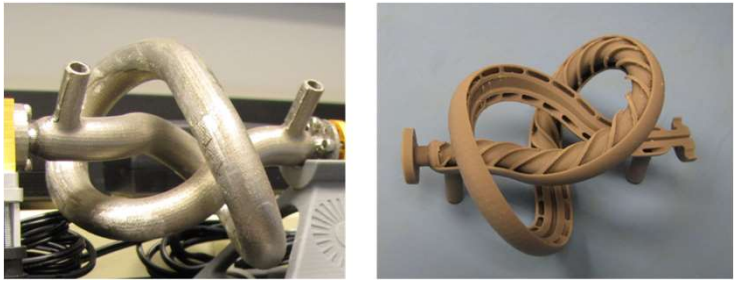
Millimeter wave parts on PCB

60 GHz millimeter wave transmitter and receiver (www.analog.com)



TX RX

Communication circuitry design/manufacturing at RTRC



Task 4.0 – Integration into Blade Health Monitoring and Power Diagnostics®

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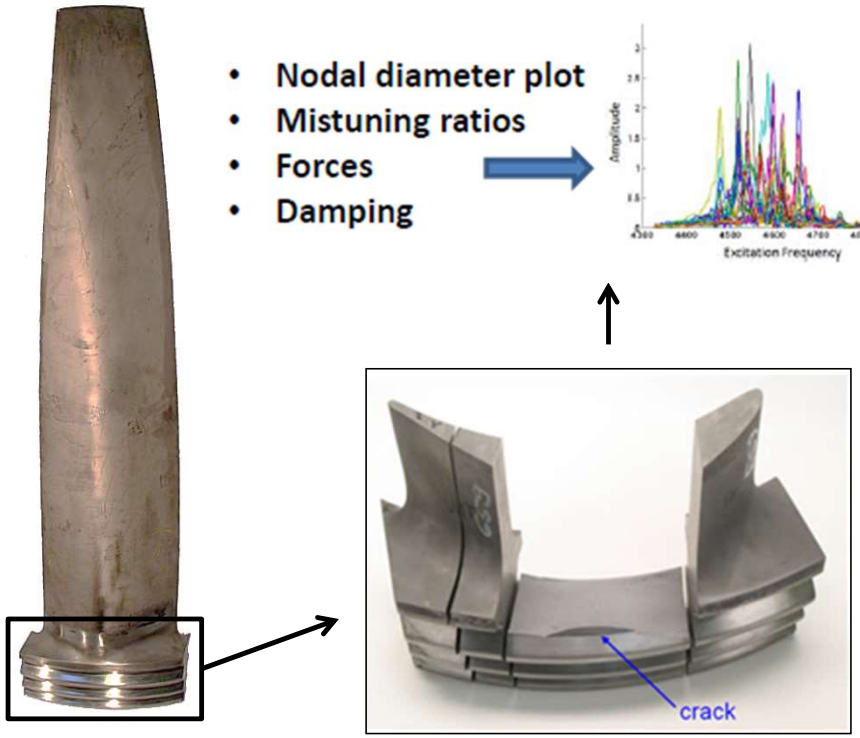
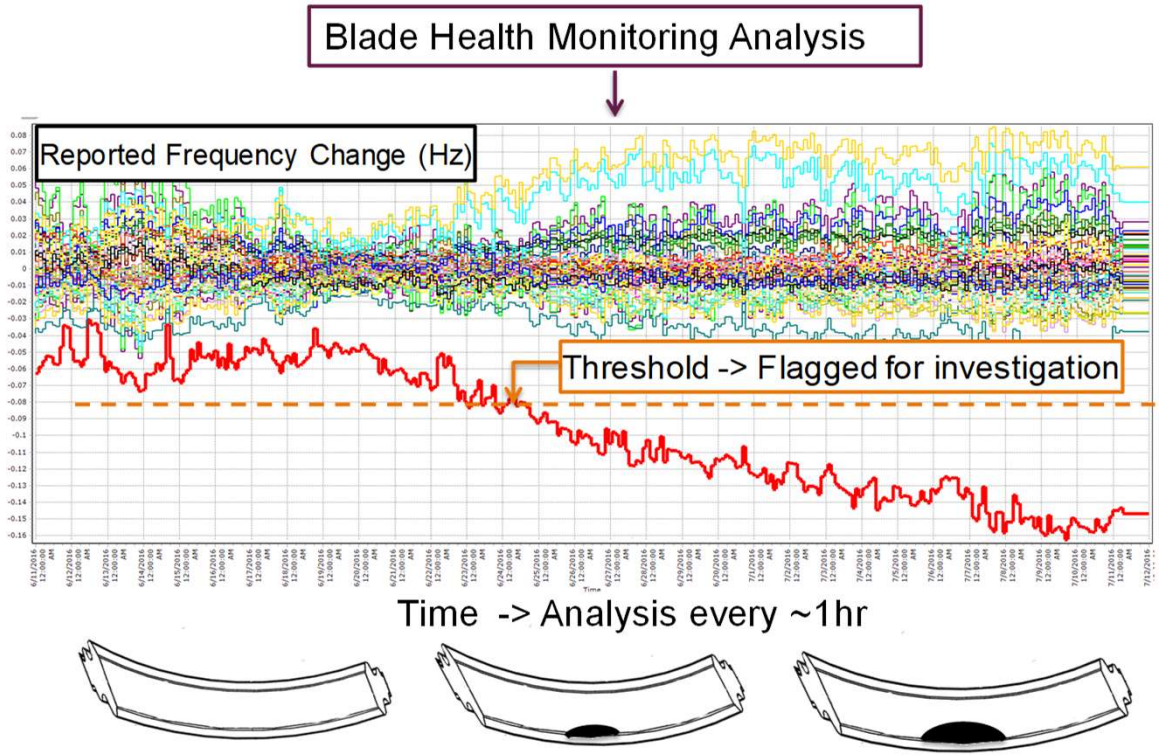
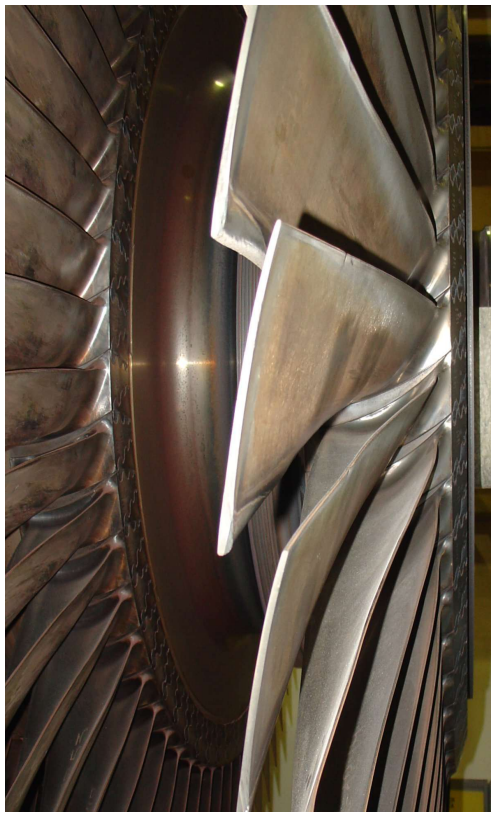
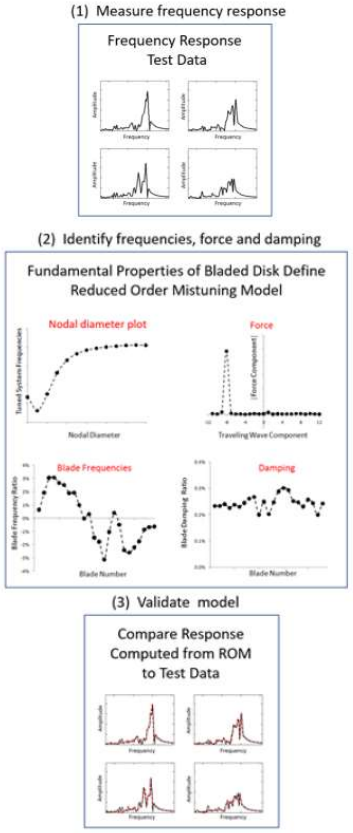




Need for Real-time Online Monitoring for Blade Vibration Monitoring





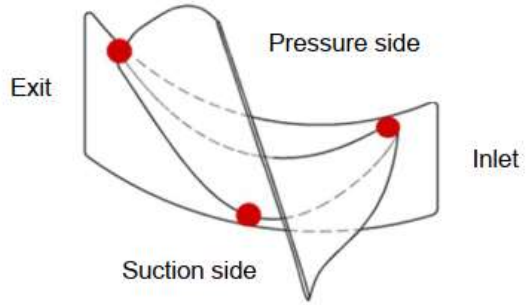


FIGURE 9: LIFE-LIMITING LOCATIONS IN BLADE ROOT

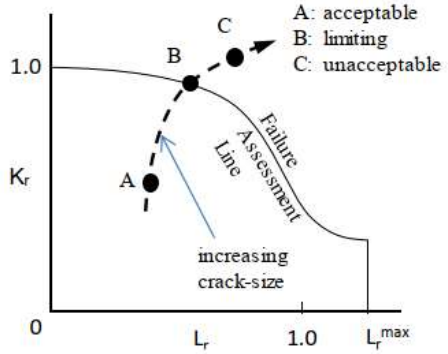


FIGURE 15: FAILURE ASSESSMENT DIAGRAM, CRACK-TIP-DOMINATED FAILURE

DETECTION OF CRACKS IN TURBOMACHINERY BLADES BY ONLINE MONITORING

RF Data Ingestion from Sensors

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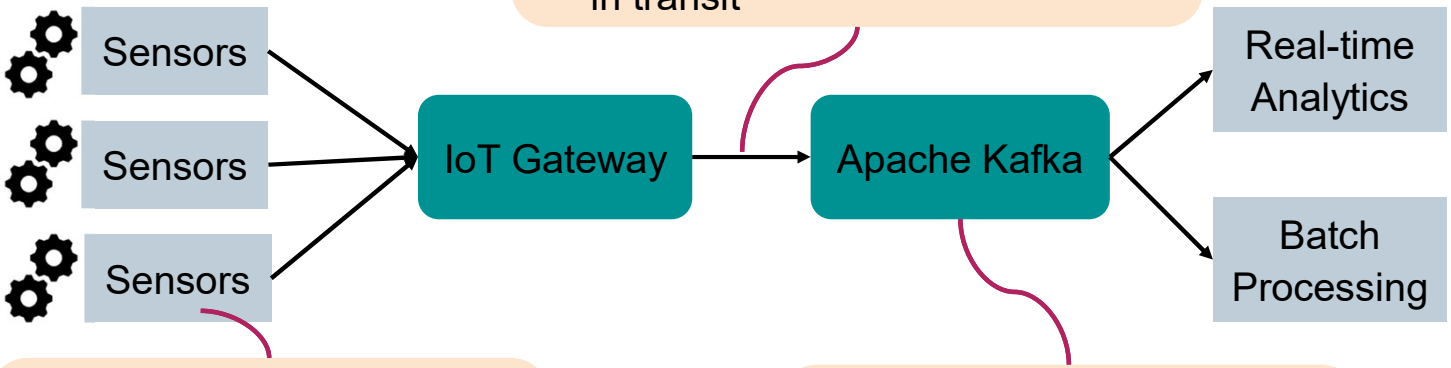

- IPsec VPN tunnels for securing network connections
- Data encryption both at rest and in transit

- Create RF sensor performance Baseline
- Integrate with Siemens Power Diagnostics
- Monitoring dashboard
- Alerting capability

- RF (Radio Frequency) sensors data
- Used to measure blade tip ratio and deformation

- Real-time streaming data pipelines
- Decouples streaming data producers from data consumers
- Deployed on Edge or Cloud

Project Approach for Embedded Sensors for Steam Turbine Blade Vibration Monitoring

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Year 1 Embedded AM Sensors, RF Communications, Health Monitoring (HM) Tool	**Year 2** Smart blade component, Develop HM Approach, **Engine testing of integrated blade**
Technical Progress Develop RF sensors and communication circuitry for bench testing Develop health monitoring tool Collect baseline blade monitoring data for specifications **Go / No-Go** AM deposition for embedded sensors RF Sensor/ Wireless telemetry demonstrated on lab rig setup Health monitoring framework	**Technical Progress** Robust embedded RF sensor/ Communications demonstrated Integrated sensor/communication on steam turbine blade Integration with power diagnostics **Go / No-Go** Spin test miniature embedded sensor wireless telemetry system Demo high throughput Embedded sensor manufacturing process Engine test validation of novel approach vs non-contact blade monitoring

Project Schedule

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ID	Task Name	Duration	Start	Finish
1	***Embedded sensors integrated into critical components for in situ health monitoring of steam turbines***	523 days?	Tue 10/1/19	Thu 9/30/21
2	**Task 1: Program Management and Planning**	523 days?	Tue 10/1/19	Thu 9/30/21
3	Update SOPO	30 days	Tue 10/1/19	Mon 11/11/19
4	Kick-off Meeting	30 days	Tue 10/1/19	Mon 11/11/19
5	Project Management	523 days?	Tue 10/1/19	Thu 9/30/21
6	Contract Administration and Cost Reporting	523 days?	Tue 10/1/19	Thu 9/30/21
7	Technical Reporting	523 days?	Tue 10/1/19	Thu 9/30/21
8	Progress Reports	523 days?	Tue 10/1/19	Thu 9/30/21
9	**Task 2: Demonstrate component scale up efforts for embedded sensors**	**347 days**	**Tue 11/12/19**	**Wed 3/10/21**
10	Baseline analysis of existing blade monitoring efforts to establish sensor specifications	60 days	Tue 11/12/19	Mon 2/3/20
11	Downselect sensor location of critical areas from Engine analysis	60 days	Tue 2/4/20	Mon 4/27/20
12	Downselect sensor designs and circuitry to match specifications of blade monitoring	100 days	Tue 4/28/20	Mon 9/14/20
13	**Develop RF position sensor breadboard circuitry for bench testing**	**1 day**	**Tue 9/15/20**	**Tue 9/15/20**
14	Evaluation of sensor performance for integrated/embedded sensors for repeatability/geometry effectson lab test rig	125 days	Wed 9/16/20	Tue 3/9/21
15	**Demonstrate packaged RF position sensor for engine testing**	**1 day**	**Wed 3/10/21**	**Wed 3/10/21**
16	**Task 3: RF Communications package development**	**266 days**	**Tue 11/12/19**	**Tue 11/17/20**
17	Define communications requirements (power/position/distance) for engi	30 days	Tue 11/12/19	Mon 12/23/19
18	Design layout and fabrication iterations forRF communications circuitry	50 days	Tue 12/24/19	Mon 3/2/20
19	Functionality testing iterations for RF wireless circuitry	100 days	Tue 3/3/20	Mon 7/20/20
20	Demonstrate integrated sensors with wireless telemetry for signal transmission in a lab test rig	85 days	Tue 7/21/20	Mon 11/16/20
21	**Demonstrate RF communication package for engine testing**	**1 day**	**Tue 11/17/20**	**Tue 11/17/20**
22	**Task 4: Integration into Blade Health Monitoring and Power Diagnostics®**	**311 days**	**Tue 11/12/19**	**Tue 1/19/21**
23	Field feedback for observed failure mechanism from blade monitoring	100 days	Tue 11/12/19	Mon 3/30/20
24	Health monitoring methodology for complex damage mechanisms for steam turbine blade	150 days	Tue 3/31/20	Mon 10/26/20
25	Model calibration using Machine Learning techniques to multi-dimensional inputs correlated to sensor data	60 days	Tue 10/27/20	Mon 1/18/21
26	**Develop interface with Power Diagnostics® with results/predictions dashboard for quick in-field application**	**1 day**	**Tue 1/19/21**	**Tue 1/19/21**
27	**Task 5: Define and Manufacturing Test Article for engine test**	**412 days**	**Tue 11/12/19**	**Wed 6/9/21**
28	Define test article blade with identified sensor locations and RF communications package	150 days	Tue 11/12/19	Mon 6/8/20
29	Integration of embedded RF sensors with wireless telemetry package on steam turbine blade	100 days	Wed 9/16/20	Tue 2/2/21
30	Conduct a thorough inspection of the test article with functionlity	90 days	Wed 2/3/21	Tue 6/8/21
31	**Manufacture test article instrumented blade to compare with non contact blade monitoring**	**1 day**	**Wed 6/9/21**	**Wed 6/9/21**
32	**Task 6: Conduct Engine testing of InstrumentedTurbine blades**	**206 days**	**Tue 11/17/20**	**Tue 8/31/21**
33	Define Instrumentation Plan and Install Instrumented component in engine for testing and validation	35 days	Tue 11/17/20	Mon 1/4/21
34	Simulate Engine Test to provide Predictions based on computational fluid dynamics and heat transfer models for analysis of the engine test results.	60 days	Tue 1/5/21	Mon 3/29/21
35	Achieve a successful engine test with baseline blade monitoring	50 days	Tue 3/30/21	Mon 6/7/21
36	Analyze the results of the experiment, comparing and understanding the differences between RF sensing and non contact blade monitoring	60 days	Tue 6/8/21	Mon 8/30/21
37	**Engine test validation of novel embedded sensor vs non-contact blade vibration monitoring**	**1 day**	**Tue 8/31/21**	**Tue 8/31/21**
38	**Final Technical report detailinEmbedded sensors integrated into critical components for in situ health monitoring of steam turbines**	**23 days**	**Tue 8/31/21**	**Thu 9/30/21**

Milestones and Deliverables

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	Success Criteria at Decision Points	
Milestone No.	**Year 1**	**Plan**
3	**Develop RF position sensor breadboard circuitry for bench testing, demonstration of embedded sensor on turbine hardware** • Demonstrated for RF position sensor circuitry on bench test, also demonstrate embedded sensor on turbine blade hardware	**09/15/20**
Milestone No.	**Year 2**	**Plan**
8	**Engine test validation of novel embedded sensor vs non-contact blade vibration monitoring** Demonstration of blade vibration monitoring utilizing novel RF sensor modality/communications for blade in steam turbine to compare with baseline non-contact vibration monitoring.	**08/31/21**

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification method
Year 1 (Oct 2019 – Sept 2020)			
1	Baseline analysis of existing intrusive blade vibration monitoring efforts to establish sensor specifications.	2/3/2020	Survey of technical reports for sensor specifications
2	Topology optimization, design layout and fabrication iterations for RF communications circuitry	3/30/2020	Electronic design for functional demonstration of RF communications
3	Develop RF position sensor breadboard circuitry for bench testing, demonstration of embedded sensor on turbine hardware	9/15/2020	Benchtop Lab testing for sensor functionality with wireless telemetry
Year 2 (Oct 2020 – Sept 2021)			
4	Develop interface with Power Diagnostics® with results/predictions dashboard for quick in-field application	1/19/2021	Model interface with integration of sensor data for real-time vs calculated vibration monitoring
5	Demonstrate packaged RF position sensor for engine testing for desired full speed and vibrations	3/10/2021	Lab testing of engine hardware for functional qualification
6	Manufacture test article instrumented blade to compare with non contact blade monitoring	6/9/2021	Embedded sensor integrated on steam turbine hardware
7	Engine test validation of novel embedded wireless sensor vs intrusive non-contact blade vibration monitoring	8/31/2021	Engine testing of existing system vs novel RF sensing of vibrations

Next Steps

SIEMENS

1. Probe design with optimum performance for the given operational range of blade tip clearances **(under Task 2.0)**
2. Further investigation of concepts **(under Task 2.0)**
3. Implementation of the benchtop set up **(under Task 3.0)**
4. Correlation of new sensing approach to existing waveform from blade vibrations **(under Task 4.0)**
5. Test sensitivity of existing vibration monitoring algorithms with signal from RF sensing **(under Task 4.0)**
6. Data analytics interface with existing Siemens Power Diagnostic center **(Task 4.0)**