Evaluation of a Microwave Blade Tip Clearance Sensor for Propulsion Health Monitoring

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Outline

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Introduction

- Microwave Blade Tip Clearance Sensors
  - In-situ structural health monitoring for gas turbine engines
    - Blade tip clearance to monitor growth & wear
    - Blade Tip Timing to monitor deflection & vibration
  - Active closed loop clearance control
    - Closed loop control on turbine tip clearances

- Targeting use in the High Pressure Turbine (HPT) and High Pressure Compressor (HPC) sections
  - Survivability and operation in the high temperature environment has been a major issue
  - Microwave sensor technology has the potential to operate in this high temperature environment and fulfill this in-situ health measurement need

- Summarize previous efforts in evaluating this technology
- Discuss future plans to evaluate technology on an engine ground test
Motivation – Aviation Safety

- **Enhance & improve aviation safety**
- NASA Aviation Safety Program (AvSP), Vehicle Safety Systems Technology Project (VSST)
  - Develop new instrumentation and techniques
  - *Detect pre-cursors to events in order to take action and prevent failure*

Turbine Disk Failure – June 2, 2006

Crack Detection Experiments in GRC Rotordynamics Lab

Crack Detection Experiment Results
Motivation – Aviation Safety

- FAA Report AR-08/24 “Engine Damage Related Propulsion System Malfunctions”
- Damage in the HPT and HPC sections
  - \(~32\%\) of damage events that caused engine removal for unscheduled maintenance
  - \(~12\%\) of “in flight shut down” events
Motivation – Engine Efficiency

• **Secondary goal (or primary depending on point of view!)**
  – Improve overall engine efficiency
  – Was being pursued under the NASA Fundamental Aero Program’s, Supersonic Cruise Efficiency Project

• Active Closed Loop Clearance Control in the HPT*
  – It is estimated for every ~25um (~0.001)” decrease
    – SFC decreases ~0.1%
    – EGT decreases ~2 deg. F
  – Fuel savings
  – Reduced emissions
  – Extended service life

• **Sensor “buys” its way onto the airplane for Structural Health Monitoring**

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Evaluation Approach 2006 to Now

- Microwave tip clearance sensors and measurement developed by Radatec, Inc (now Meggitt) through the NASA Small Business Innovation Research (SBIR) Program and other commercial contracts
  - Phase III SBIR commercialization contract 2006-2007
  - First generation (5.8GHZ) production probes delivered in 2008
  - Second generation (24GHZ) probes delivered in 2009

- The use of microwave sensors for making tip clearance and tip deflection measurements is an emerging technology
  - Techniques on their use and calibration need to be developed
  - The sensor’s overall accuracy and ability to make clearance measurements need to be evaluated

- Several evaluation experiments were accomplished from 2006 to now as a means of building toward primary goal of using these sensors on an actual engine
Sensor Description

- 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

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

<table>
<thead>
<tr>
<th>Measurement Range:</th>
<th>Accuracy:</th>
<th>Temperature:</th>
<th>Response:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to ~6 mm (~0.250 inches)</td>
<td><del>0.025 mm (</del> 0.001 inch)</td>
<td>~900°C (~1600°F)</td>
<td>&gt; 1 MHZ (5 MHZ typical, in theory up to 25 MHZ possible)</td>
</tr>
</tbody>
</table>
Sensor Description

- Microwave Blade Tip Clearance Probe
  - First generation probes (5.8 GHZ)
    - For “large” rotating machinery
    - Measurement range ~25mm (~1”)
  - Second generation probes (24 GHZ)
    - 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
Calibration Experiment (FY08)

- **Objectives:**
  - To develop calibration techniques
  - To evaluate 5.8GHz probe’s accuracy
    - Specific to the blade geometry
    - 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

- Calibrated the microwave sensors against two geometries
  - Over a range from 1 mm to 13 mm (.04” to .51”)
  - “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 ~+/- 0.17mm (~0.007”) during this initial experiment (on thin blade)
  - Reduced to ~+/- 0.05mm (~0.002”) in subsequent calibration experiments for use on NASA Turbofan
Results – Calibration Experiment (FY08)

- Same sensor calibrated against two different geometries
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 (~1”) ,~362 mm (~14”) long, ~267 (~10.5”) mm chord length
  - One 5.8GHZ probe installed

- **Outcome / Results:**
  - NASA’s first use of these sensors on actual rotating machinery
  - 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*
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
Results - NASA Turbofan Experiment (FY08/FY09)

Polar Plot, Clearance vs Speed
Blade Tip Clearances in mm, Probe #1, 90 Degree Position
Run #7 9-25-2008

Blade 1
Blade 2
Blade 3
Blade 4
Blade 5
Blade 6
Blade 7
Blade 8
Blade 9
Blade 10
Blade 11
Blade 12
Blade 13
Blade 14
Blade 15
Blade 16
Blade 17
Blade 18

Average $\Delta = \sim 0.22$ mm (~.009")
Spin Rig Tests (FY10-FY12)

- **Objectives:**
  - Evaluate second generation (24 GHZ) sensor’s ability to make *low range clearance measurements and deflection measurements*
  - Evaluate their use in sensor based fault & crack detection schemes that are being developed to monitor rotor structural health

- **Tested on several engine like disks on GRC’s Calibration Rig and the High Precision Spin Rig**
  - Disk with blades pre-bent at specified angles for tip deflection evaluation
  - Several disk with notches introduced to simulate cracks

- **Results:**
  - Operated at clearances down to 0.10mm (0.004”)
    - Evaluation range: 0.10mm to 0.60mm (0.004” to 0.024”)
  - Investigated ability to make deflection measurements
  - Sensor successfully used to monitor blade tip clearance in several crack detection experiments accomplished in our Rotordynamics Laboratory
Spin Rig Tests (FY10-FY12)

Sensor #1 - Run #4B, SN007
Blade Tip Deflection at 0.1mm Clearance - 9/09/09

Blade Tip Deflection (mm) vs Blade Number

- Measured Blade Tip Deflections
- Actual Blade Tip Deflections

Key Points:
- Blade Tip Deflections at various blade numbers:
  - +2° at Blade 1
  - +4° at Blade 7
  - +8° at Blade 12
  - -2° at Blade 20
  - -4° at Blade 30
  - -8° at Blade 32
Vehicle Integrated Propulsion Research (VIPR) Overview

VIPR test approach:
- A series of on-wing engine ground tests
- Technologies under evaluation include advanced EHM sensors and algorithms
- Includes “nominal” and “faulted” engine operating scenarios

Partnerships:
- Sharing of costs, results and benefits
- VIPR partners include NASA, other government agencies and industry partners.

VIPR Test Schedule
- VIPR I (Dec. 2011)
- VIPR II (2013)
- VIPR III (TBD)

Testing is a necessary and challenging component of Engine Health Management (EHM) technology development.
VIPR I Test Overview

• VIPR I test was conducted in December 2011 at NASA Dryden / Edwards Air Force Base

• Test vehicle:
  – Boeing C-17 Globemaster III
  – Equipped with Pratt & Whitney F117 turbofan engines

• VIPR 1 EHM ground tests included:
  – A series of nominal and faulted engine test cases
  – Data collected over a range of power settings including quasi-steady-state and transient operating conditions
Results & Future Plans

• VIPR 1 (2011) - Microwave blade timing / tip clearance sensor
  – Not installed on engine, close as possible for EMI/EMC checkout
  – Successfully passed electro-magnetic interference (EMI) / electro-magnetic compatibility (EMC) checkout.
  – Cleared for actual on-engine use for future VIPR tests at DFRC.

  – Install microwave blade tip clearance sensors on engine in HPT section.
    – Goal of evaluating for EHM and closed loop clearance control
  – Other Advanced sensors will be installed.
  – Evaluate additional EHM sensors and algorithms under nominal and faulted engine operating scenarios
  – Initial steps towards EHM sensor fusion with advanced sensor suite.
  – Run engine to end of life.
Conclusion

- Testing to date has shown that microwave tip clearance sensor technology has proven successful in acquiring blade tip clearance measurements on rotating machinery and other “aero engine” like hardware
  - Demonstrated the techniques and infrastructure required for probe calibration
  - Used 5.8 GHZ sensors to make measurements on an Axial Vane Fan and a NASA Turbofan
  - Used 24GHZ sensors to make measurements on smaller aero engine like hardware in various test rigs

- Demonstrate in an actual turbine engine environment
  - Full scale test with a suite of EHM sensors being targeted for 2013-2014