INTEGRATED VEHICLE
HEALTH MANAGEMENT

A Microwave Blade Tip Clearance Sensor for Propulsion Health Monitoring

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Outline

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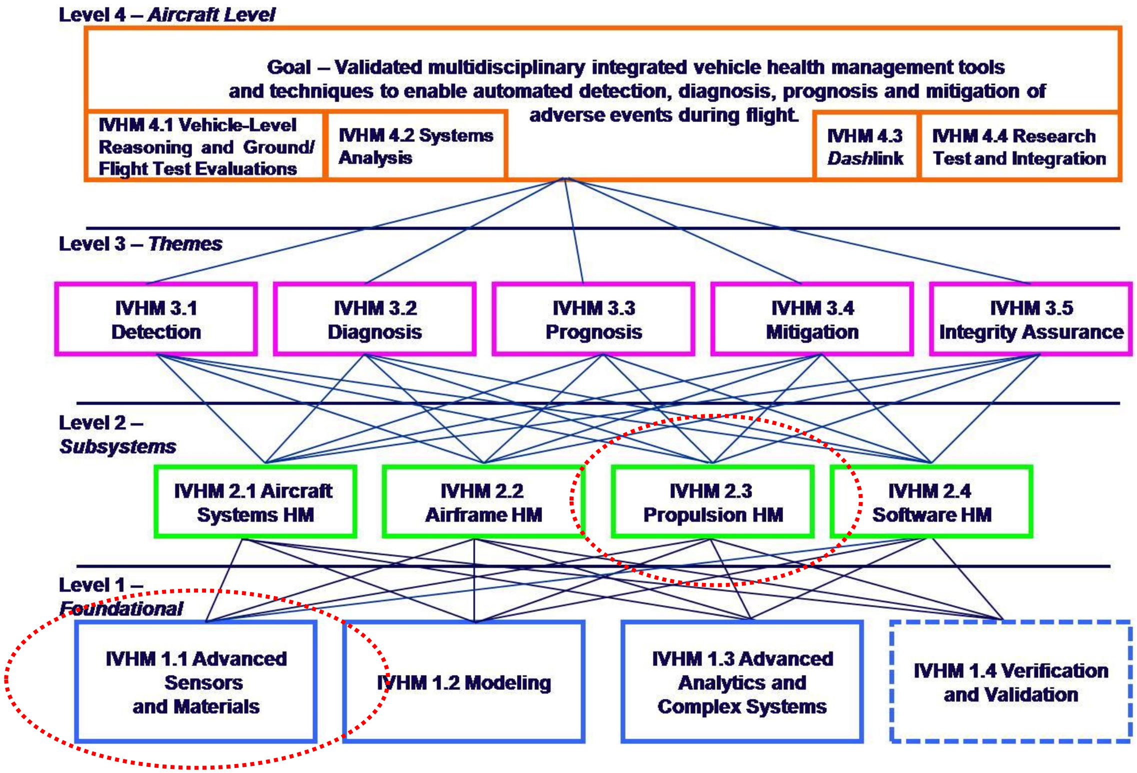


Problem Statement

- Microwave Blade Tip Clearance Sensor for in-situ structural health measurements of rotating components in the high temperature environment of a turbine engine
  - Blade Tip Clearance
  - Blade Tip Deflection (Time of Arrival)

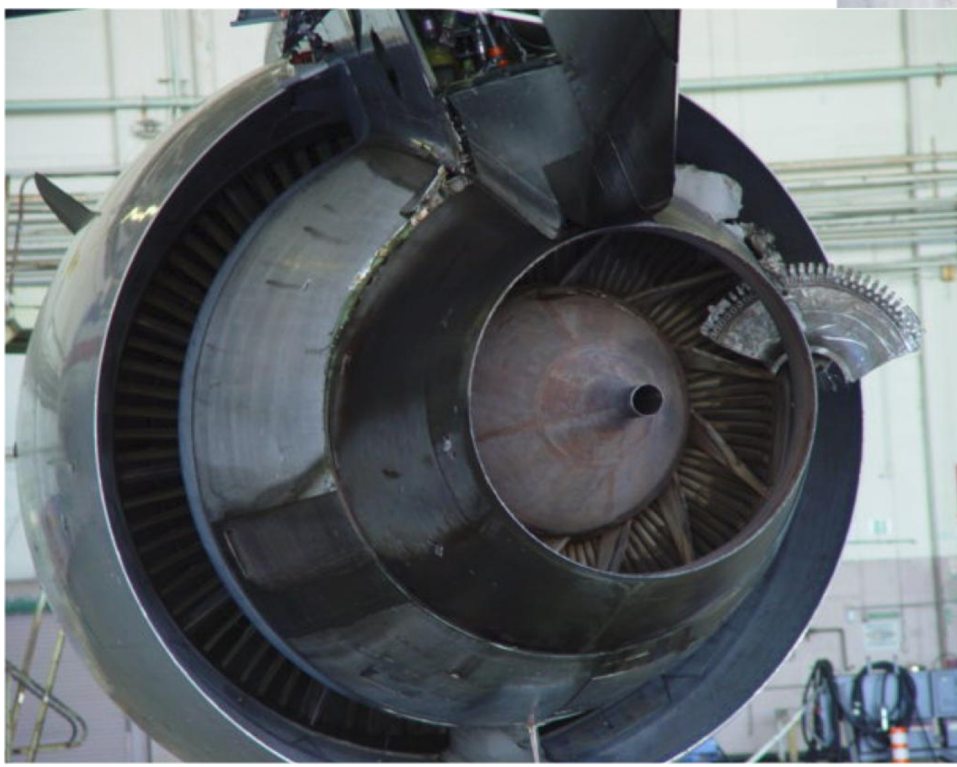
- The capability to make in-situ health measurements on a turbine engine is a need that has been identified by the IVHM community
  - High Pressure Turbine (HPT) and High Pressure Compressor (HPC) sections

- Why is it needed?
  - No sensor is currently being used in these areas now that can directly monitor blade & disk health
  - Currently rely on secondary measurements and scheduled based inspection & maintenance

- Federal Aviation Agency Report AR-08/24 "Engine Damage Related Propulsion System Malfunctions"
  - Damage in the HPT and HPC sections account for ~32% of damage events that caused engine removal for unscheduled maintenance
  - Damage in the HPT and HPC sections account for ~12% of "In Flight Shut Down" events

Problem Statement

AA 767 June 2, 2006 Engine Failure



Problem Statement

- Problem:
  - To date no commercial off-the-shelf sensor is being used in the hot sections of production aero gas turbine engine for health monitoring……….Reliable flight ready sensor for this purpose has not previously existed
  - Survivability and operation in the high temperature environment is major issue
  - Emerging area that is being developed, several technologies are being investigated by several entities…US AFRL, Engine manufacturers, Propulsion Instrumentation Working Group (PIWG)

- Microwave blade tip clearance sensor performance goals (aero engine applications):

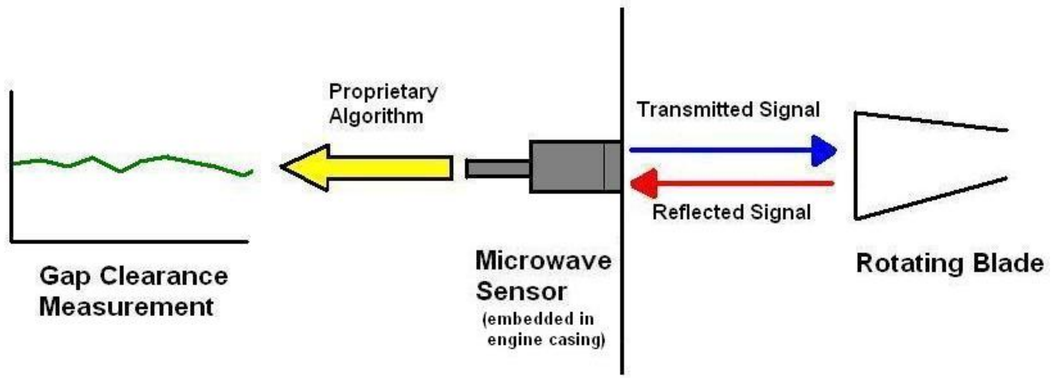
Measurement Range:	Accuracy:	Temperature:	Response:
Up to ~6 mm (~0.250 inches)	~0.025 mm (~ 0.001 inch)	~900ºC (~1600ºF) un-cooled ~1200ºC (~2200ºF) cooled	> 1 MHZ (5 MHZ typical, in theory up to 25 MHZ possible)

- State-of-the-art for other clearance sensors:
  - Optical — Most accurate but more applicable for use in labs, require complex cooling for high temperature usage
  - Eddy Current — Tend to be limited in frequency response and at temperature ~1000˚F (540ºC)
  - Capacitive — Competing technology. Seems promising. However commercially available products are somewhat limited in frequency response

Background

- Microwave tip clearance sensors and measurement system developed by **Radatec, Inc (currently Vibro-Meter SA)** through the NASA Small Business Innovation Research (SBIR) Program and other commercial contracts
  - Tip clearance measurement system with prototype probes delivered in 2006/2007 as part of a Phase III SBIR commercialization contract
  - First generation (5.8GHZ) production probes delivered in 2008
  - Second generation (24GHZ) probes delivered in 2009

- Sensor works on principles that are very similar to a short range radar system
  - Probe is both a transmitting and receiving antenna
  - The sensor sends a continuous microwave signal towards a target and measures the reflected signal
  - The motion of the blade phase modulates the reflected signal
  - The phase difference of the reflected signal is directly proportional to the distance between the sensor and the target

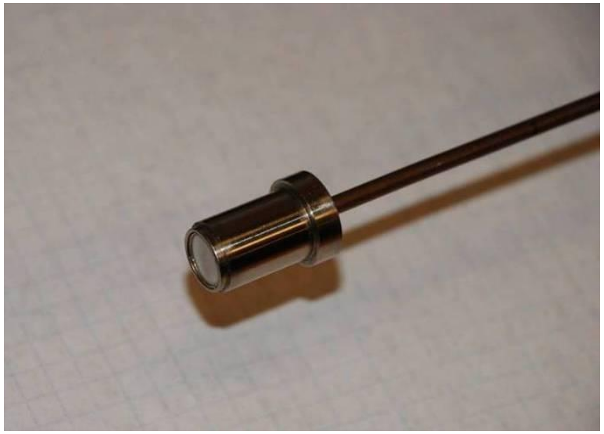


Background

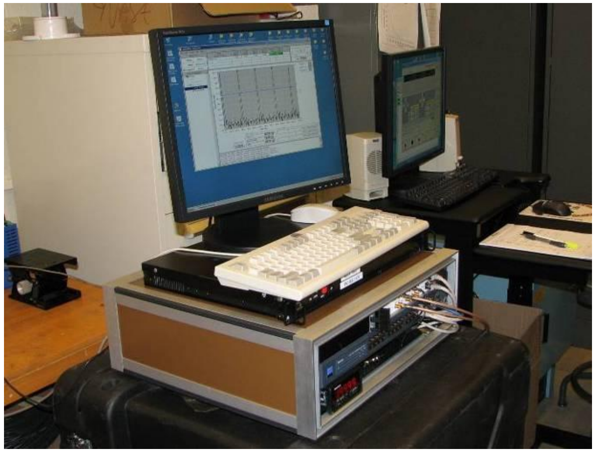
Sensor Overview

- Clearance Probe
  - Contains Transmitting/Receiving Antenna
  - Installed in the engine casing
    - First generation probes (5.8 GHZ) are designed to be used on "large" rotating machinery
      - Measurement range ~25mm (~1")
    - Second generation probes (24 GHZ) are for aero engine size hardware and clearances
      - Measurement range ~6mm (~1/4")

- Sensor Electronics
  - Contains the microwave generator and detector
  - Data acquisition & display computer
  - Located off board of test article or engine
  - Connected to sensors via co-axial cable



Microwave Tip Clearance Probe



Microwave Sensor Electronics

IVHM milestones(s) being worked

- Supporting two IVHM milestones

- 1.1.1.11 Demonstrate microwave sensor system's ability to make blade health measurements on a rotating blade
  - » Measure blade inclinations < +/- 5º and absolute tip clearances on the order of 250 microns in a lab environment (FY10Q1)
  - » Measure blade inclination of +/- 5º and tip clearances of 100 microns in an ambient environment of 150ºC (FY10Q3)

- 2.3.1.2 Demonstrate multiple sensor technologies to enable detection in propulsion structural health monitoring systems
  - » Demonstrate rotating structural health using a microwave sensor system at 800ºC in an operating engine environment (FY10Q4)

Approach

- Milestone is to use this technology on an actual engine in a relevant high temperature environment

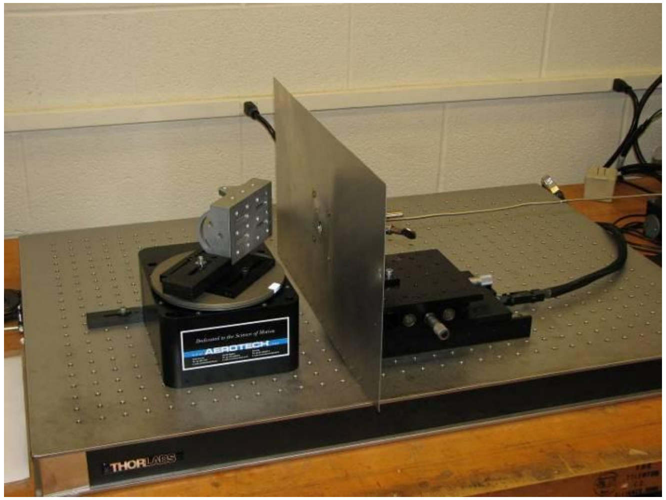
- The use of microwave sensors for making tip clearance and tip deflection (tip timing) measurements is a new concept
  - Techniques on their use and calibration need to be developed
  - The sensor's overall accuracy and ability to make clearance measurements need to evaluated

- Three experiments were accomplished in FY08/FY09 as a means of building toward primary goal of using these sensors on an engine
  - Calibration Experiment
  - Axial Vane Fan Experiment
  - NASA Turbofan Experiment

- Two additional experiments currently in process
  - Blade Tip Deflection Experiment
  - Calibration Experiment (T700 Rotor)

Results – Calibration Experiment (FY08)

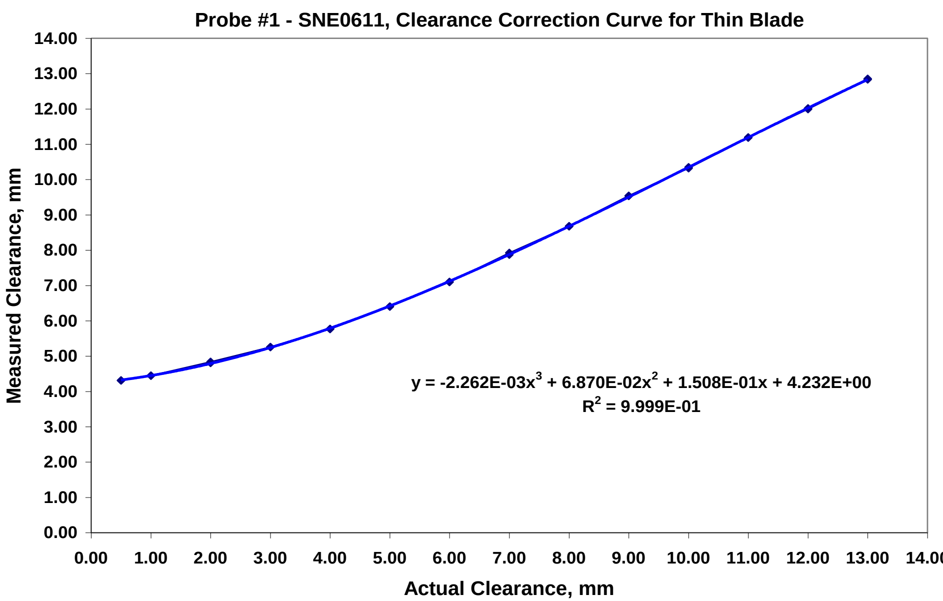
- Objectives:
  - To develop calibration techniques
  - To evaluate 5.8GHZ probe's accuracy
    - Measurements are very specific to the blade geometry being measured
    - Sensor makes an average measurement of the geometry that is within the spot size caste on the blade
    - Need to map this average reading to the actual minimum clearance



Probe Calibration Rig

- Calibrated the microwave sensors against two geometries
  - "Thin" compressor blade (~6 mm thick)
  - "Thick" simulated fan blade (~26mm thick)

- Outcome / Results:
  - Developed techniques and infrastructure required for calibration
  - Observed worst case error of ~+/- 0.15mm during this initial experiment
  - Reduced to ~+/- 0.05mm in subsequent calibration experiments for use on NASA Turbofan

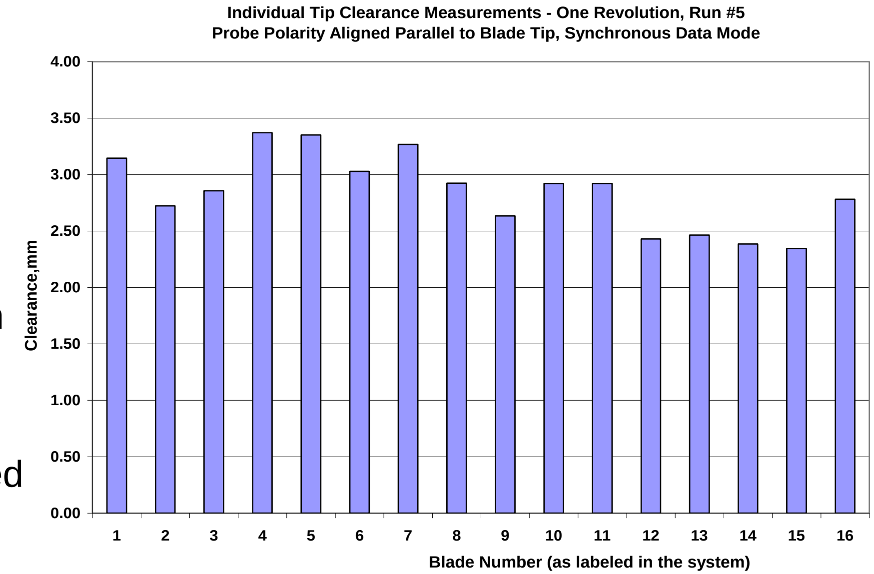


Calibration Curve – Thin Blade

Results – Axial Vane Fan Experiment (FY08)

- Objectives:
  - Use the microwave sensor to make clearance measurements on actual rotating machinery
  - Evaluate how well the calibrations accomplished in the laboratory transfer into an actual use in the field
- Axial Van Fan
  - 1.8 M Diameter, operates at 1200 RPM
  - 16 Blades, ~26 mm thick ,~362 mm long, ~267 mm chord length
  - One 5.8GHZ probe installed
- Outcome / Results:
  - NASA's first use of these sensors on actual rotating machinery
  - Acquired data for several operations of the fan
  - Measured clearances were consistent with known operation of fan
  - Calibrations done in the lab against a simulated geometry appeared to transfer well into actual use in the field
  - Qualitative test to gain experience w/ sensors

Axial Vane Fan at the Glenn Research Center's 10x10 Wind Tunnel



Axial Vane Fan – Blade Tip Clearances for 1/Rev

Results – NASA Turbofan Experiment (FY08/FY09)

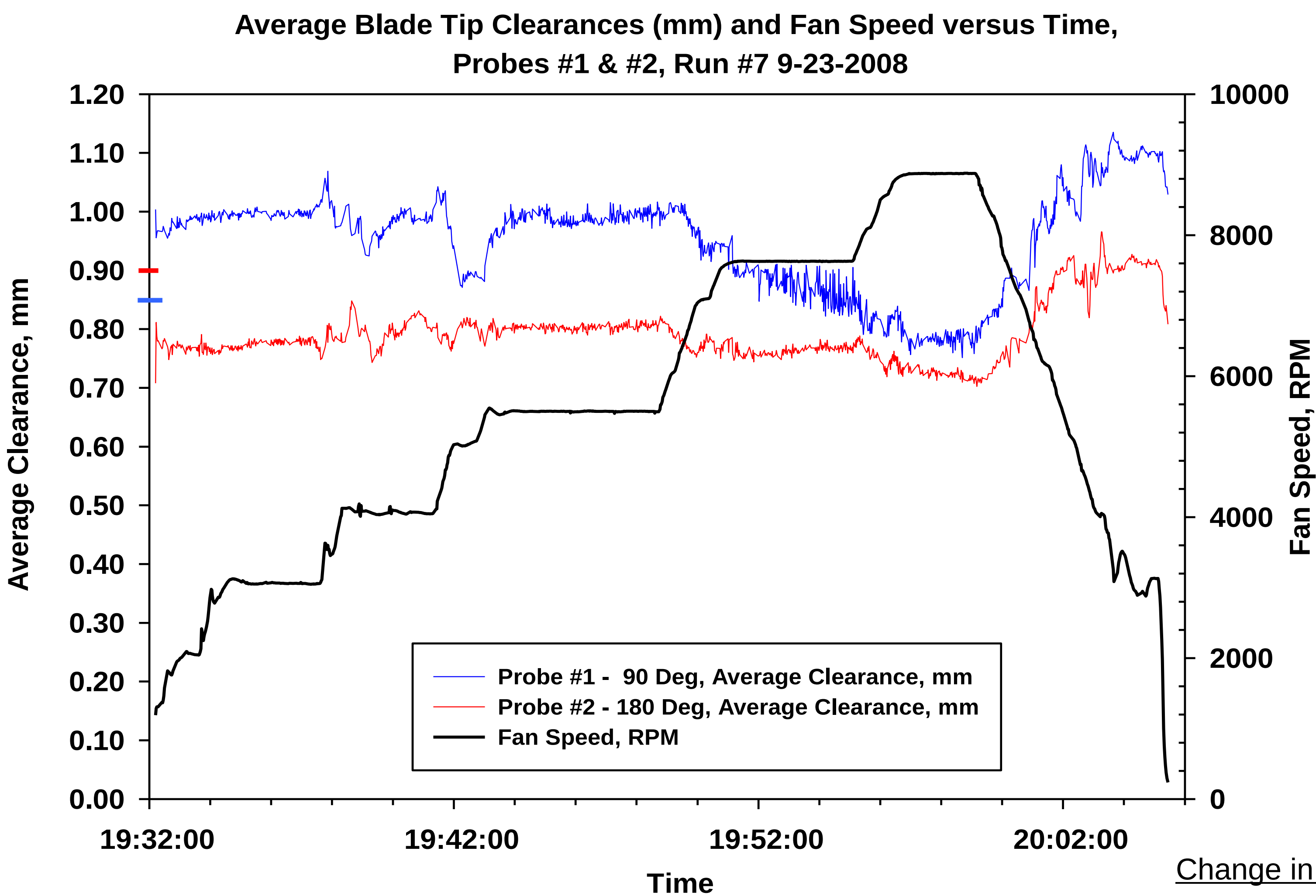
- Objectives:
  - Demonstrate the microwave sensors ability to acquire blade tip clearance measurements on an aero engine size test article and blades

- NASA Turbofan
  - Subscale turbofan propulsion simulator
  - 2 probes (5.8GHZ) installed, 90º apart
  - 18 Composite Blades
    - Blade tips were coated with nickel to allow measurement by microwave probes

- Outcome / Results:
  - Acquired tip clearance data for several test runs of the turbofan
  - The change in tip clearances measured during fan operation was in-line with previous data acquired with capacitive probes on earlier test entries
  - Demonstrated the sensor’s ability to make measurements on “aero” engine size hardware

NASA Turbofan at the Glenn Research Center’s 9x15 Wind Tunnel

Results – NASA Turbofan Experiment (FY08/FY09)

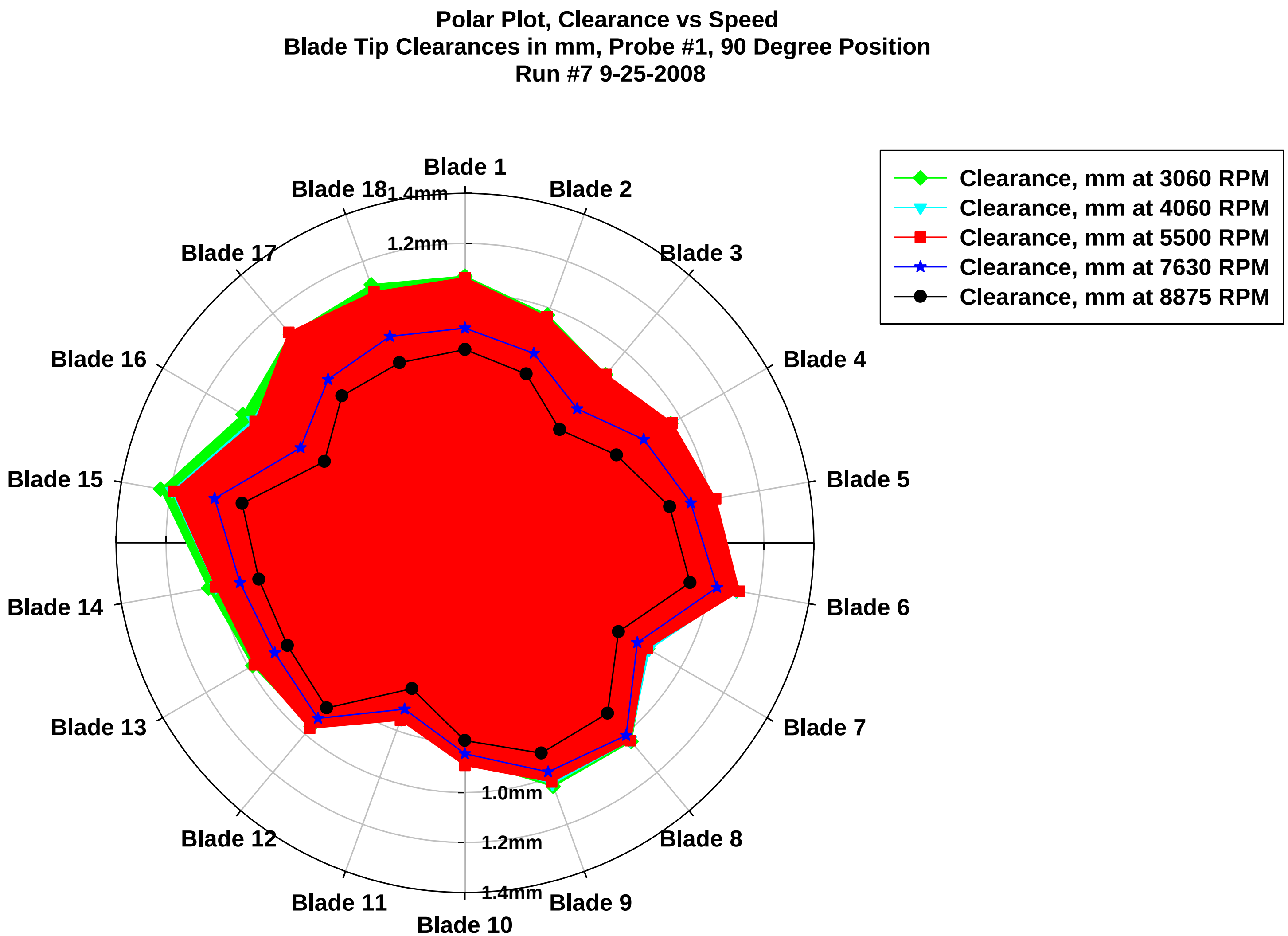


Change in Clearance

Probe #1 Δ = 0.22 mm

Probe #2 Δ = 0.06 mm

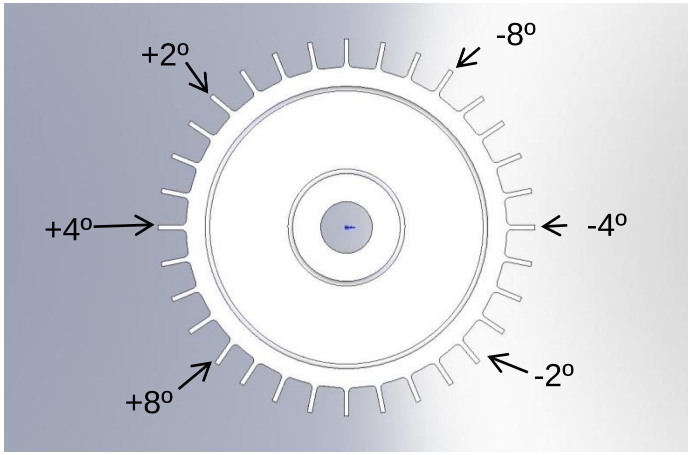
Results – NASA Turbofan Experiment (FY08/FY09)



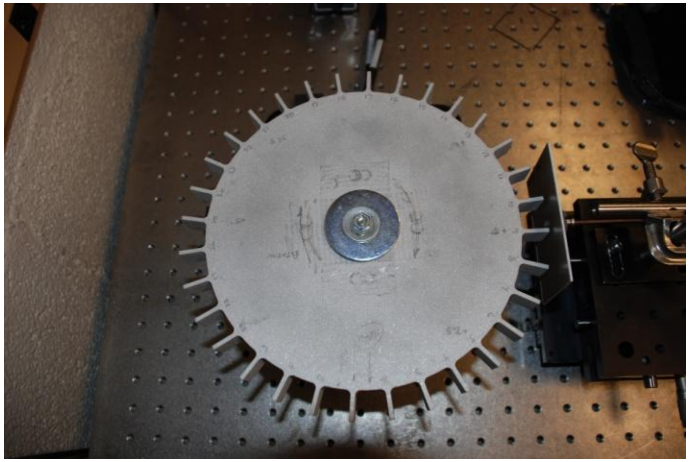
Average Δ = ~0.22 mm

Results – Tip Deflection Experiments (FY09/FY10)

- Objectives:
  - Evaluate second generation (24 GHZ) sensor's ability to make blade tip deflection measurements and low range clearance measurements
- Subscale Simulated Turbine Disk
  - ~25cm (10") diameter disk with 32 blades installed on sensor calibration rig
  - 6 symmetrically spaced blades were bent at pre- defined angles (proof of concept test)
    - +/- 8º , +/- 4º, +/- 2º deflections
  - Calibrated at clearances down to 0.100mm
    - First Cal Run, 0.10mm to 0.60mm
    - Second Cal Run, 0.05mm to 0.70mm
- Outcome / Results:
  - Was able to detect/measure blade tip defections down to +/- 2º level. Deflection error is still being analyzed.
  - Will make disk with smaller blade deflection angles to find bottom limit
  - Was able to make repeatable clearance measurements approaching 0.100mm (max error of +/- 0.033mm observed in initial verification experiments).

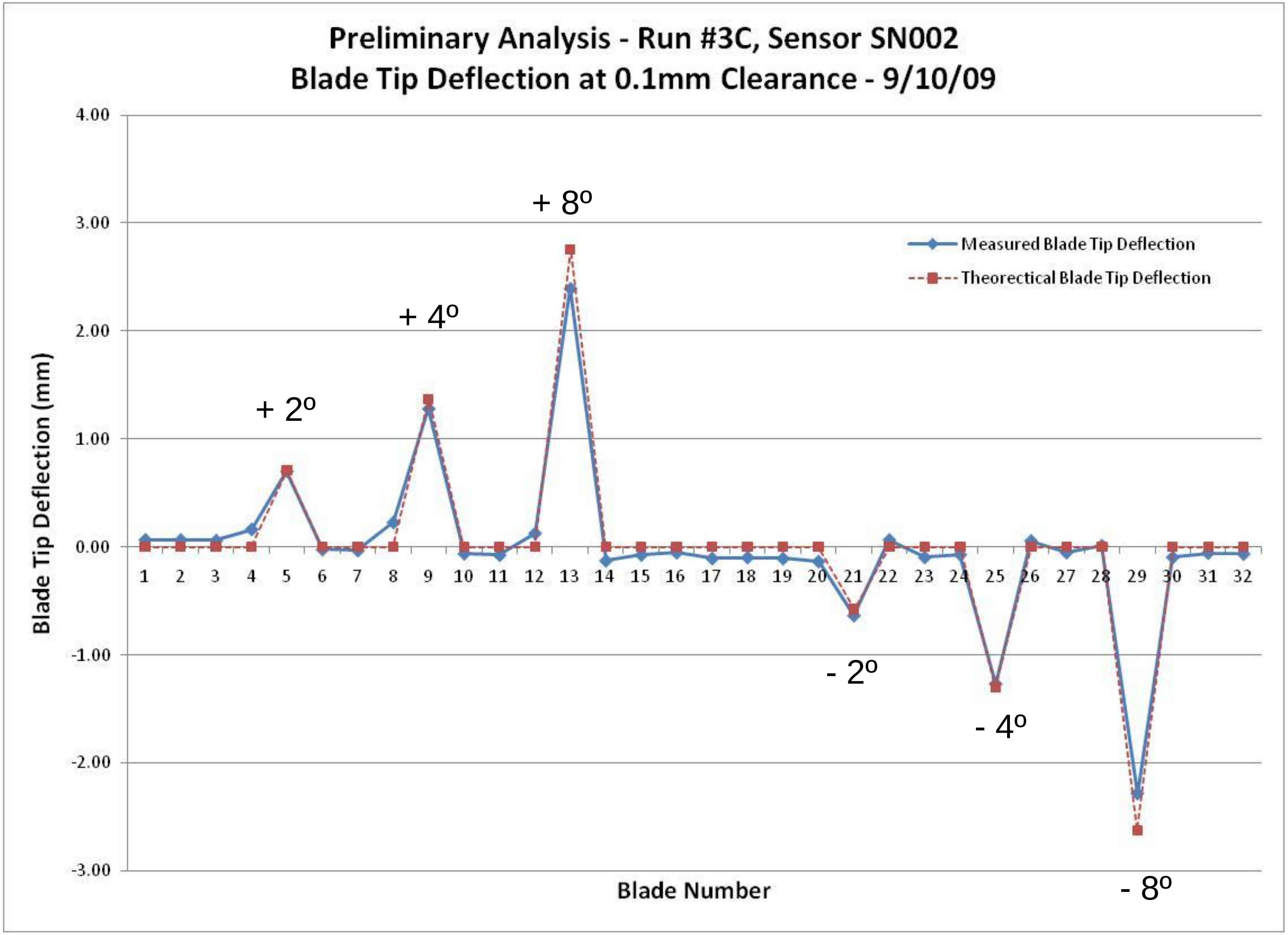


Bent Blade Disk Concept



Bent Blade Disk Mounted on the Sensor Calibration Rig

Results – Tip Deflection Experiments (FY09/FY10)



Results – Calibration Experiment (T700 Rotor) / (FY10)

- Objectives:
  - Calibrate microwave sensor for possible use on a compressor stage of a T700 engine that will be tested in GRC's Engine Components Research Laboratory (ECRL) later this year
  - Evaluate probes ability to make low range clearance measurements on aero engine like hardware

- Experimental Setup:
  - Calibrated sensors using a "old" compressor stage from a T700 as the target
  - Installed the compressor stage on the microwave sensor calibration rig
    - Calibration rig previously shown in slides 10 & 15
  - Calibrated over a range from 0.10mm to 1.50mm for this sensor calibration experiment

- Outcome / Results:
  - Successfully calibrated sensors against actual aero rotor hardware
  - Was able to make repeatable tip clearance measurements down to 0.100mm in a lab environment on the calibration rig
    - Max error of +/- 0.021mm observed in verification runs

Conclusions

- Testing to date has shown that microwave tip clearance sensor technology has proven successful in acquiring blade tip clearance and deflection measurements on rotating machinery and other "aero engine" like hardware
  - Successfully used to make measurements on an Axial Vane Fan and a NASA Turbofan
  - Matched clearance data previously acquired with capacitive probes on the NASA Turbofan
  - Achieved intermediate metric of measuring deflections under +/- 5º and clearances under 250 microns (0.25mm) in a lab environment using a disk with blades bent at pre-defined angles
  - Have been able to make clearance measurements down to 100 microns (0.10mm) in a lab environment on a actual hardware from an "aero" type engine
- Still need to demonstrate and evaluate at elevated temperature, ("final" metric for milestone 1.1.1.11)
- Still need to demonstrate in an actual turbine engine in a relevant environment (metric for milestone 2.3.1.2)

Next Steps

- Wrap up current phase of blade tip clearance and deflection testing
  - Finish analyzing data & associated errors
  - Get additional disks made and find bottom limit on deflection angles that can be detected
  - Get additional low range clearance data
  - Investigate methods of improving tip timing / tip deflection acquisition with system (possibly contract with Radatec / Vibro-Meter for real time waveform display)

- Evaluate the sensors operation at elevated temperatures. End metric for milestone 1.1.1.11 is to test at 150ºC
  - Planning for a test in GRC's High Temperature Spin Rig
  - **Evaluating at temperature has been an issue…….locating the right venue has been a challenge**

- Test microwave sensors against another technology (capacitive and /or fiber probes) to obtain comparison data
  - T700 Engine Test in ECRL
  - GRC's Rotor Dynamics Laboratory

- Plan for test on an actual engine at Dryden
  - Targeting the 2010 timeframe