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

Anand Kulkarni, Siemens Corporation

DOE Award: DE-FE-0031832

Joseph Mantese, Gurkan Gok, Joe Zacchio –
Raytheon Technology Research Corporation

Acknowledgements

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Outline

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Introduction

Project Objective

Project Approach to Meet Technical Targets

Project Schedule and Milestones

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 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

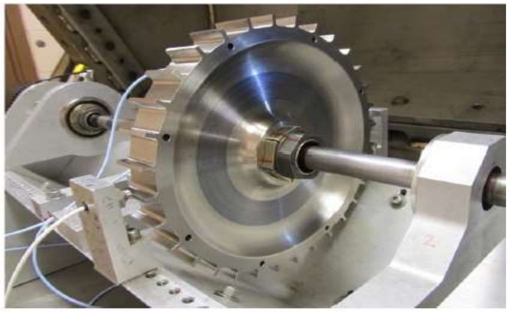
Total Project Funding: $1.25M ($1M Federal/$250K Cost share)

Project Details

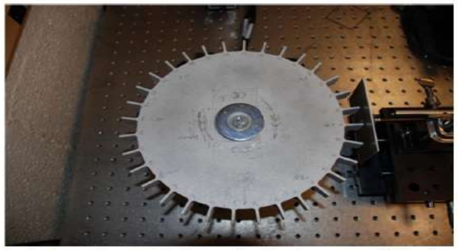
- **Design and develop embedded elements and communication/sensing circuitry for blade health monitoring of steam turbine.**
- **Baseline the performance of RF sensor/ communication with current multi-probe blade vibration monitor utilized in service on a test rig.**
- **Integrate the novel RF-based 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
Individual Contributions

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Team member	Skill and expertise	Expectation
Principal Investigator: Anand Kulkarni	Specialist in materials/coatings/sensors for power systems.	Lead the research project, sensor expertise
Siemens Team: Jason Weissman (JW) Kyle Stood (KS) Tobias Ahlgrim (TA) Ramaraj Ramamani (RR)	JW: Sensor testing and evaluation KS: Additive Manufacturing Specialist TA: Project management / Embedded Developer RR: Quality Manager	JW: Travel to RTRC for sensor/wireless testing and integration KS: Support RTRC on AM /waveguide integration of blades TA: Resource allocation and project organization RR: Assure ISO 9001 process compliance
RTRC Team: Joseph Mantese (JM) Gurkan Gok (GG) Brian McCabe (BM)	JM: Specialist for electronic materials, sensors and RF sensing /communication circuitry GG: Specialize in sensors and communication circuitry BM: Specialist for electronic systems and system level design	Provide the RF sensing device that will be integrated with the steam Turbine.
Siemens Energy Team Xavier Montesdeoca (XM) Robert	XM: Steam turbine frame owner/ Team Coordinator RH: Blade vibration analyst expert for current approach	Support in the Steam turbine health monitoring and design analysis, engine testing of embedded sensors

Project Overview and 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

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

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

Need for Real-time Online Monitoring for Blade Vibration Monitoring

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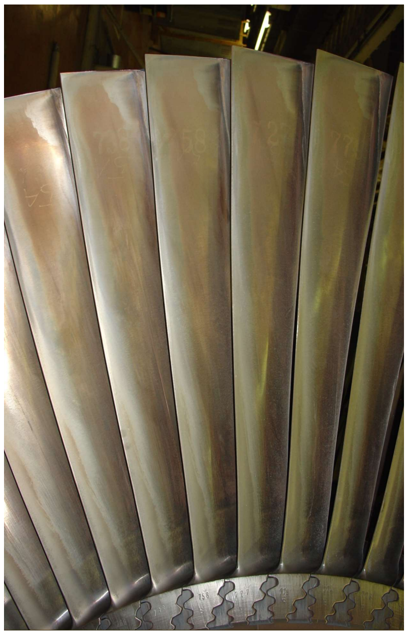
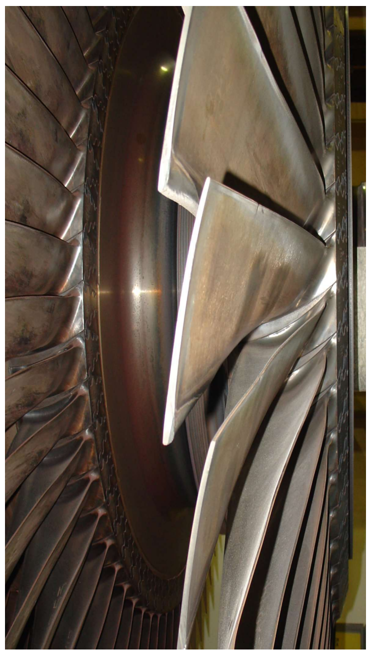
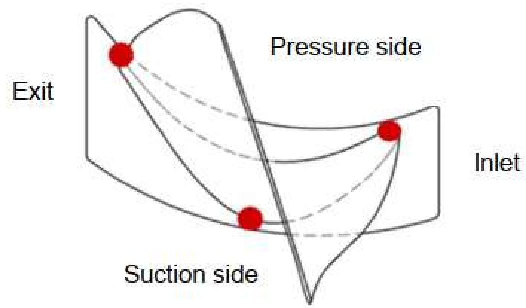
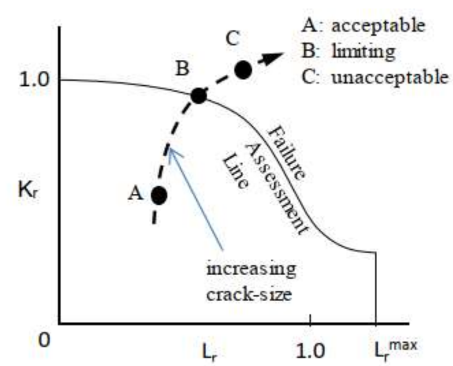


Water droplet induced blade root cracking for L0 blades in steam turbine

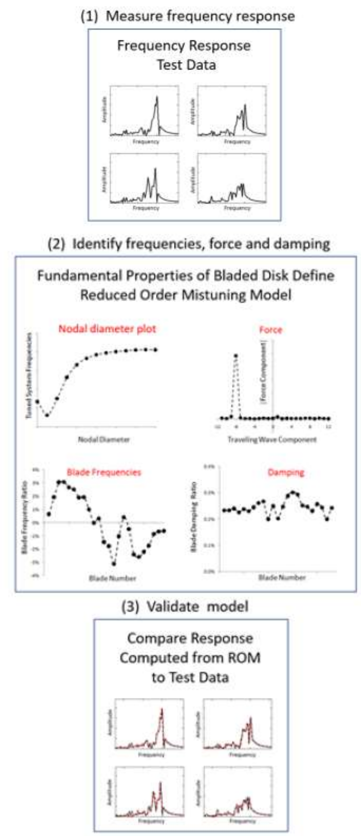




Life limiting locations in blade root



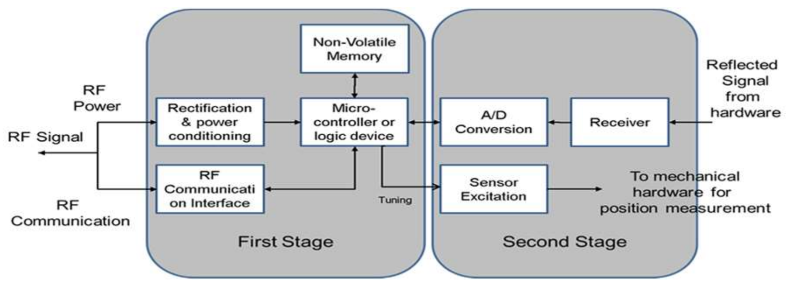
Life limiting locations in blade root



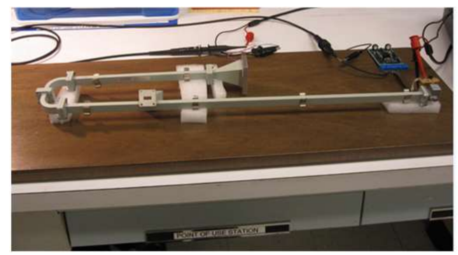
Detection of cracks in turbomachinery blade via online monitoring

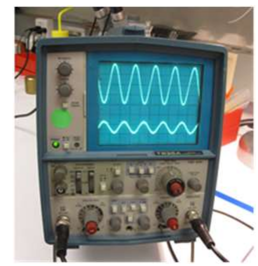
New Generation of sensing utilizing an RF modality with miniaturized high efficiency antenna structures

Architecture

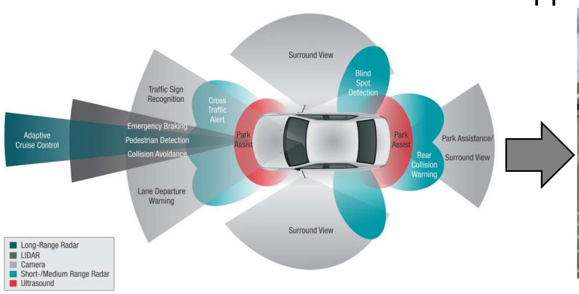


Lab setup

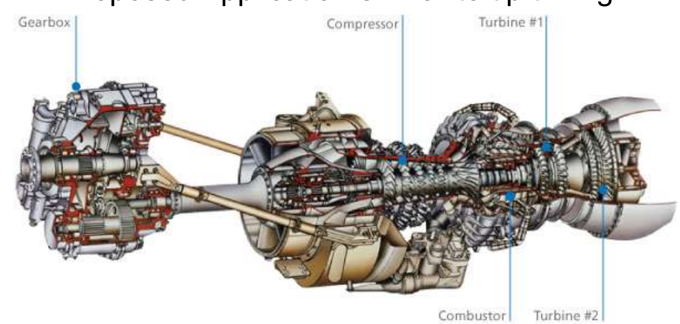




Mobile Application



Proposed Application similar to tip timing



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

Task 2.0 – Demonstrate component scale up efforts for embedded sensors

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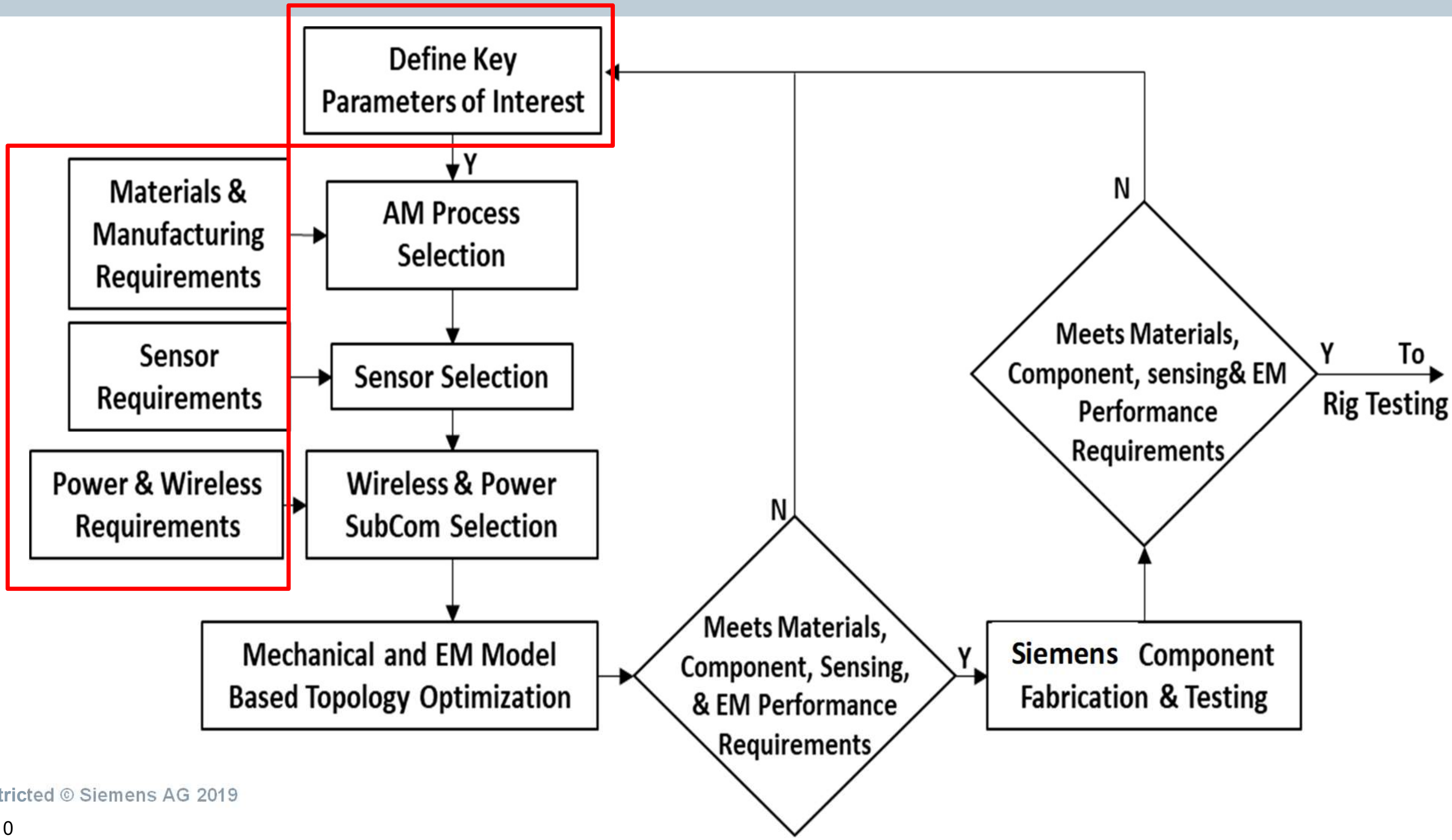

Simulated Sensor Performance

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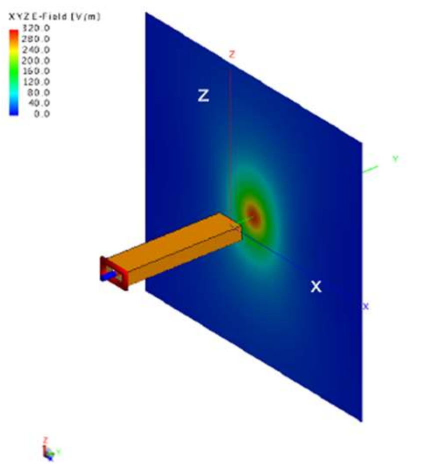
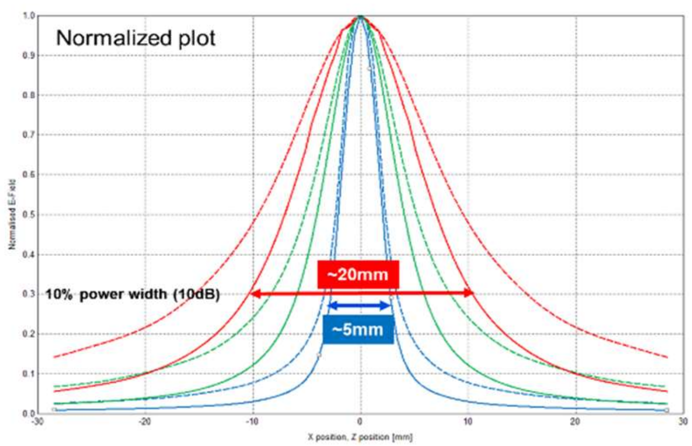
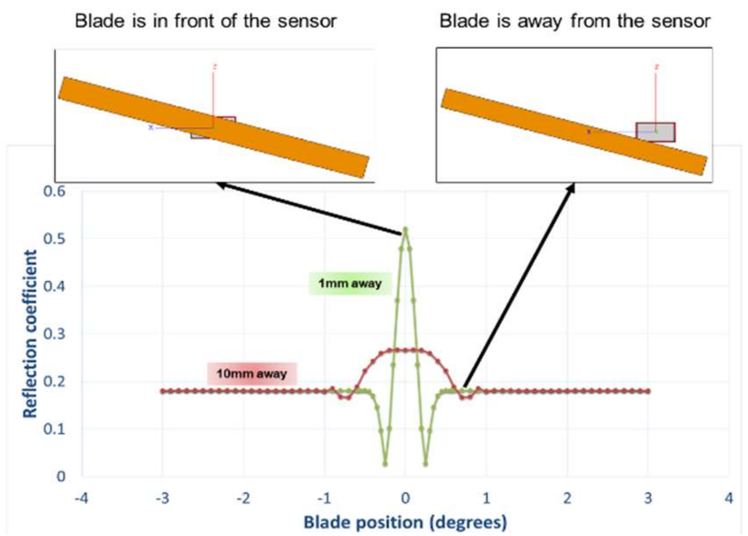
- A preliminary performance analysis of the Radio Frequency/Microwave probe was investigated.
- Waveforms as blade sweeps across the aperture were simulated for two extreme clearances.
- The sensor was not optimized for best performance and does not include proper protective packaging/housing for its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

60 GHz, at 5 mm away from sensor



Illumination field at 1 mm, 5mm and 10mm away from sensor





RF-based Blade Tip Timing Sensor

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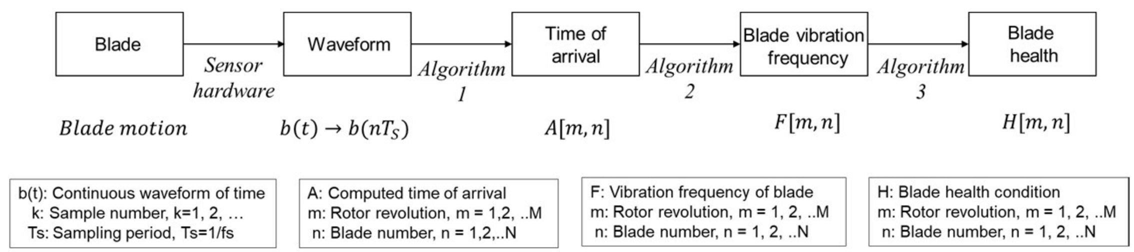
- Blade vibration monitoring system aims to assess changes in vibration frequency of blades over time.
- RF/MW based blade tip timing sensor hardware consists of a transceiver, a waveguide and sensor.
- Received signal waveform provides information about the position of the blade with respect to aperture.

Waveform

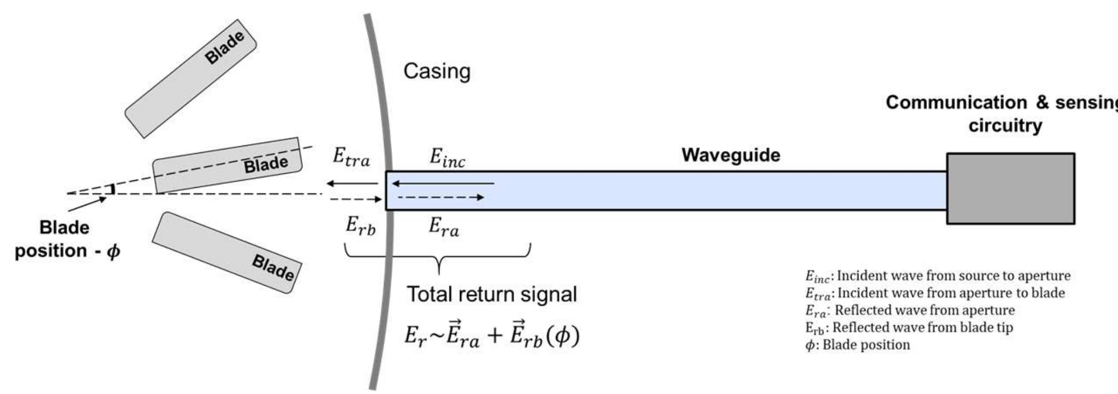
$$E_r \sim \vec{E}_{ra} + \underbrace{\vec{E}_{rb}(\phi)}$$

Carries blades position information

Functional block diagram of a generic blade vibration monitoring system



Schematic of an RF-based sensor for blade vibration monitoring

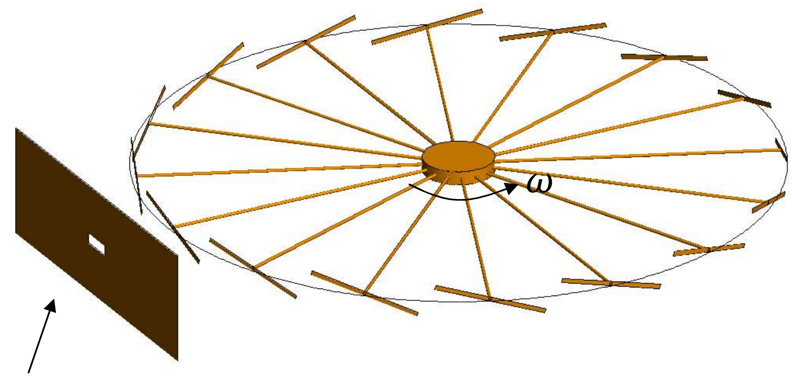


Benchtop Model for Technology Validation

- Aims to record the return signal variation with respect to various blade tip positions.
- Able to test the detectability of blade tip by the microwave sensor at various positions with respect to aperture, while preserving compact size and reasonable data rotor speed and data sampling speed.
- The setup will preserve the followings from the actual model: (1) blade cross section width, (2) number of data points collected per arch length, (3) arc length distance between the blades, and (4) sensor aperture size and location.
- Rpm, radius and number of blades are adjusted as shown in the table below.
- The setup will allow the adjustment of clearance distance between 1mm - 10mm.
- The setup will not allow to replicate the vibrational modes observed in actual set up due to reduced rpm and reduced length.
- As blade tips, aluminum rectangular cross sections with 3.1mm width and 80mm length will be used. Tilt angle is 15.4° .

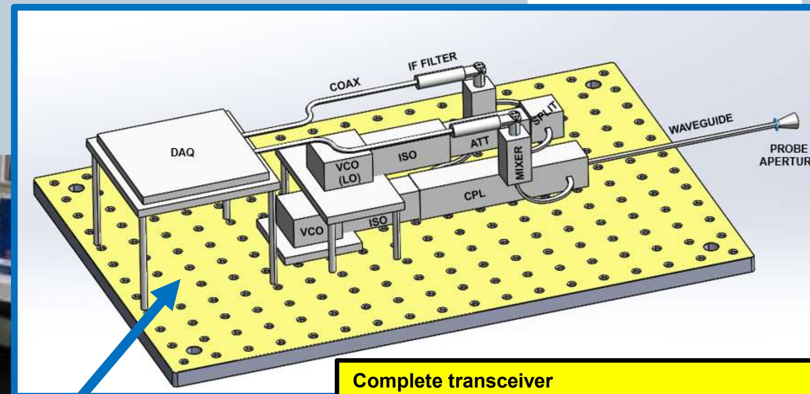
		Actual	Benchtop
rpm	NA	3600	36
r	m	1.6	0.2
N (number of blades)	NA	64	8
Ns over blade width	NA	321	321
Blade cross section width	m	0.0031	0.0031
Blade to blade angle	degree	5.625	45
w	rad/s	376.9911184	3.769911184
fs	MHz	62.459	0.078
tip speed	m/s	603.1857895	0.753982237
Arc length between blades	mm	157.0796327	157.0796327
Blade to blade arc length/blade width	NA	50.67084925	50.67084925

Keep same between actual system and benchtop

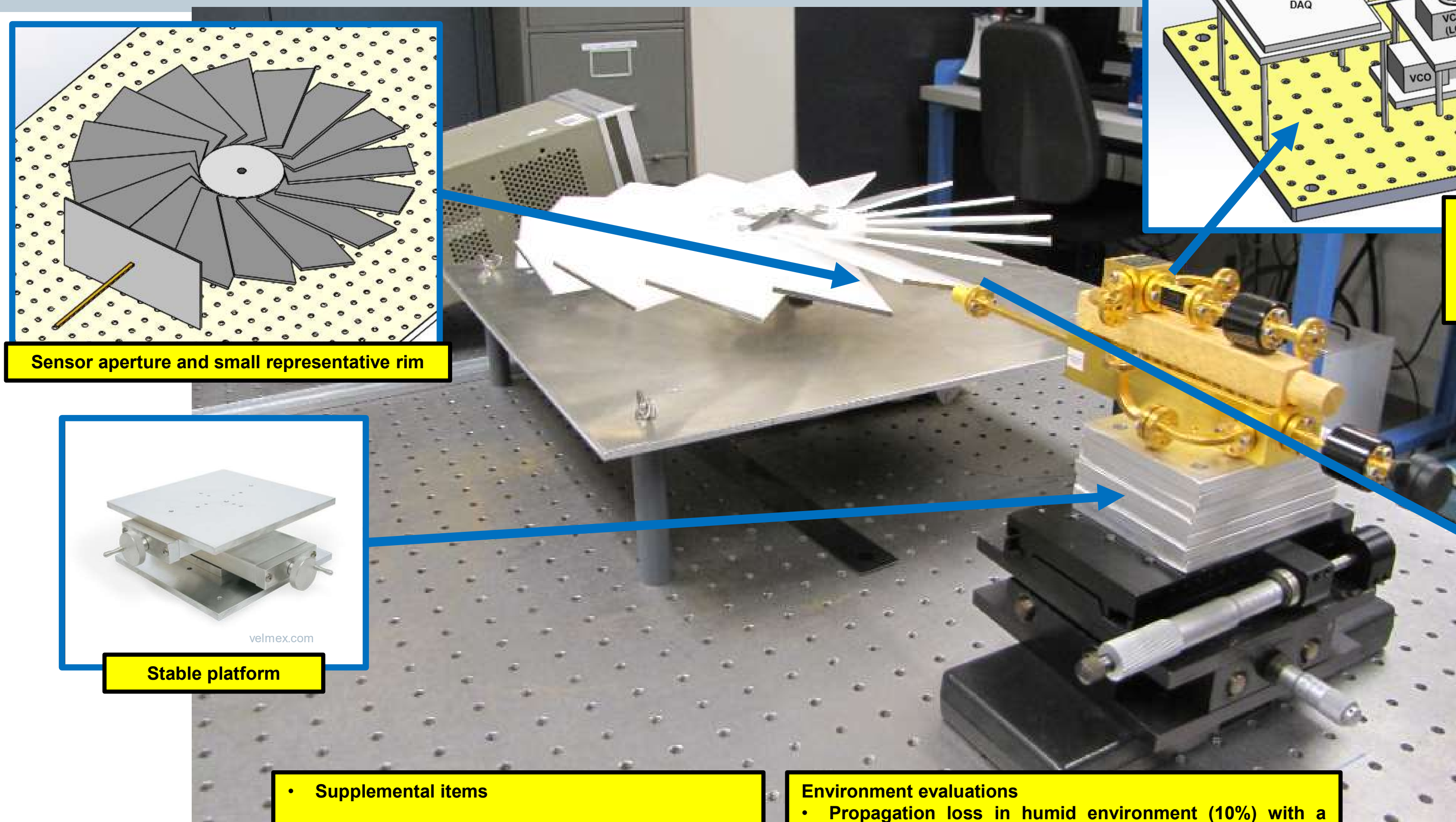


Sensor aperture and small representative rim
Blade cross sections – Aluminum
Rest of the structure will be made of relatively less reflective plastic material

Benchtop Test Rig Development

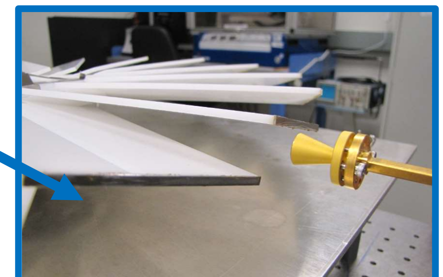


Complete transceiver
- Synthesizers (selected, lead time)
- Mixers (selected, no significant lead time)
- Detector (selected, no significant lead time)
- DAQ/Processor (not selected yet)



Sensor aperture and small representative rim

Stable platform



Sensor design (open points)
- Sensor apertures
- Aperture covering/housing, sealed front-end
- Sensor material for environment
- Effect of lens

- Supplemental items
- One per revolution sensor
- Sensor calibration setup on micrometer platform

Environment evaluations
- Propagation loss in humid environment (10%) with a network analyzer setup
- Temperature evaluation in simulation or experiment.

Measurement Setup - Schematic

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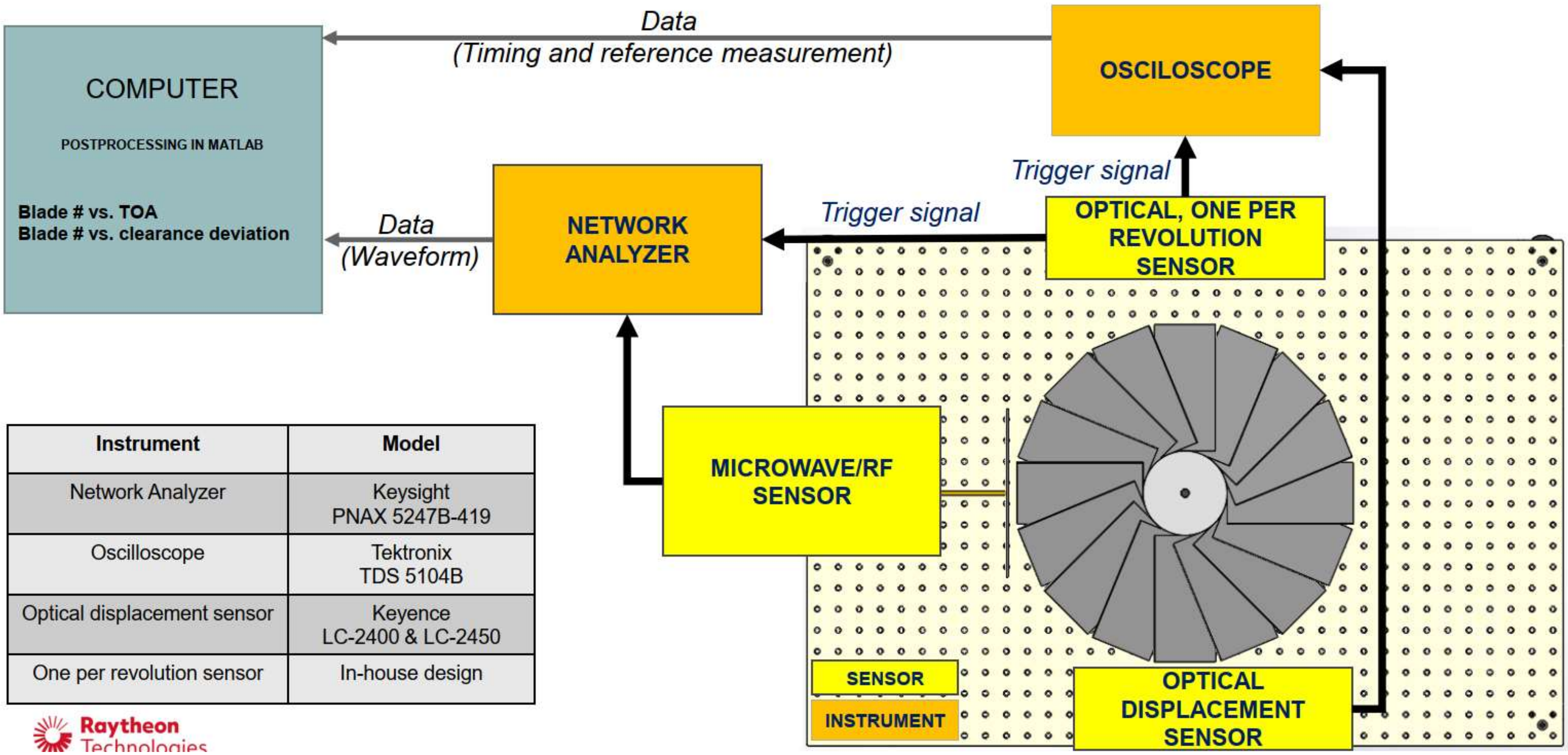
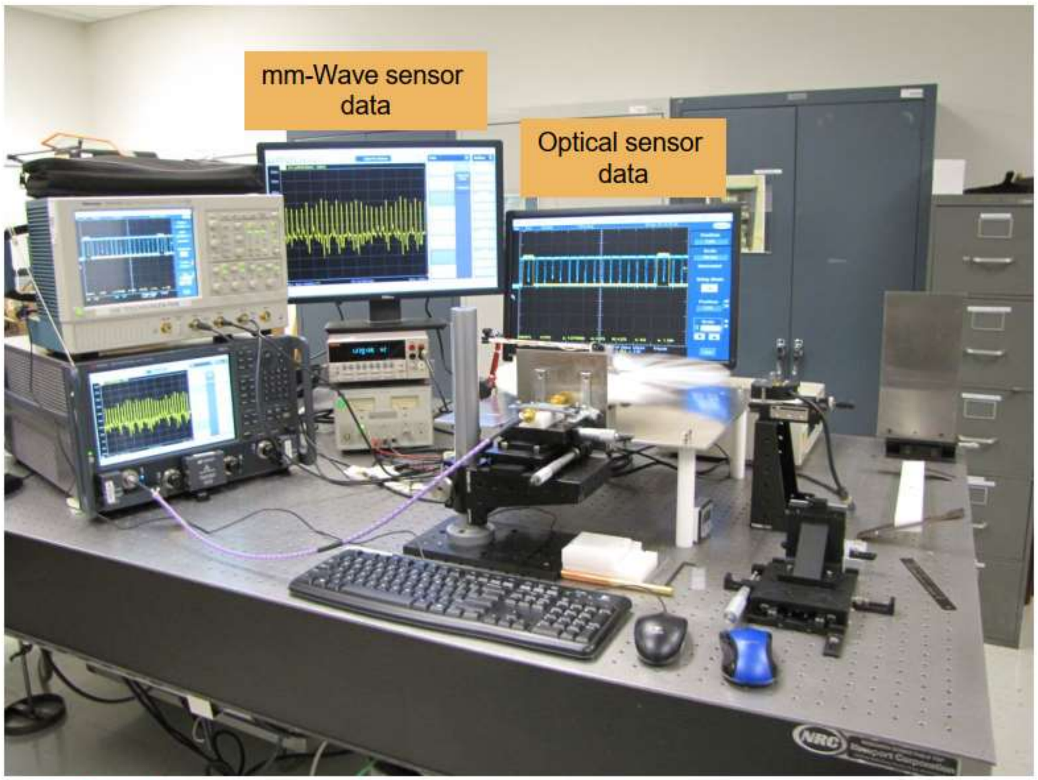


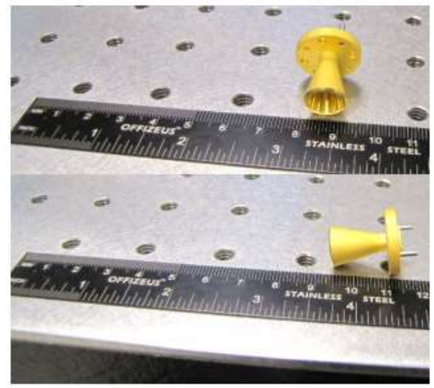
Instrument	Model
Network Analyzer	Keysight PNAX 5247B-419
Oscilloscope	Tektronix TDS 5104B
Optical displacement sensor	Keyence LC-2400 & LC-2450
One per revolution sensor	In-house design

Raytheon Technologies

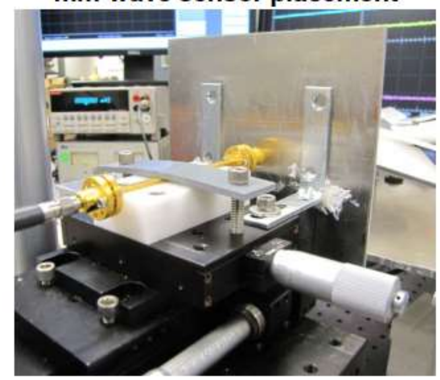
Measurement Setup



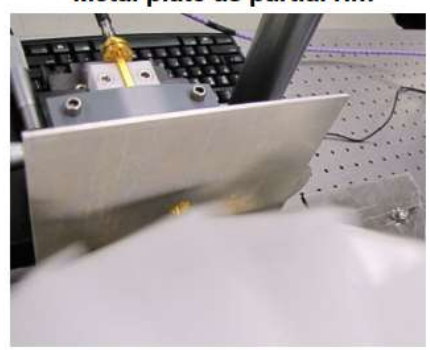
mm-wave sensor



mm-wave sensor placement



Metal plate as partial rim



Optical sensor

Collected Sensor Data from Benchtop Model

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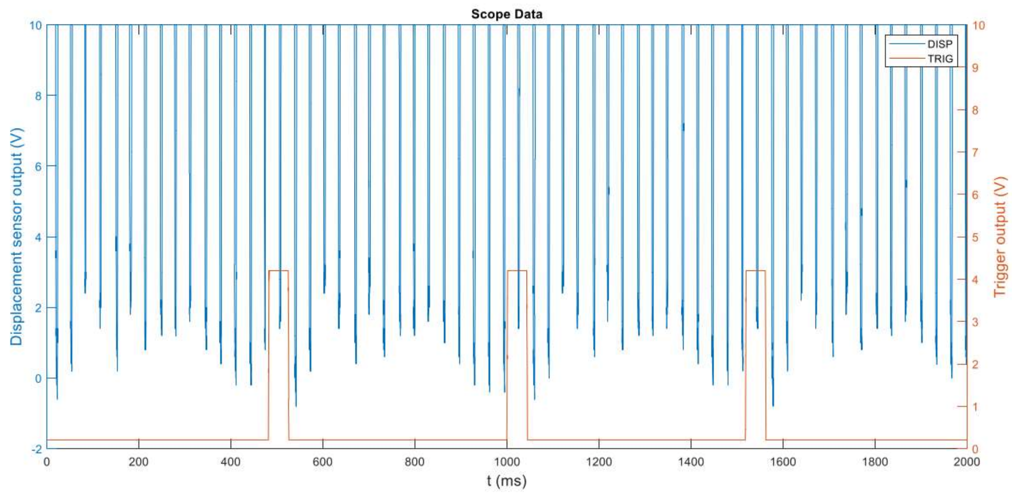
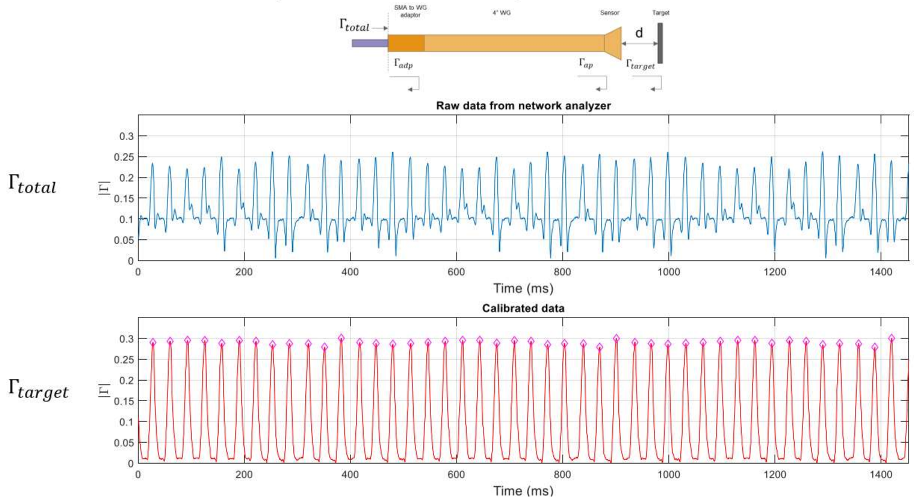
Collected data from optical sensors (displacement and one per revolution sensor) by the scope.



- mm-Wave sensor data captured with network analyzer and extracted blade reflection are shown.



- **Time of Arrival (TOA): Middle point of the waveform decided by intersecting the selected the raising and falling edge of sensor output**

- **Clearance: Averaging the displacement value around TOA within ±1ms (100 data points)**

Data Analysis: mm-wave vs. optical sensor

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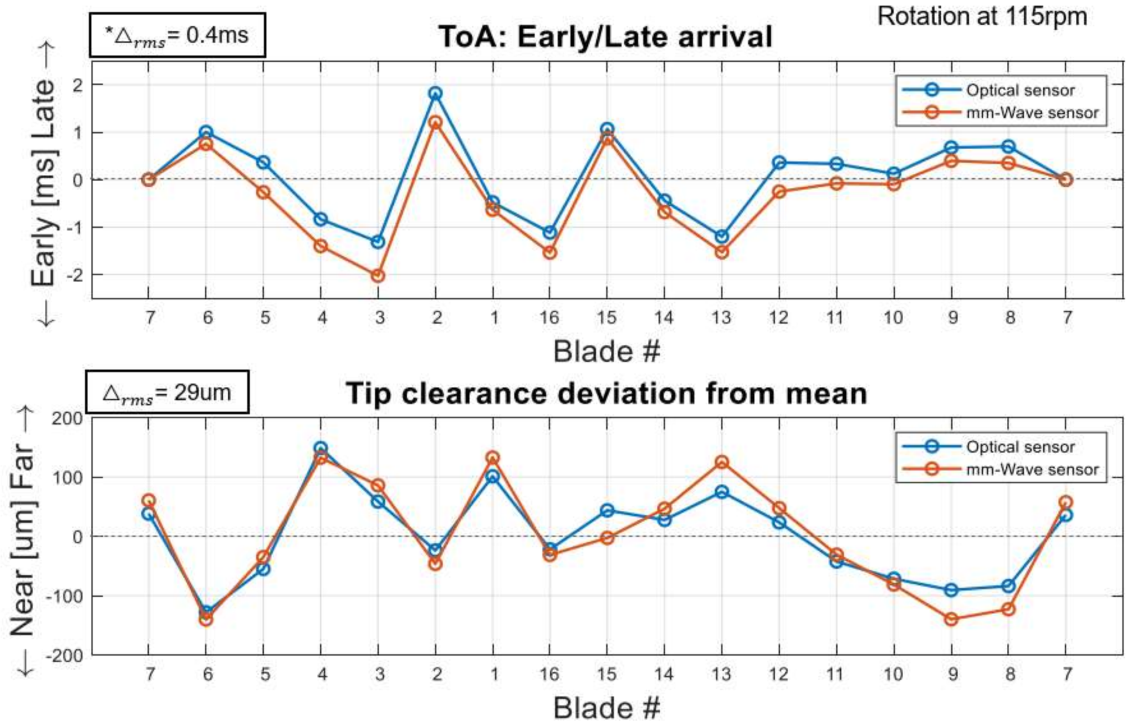
Comparison for TOA and tip clearance data obtained by mm-wave (62.5 GHz) and optical sensors when blade is 7.5mm away from the mm-Wave sensor aperture



Root mean square deviation between mm-wave and optical sensor

$$\triangle_{rms} = \sqrt{\frac{\sum_{i=1}^{N}\left(x_{mw} - x_{opt}\right)^2}{N}}$$

x_{mw}: mm-Wave sensor data

x_{opt}: optical sensor data

N: number of blades, N=16

Measurement with Real Blade

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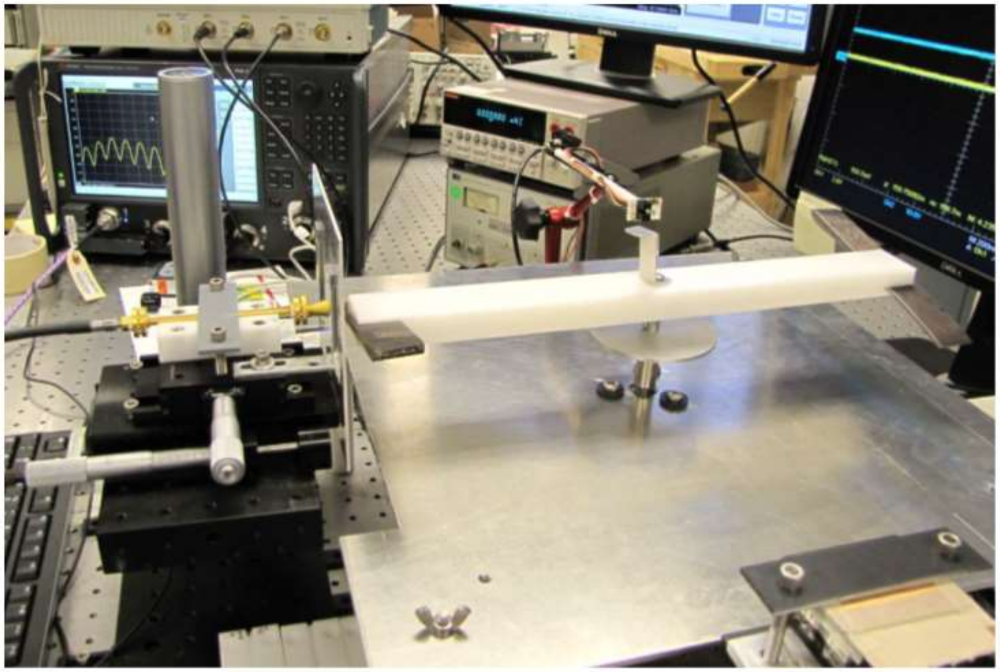
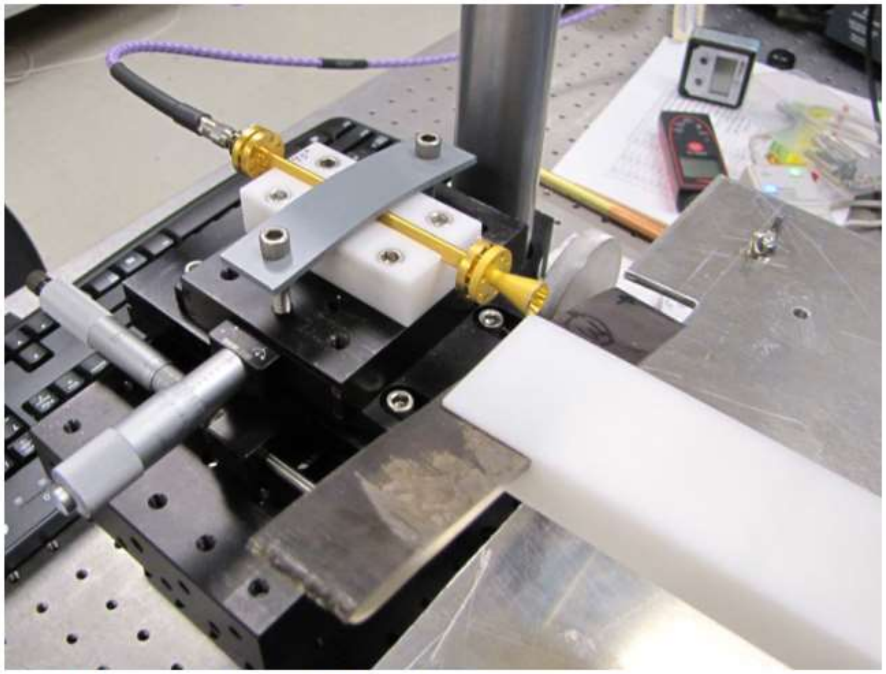
Static measurement



- Measurements taken when blade stands still while metal plate is in place.
- Waveform measurement: Sensor movement parallel to the blade in steps.
- Clearance measurement: Sensor movement normal to the blade in steps.

Dynamic measurement



- Measurements were taken when blade was rotating.
- No metal plate used because the blade tip hits the metal plate due to its longer length as compared to representative blade in earlier slides.

Task 3.0 – RF Communications package development

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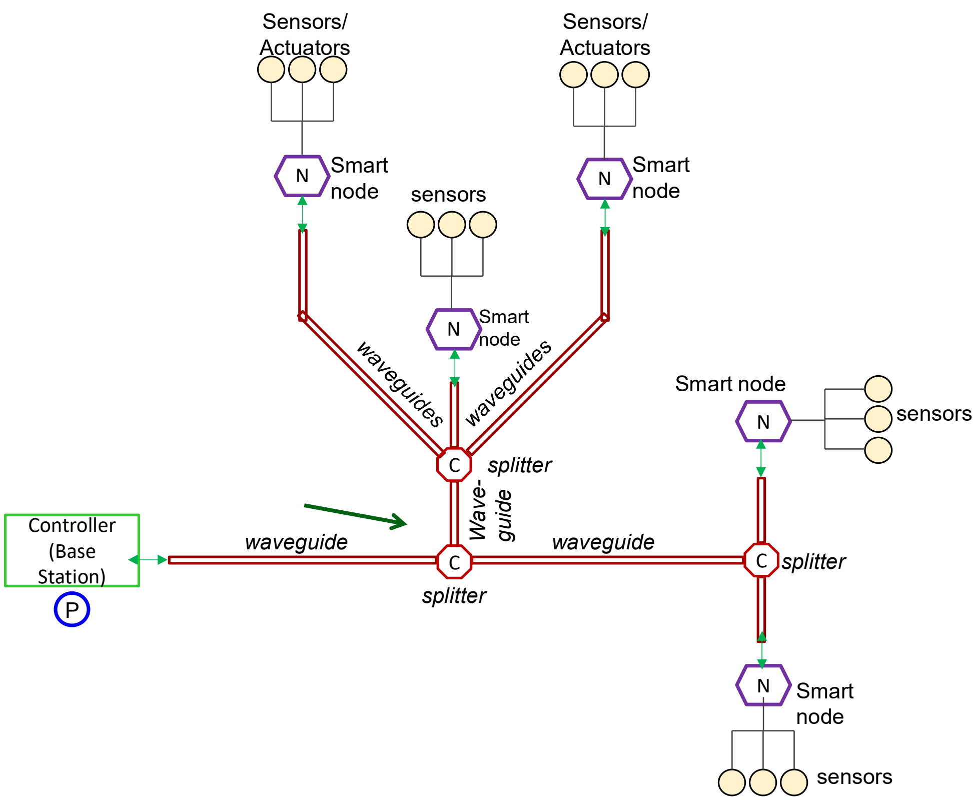

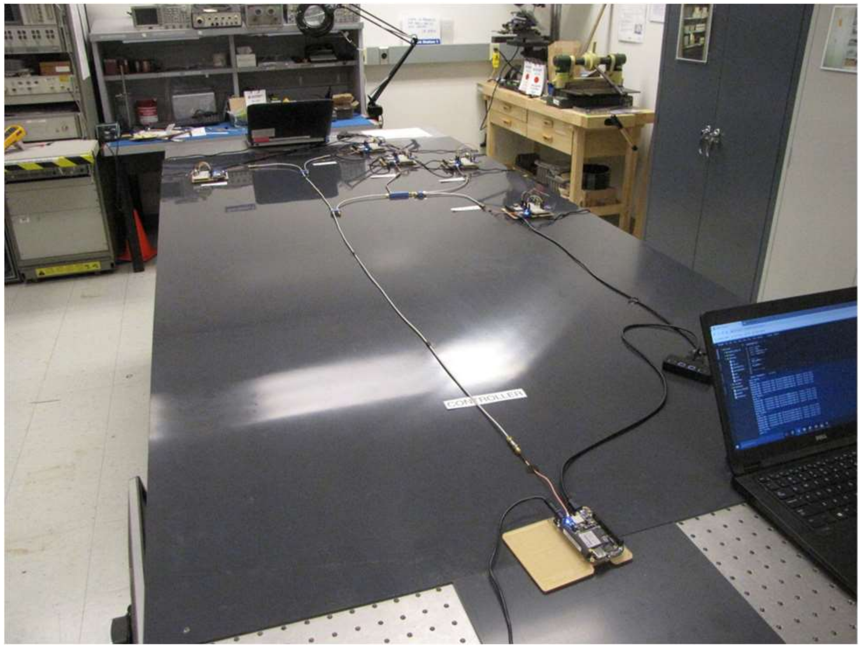

Benchtop Model and RF Communication Package Development

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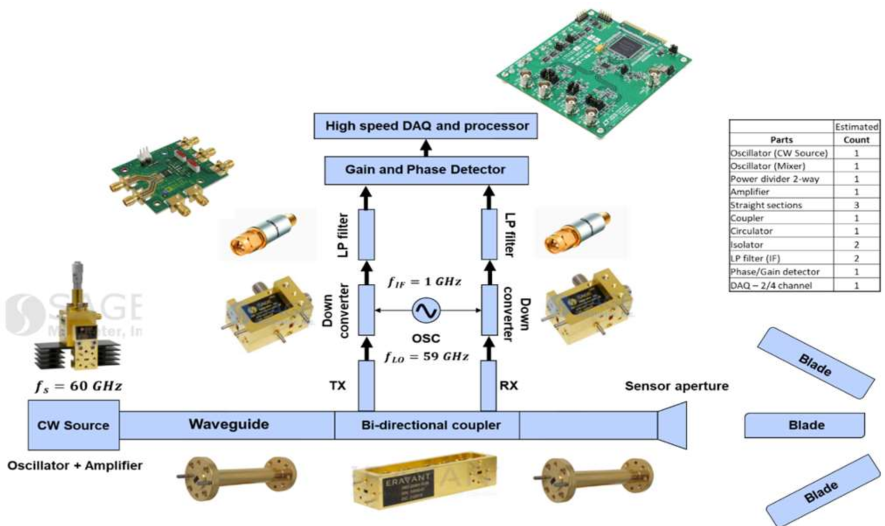
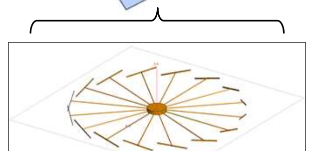
Preliminary design of bench-top model for testing sensor and communication/sensing circuitry

Communication/sensing circuitry for benchtop model



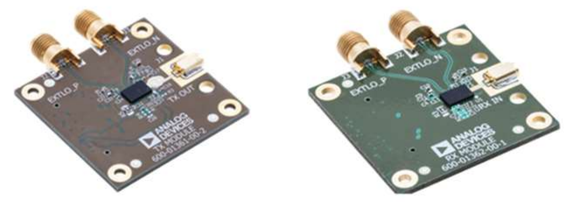
Parts	Estimated Count
Oscillator (CW Source)	1
Oscillator (Mixer)	1
Power divider 2-way	1
Amplifier	1
Straight sections	3
Coupler	1
Circulator	1
Isolator	2
LP filter (IF)	2
Phase/Gain detector	1
DAQ – 2/4 channel	1

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)

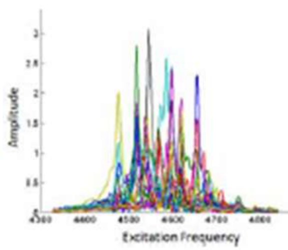


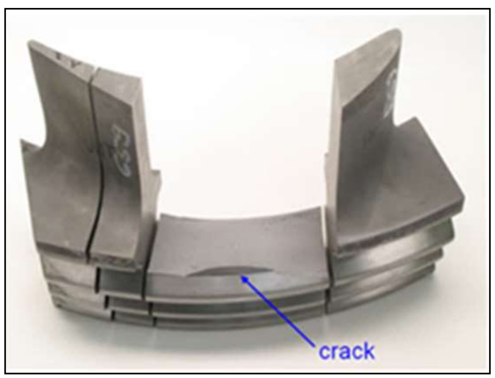
TX RX

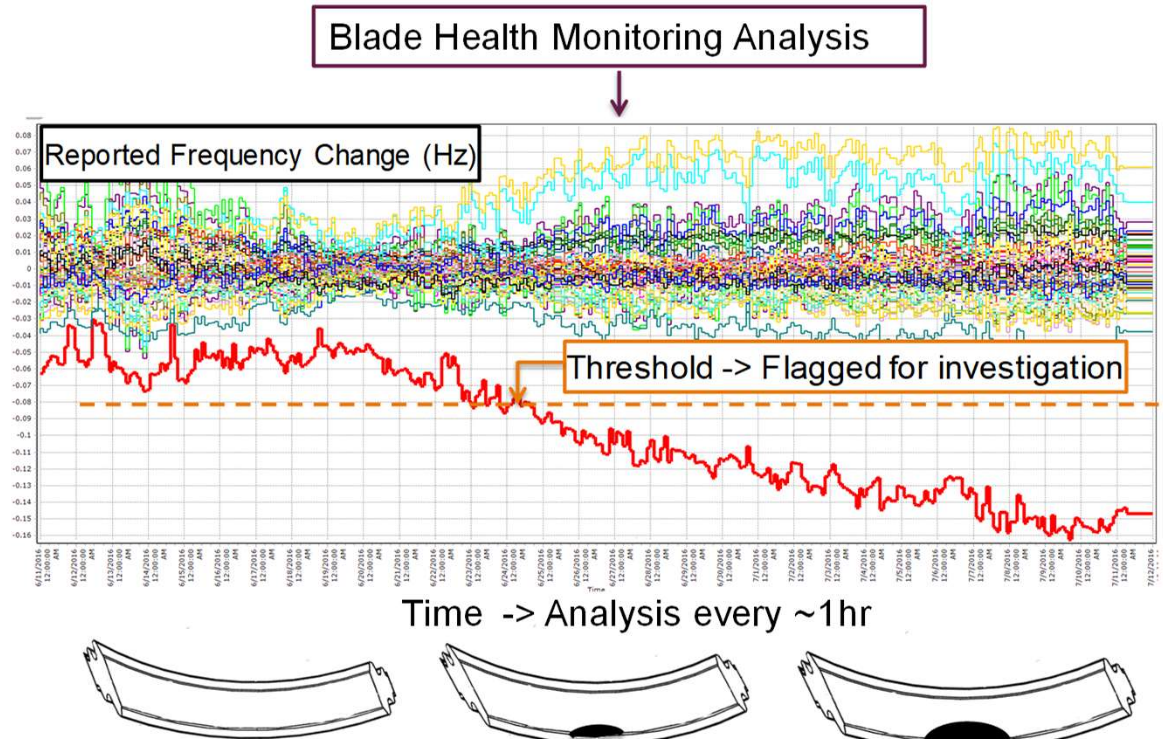
Waveguide design/manufacturing at RTRC

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

- Nodal diameter plot
- Mistuning ratios
- Forces
- Damping







Task 5.0/6.0 - Manufacturing Test Article and Engine Testing for Comparison with Existing Blade Vibration Monitoring

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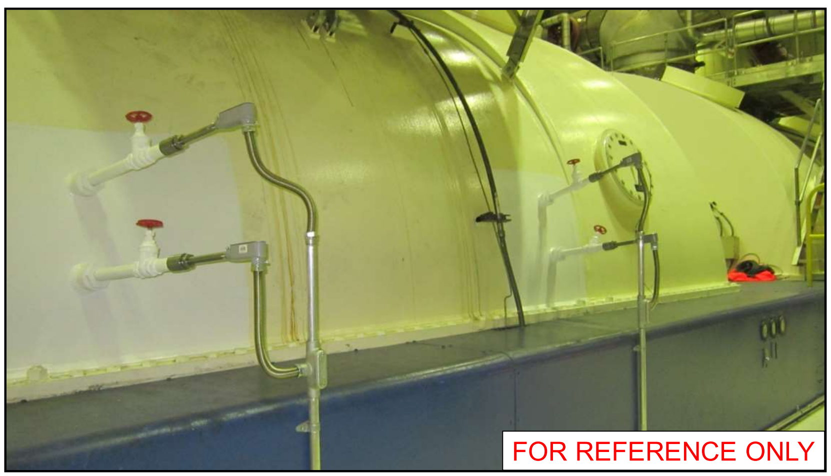
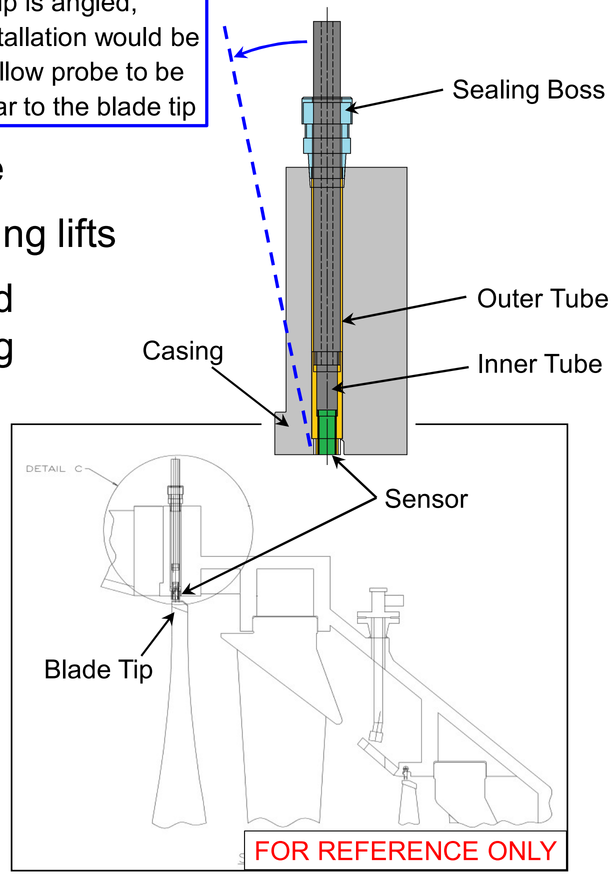
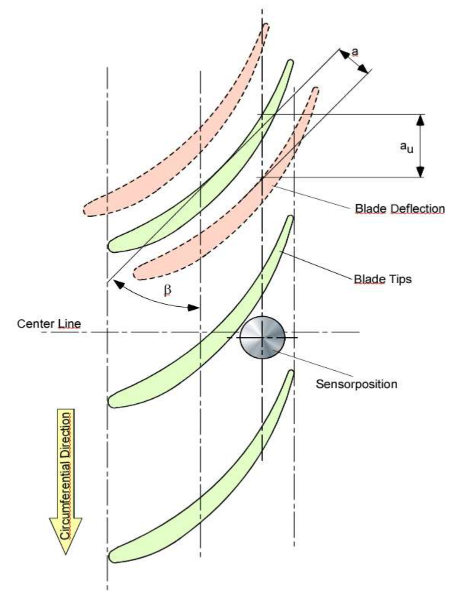
- Probe installation features
  - Ease of access for maintenance
  - Probes can be removed / replaced in-service
  - Probe(s) in upper half to be removed for casing lifts
- Recommend to install 3 probes, equally-spaced (120 deg apart) around circumference of casing





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



Progress Highlights

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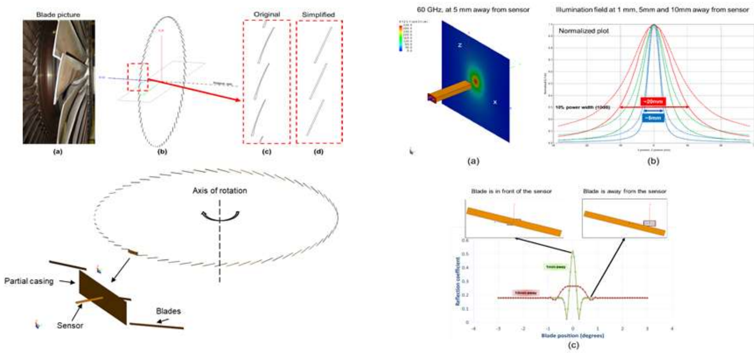
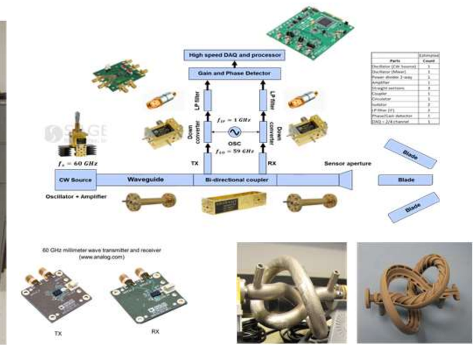
(i) Simulation model and performance

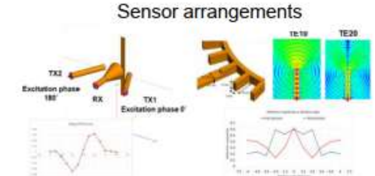


(iii) Benchtop model and testing

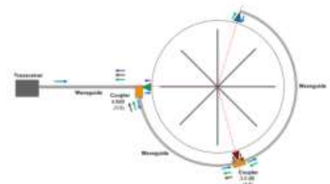


Low SWaP transceiver

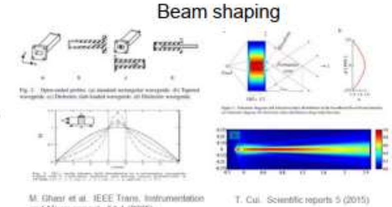
Sensor arrangements



Multiplexing



Beam shaping



Potential next steps

- **Integration with Siemens' rig, compare with benchtop results**
- **Evaluating the waveform data with Siemens' data analysis algorithms**
- **Sensor multiplexing**
- **Sensor configurations and field/beam shaping for improved performance**
- **Sensor design for steam turbine environment (high temperature and humidity)**
- **Dedicated low SWaP mm-Wave transceiver design**

Conclusions

- Team has focused on studying the blade characteristics and sensor hardware which consists of RF-based sensor components and communication/sensing circuitry.
- A mm-wave sensor based on reflectometry at 60 GHz band that measures blade tip timing and tip clearance was tested. 62.5 GHz operation was considered in the presented results. Similar results were obtained when frequency is increased to 67 GHz (limited by the test instrument).
- Sensor utilizes linear polarization. Alignment of the polarization along the blade chord axis is best location, but the results are not sensitive to this orientation.
- Clearance measurements with high resolution (±1mil) at high data speed is possible.
- Detection of tip timing accuracy needs to be evaluated with Siemens' data analytics team to evaluate the waveform and data processing approaches with uncertainties to estimate the detection resolution and applicable algorithms.