National Aeronautics and Space Administration

Vehicle Integrated Propulsion Research for the study of Health Management Capabilities

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Vehicle Integrated Propulsion Research (VIPR) Overview

EHM technology testing is challenging:

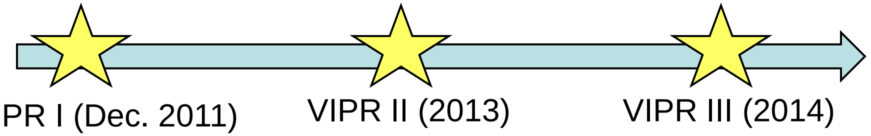
- Expensive
- Dedicated testing is necessary to demonstrate technology against known system “ground truth” state.

Partnerships make it possible:

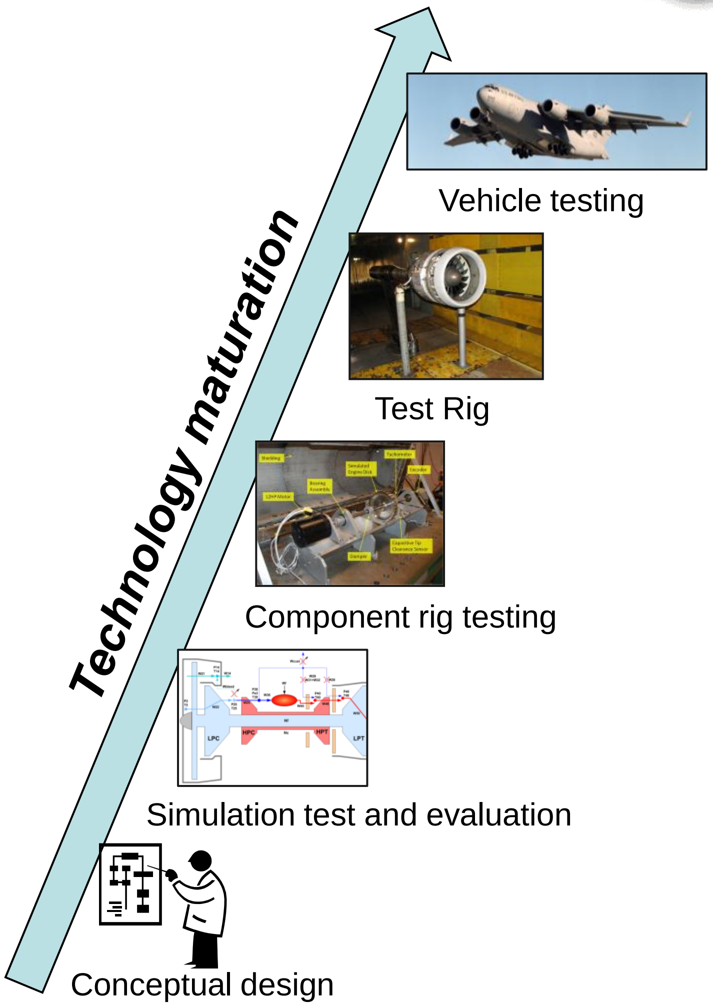
- Sharing of costs, results and benefits
- VIPR partners include NASA, Air Force, Pratt & Whitney and a growing list of other government agencies and industry partners.

VIPR test approach:

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



VIPR Test Schedule

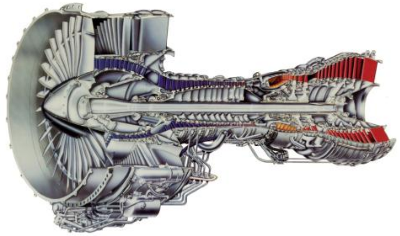


Testing is a necessary and challenging component of Engine Health Management (EHM) technology development.

VIPR I Test Overview

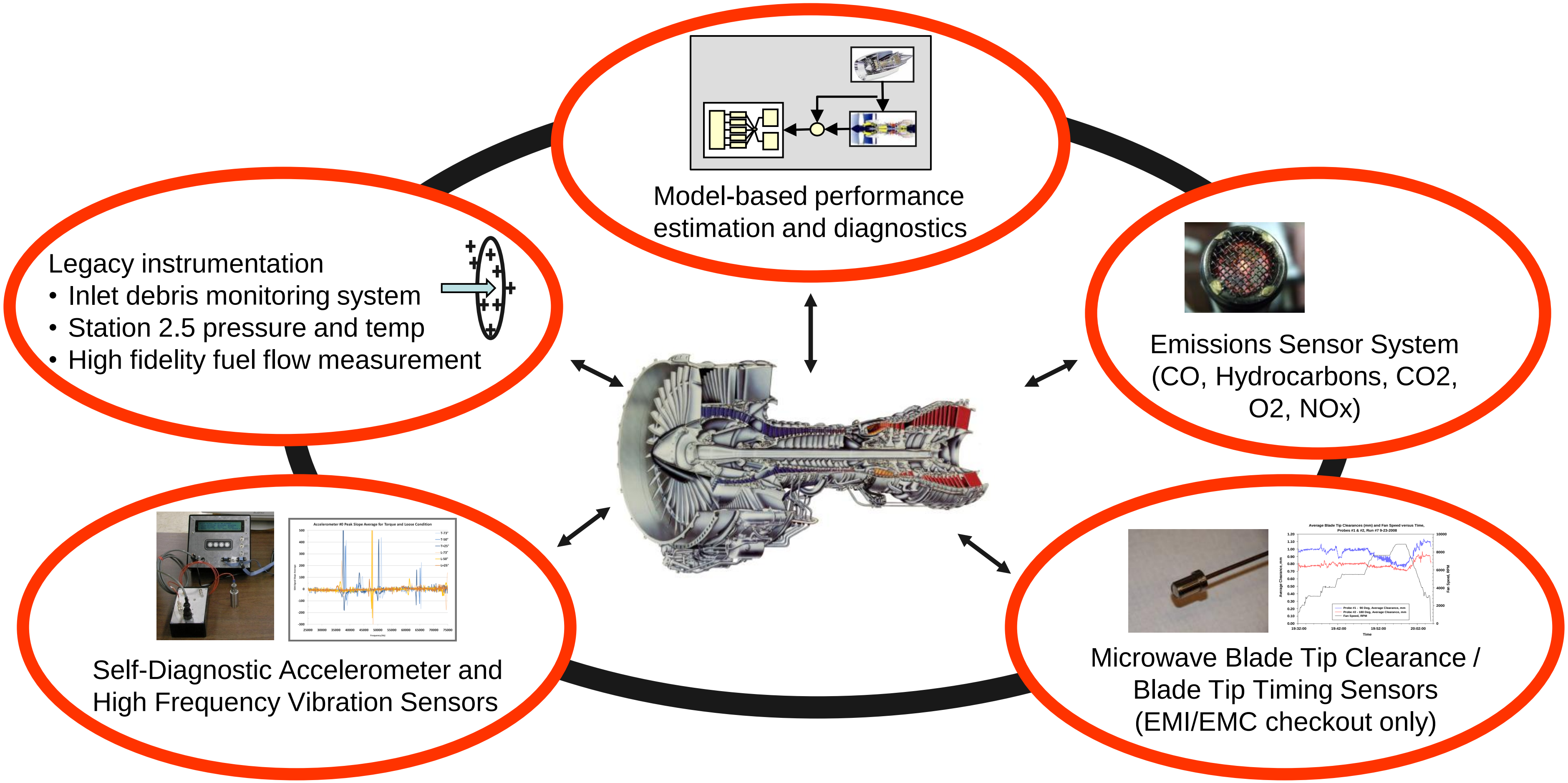
- VIPR I test was conducted in December 2011 at NASA Dryden / Edwards Air Force Base
- Test vehicle:
  - Boeing C-17 Globemaster III
  - Equipped with Pratt & Whitney F117 turbofan engines
- VIPR 1 EHM ground tests included:
  - A series of nominal and faulted engine test cases
  - Data collected over a range of power settings including quasi-steady-state and transient operating conditions

Boeing C-17 Globemaster III



Pratt & Whitney F117 Turbofan Engine

VIPR I – EHM Technologies Under Test



Multiple EHM sensors/algorithms tested during VIPR I
Valuable for identifying real-world implementation issues/concerns
Testing of multiple technologies also allows assessment of information fusion benefits

Relevance to Aviation Safety Needs

- Engine malfunction coupled with Inappropriate Crew Response is the most statistically significant issue
- Systems Analysis
  - Sensor failure is one of the largest contributors to In Flight Shut Down
  - Blade loss is one of the larger contributors to In flight Shut Down due to high vibration and power loss

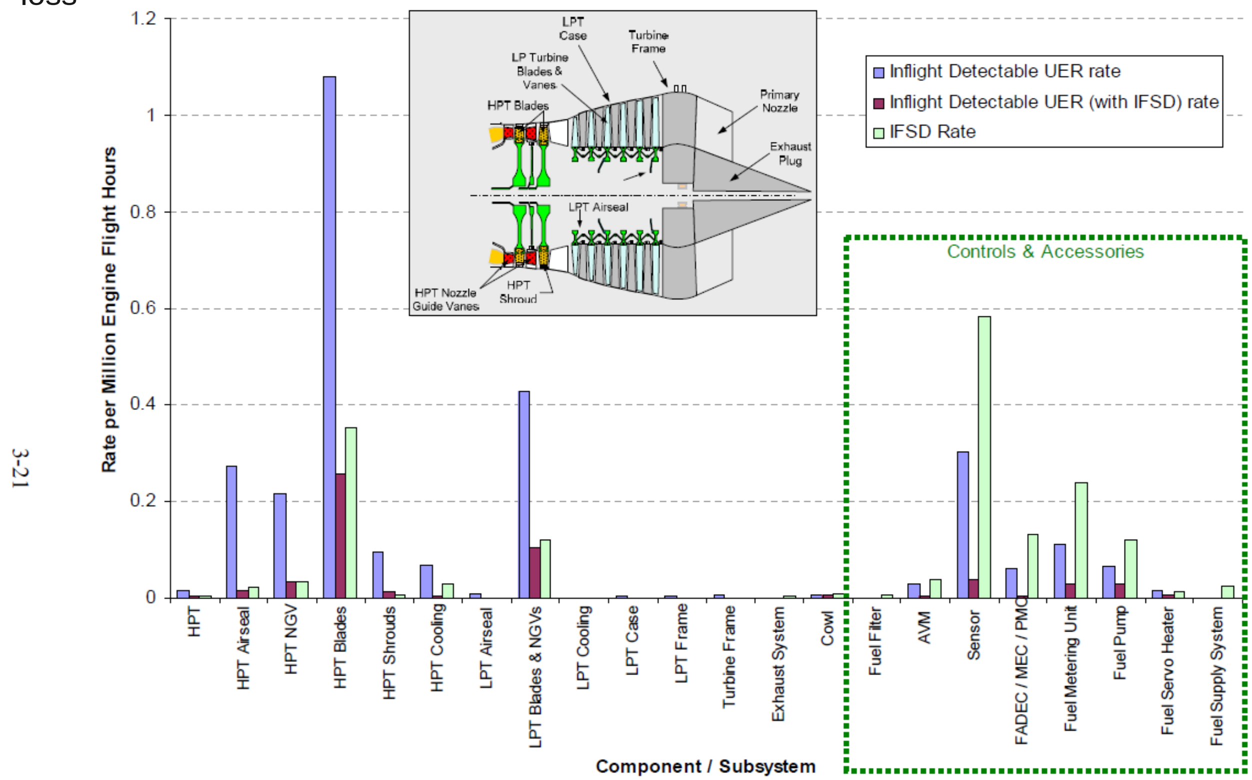
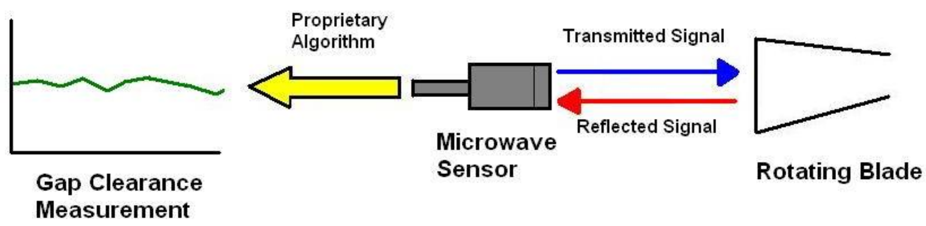


Figure 3-5. Engine Component Rates for Restrict Thrust Response Category (Continued)

Steve Clark, Grace Balut Ostrom, and Sam Clark, Engine Damage-Related Propulsion System Malfunctions, DOT/FAA/AR-08/24, December 2008.

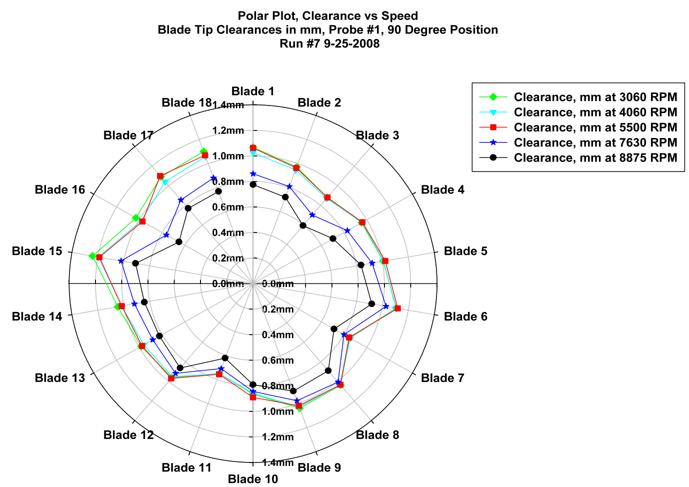
Microwave Tip Clearance Sensor Technology

- Microwave blade tip clearance sensor technology for use in turbine engines
  - Structural health monitoring – tip clearance and tip timing
  - Active closed loop clearance control - tip clearance



Microwave sensors installed on the NASA Turbofan Test Rig at the GRC's 9x15 LSWT

- Targeted for use in hot sections of turbine engines (High Pressure Turbine section)
  - Rated for use in high temperature environment, ~1200 ºC
  - Highly accurate, current goal of ~25um for this technology
  - Able to see through contaminants that exist in the engine flow
- Sensors have been used on several experiments at GRC to evaluate & demonstrate their performance. Goal is to use sensors on an actual aero engine.

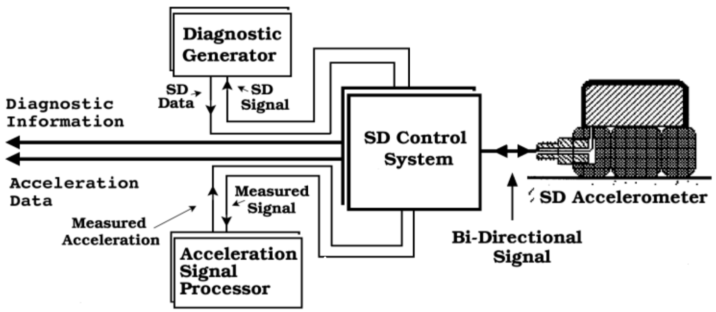


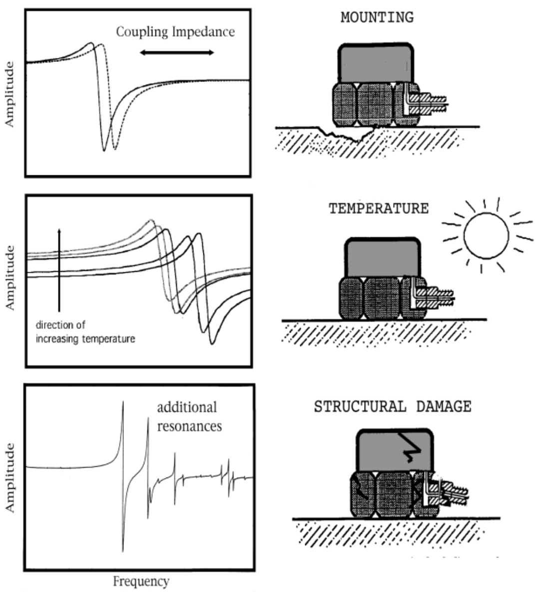
Clearance data acquired on the NASA Turbofan Test Rig

Self Diagnostic Accelerometer (SDA)

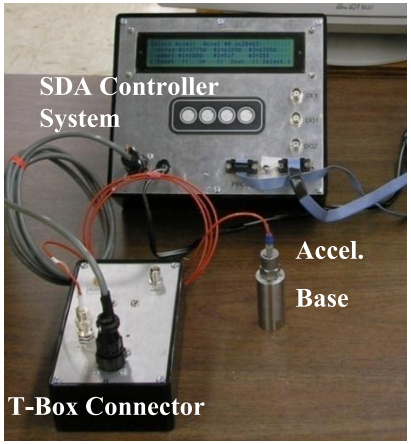
- Vehicle Health Management Systems may make mission critical health assessments based upon sensor information
- It is critical that sensor measurements be validated before a health management system may take such action
- Sensor validation is often accomplished through multiple sensors voting - MAS 777-200 flight in 2005 is a case where 2 failed sensors outvoted a third healthy sensor

Self Diagnostic Accelerometer (SDA) System

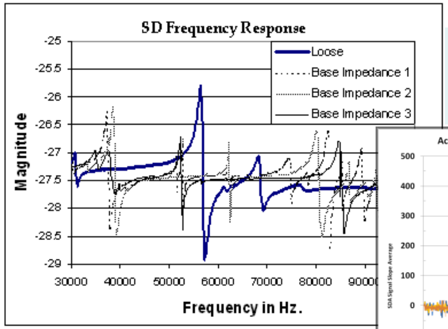




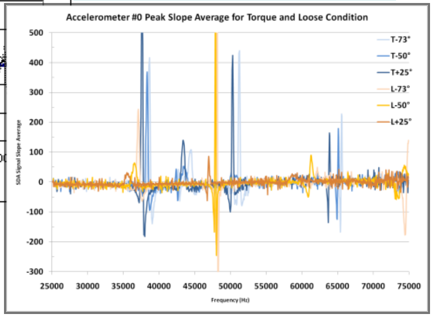
SDA System



Manual Data from Signal Analyzer



Autonomous Data from SDA System



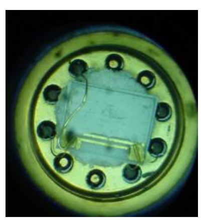
This Self Diagnostic Accelerometer System was successfully demonstrated in providing electro-mechanical data including the health of the sensor-part attachment under varying temperature, torque-attachment, and electro-mechanical noise.

High Temperature Electronic Nose

MEMS Based Emission Sensors

- Multispecies microsensor detection in single package to allow miniaturization of the detection apparatus
- Quantify composition of critical constituents in turbine engine exhaust products, E.G., CO, CO_2, NOX, O_2, HC (unburned Hydrocarbons) and H_2
- Improve accuracy in measuring exhaust products
- Engine Test Objectives:
  - Obtain correlated emissions data in conjunction with gas path diagnostics data so that the benefit for inclusion of emissions information in gas path diagnostics can be studied

Standard Multi-gas Analyzer

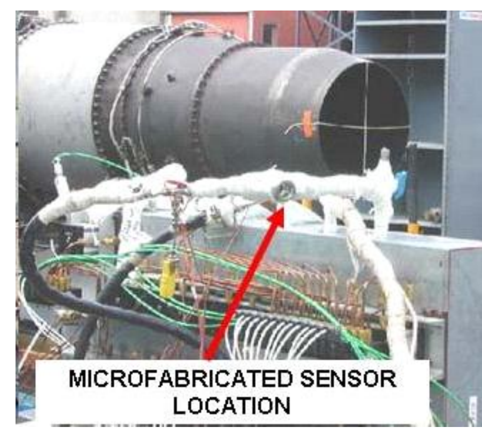


CO Sensor

SiC Hydrocarbon Sensor

CO2 Sensor

MEMS Emissions Sensors



Engine Tests and Testing

Propulsion Gas Path Health Management

Technical Approach:

- Develop optimal sensor placement methodology for gas path diagnostics
- Enhanced adaptive modeling techniques for on-line engine performance deterioration trending and fault diagnostics
- Gas Path Diagnostics also enable the model-based estimation of unmeasured parameters critical for IVHM

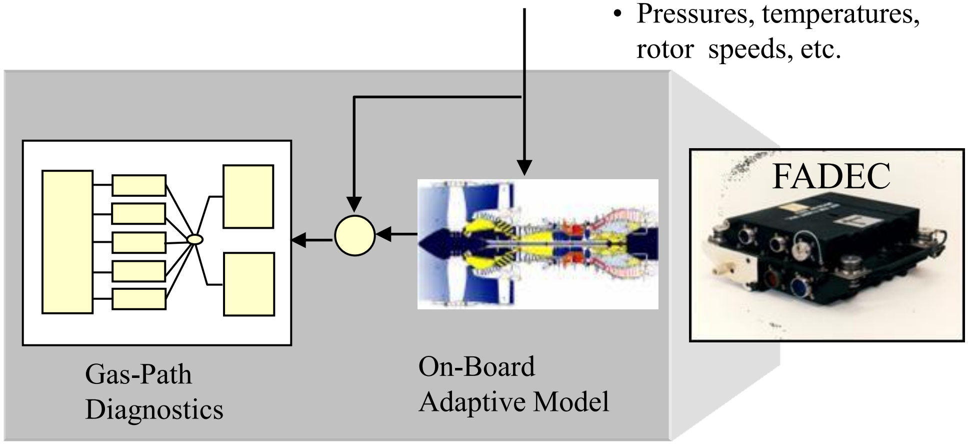
Engine Test Objectives:

- Obtain data containing simulated faults for testing of current and future diagnostic algorithms
- Obtain diagnostic data concurrently with tip clearance and emission sensor data so that initial studies for the inclusion of these sensors in a diagnostic model can be made

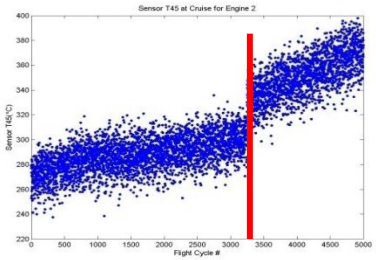
Engine

Sensed Measurements

- Pressures, temperatures, rotor speeds, etc.



Model-Based Diagnostics Architecture



Performance Trending and Fault Diagnostics

C-17 Aircraft

Test Implementation

VIPR I testing of the Self Diagnostic Accelerometer

Roger Tokars (GRC) John Lekki (GRC) December 2011

The Self Diagnostic Accelerometer (SDA) was mounted and tested on the C-17 engine in order to demonstrate the SDA's flight worthiness and robustness.

Test Locations

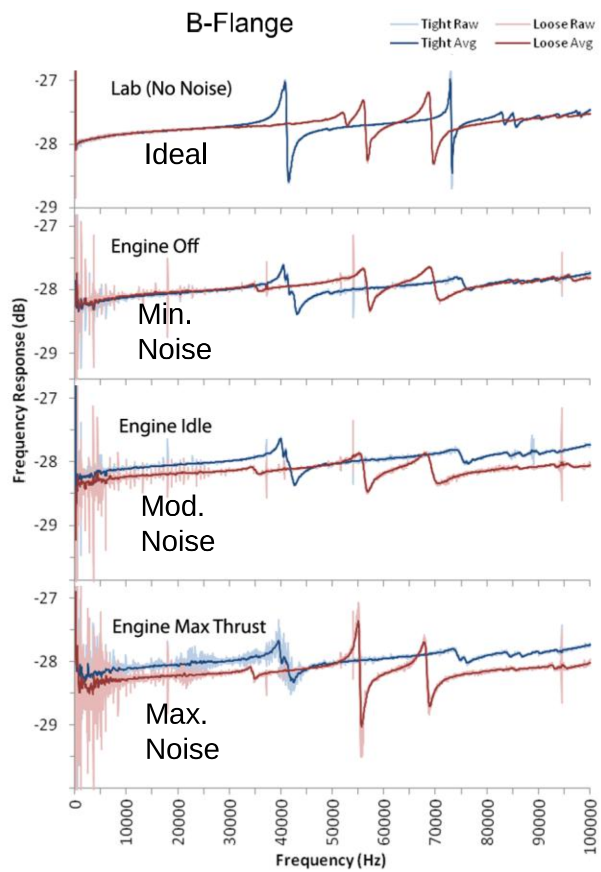
C-17 Aircraft

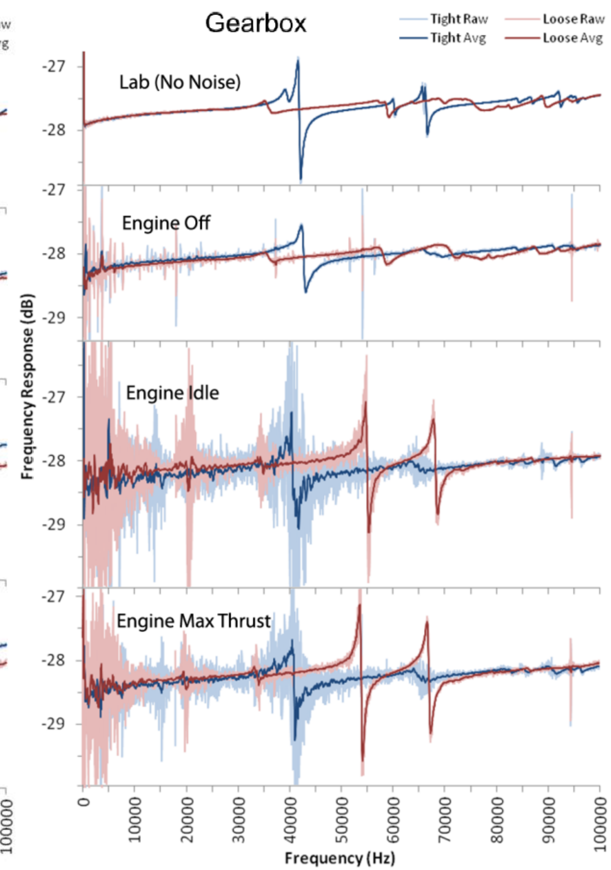
Accelerometer mount

Secured with safety wire

Results

Pattern recognition software successfully discriminates **all** tight and loose conditions.





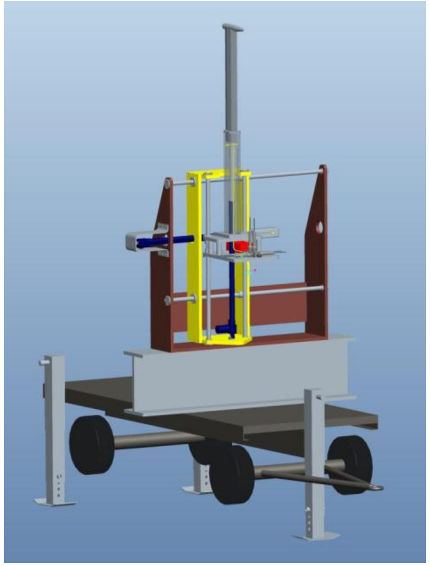
Conclusion

The Self Diagnostic Accelerometer System was successfully demonstrated in providing electro-mechanical data including the health of the sensor attachment under the extremes of an aircraft engine environment.

Preservation Oil Burn-off

- Day 1 of VIPR testing was a “green engine run” (first time the test engine was run post-overhaul)

- Provided an opportunity to evaluate the Emission Sensor System (ESS) during preservation oil burn-off

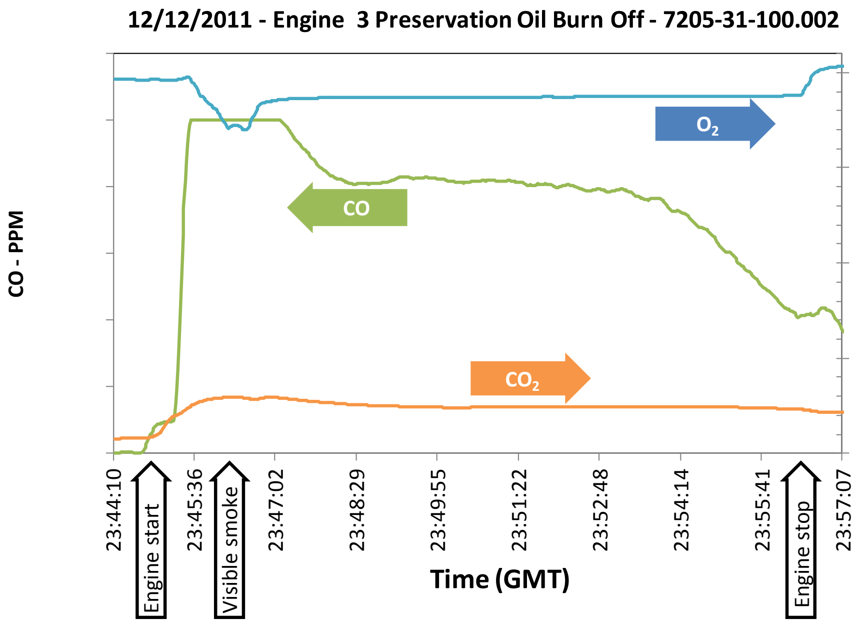


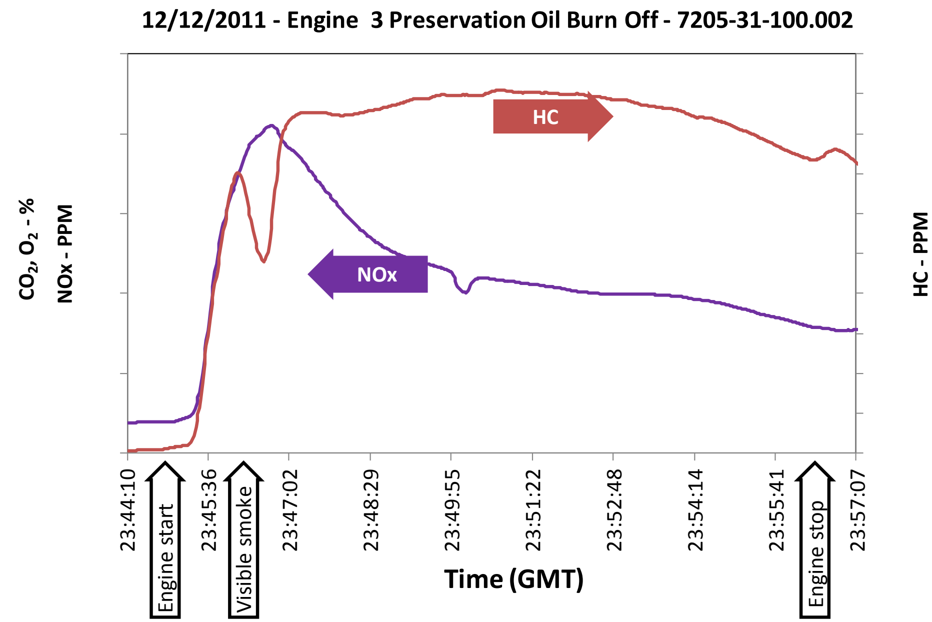
ESS Rig

Preservation oil burn-off!

Preservation Oil Burn-off Test

Engine 3 Preservation Oil Burn Off





- Start up - ESS observed fast rise in concentrations
  - Exception – oxygen concentration dropped, as expected
- ~2 min from start up - noticeable change and recovery
- The high levels eventually tapered down to somewhat lower concentrations with the engine stable at idle

VIPR I Highlights: Gas Path Diagnostic Testing

Gas Path Diagnostic Test Objectives:

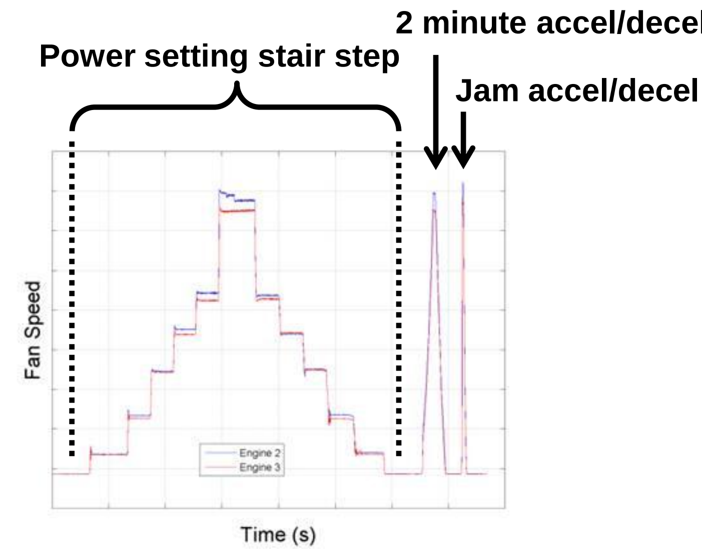
- Collect engine performance data under nominal and faulty operating conditions
- Evaluate ability of adaptive model to track engine performance
- Evaluate ability of gas path diagnostic algorithms to detect fault conditions

Engine Gas Path Fault Conditions Included:

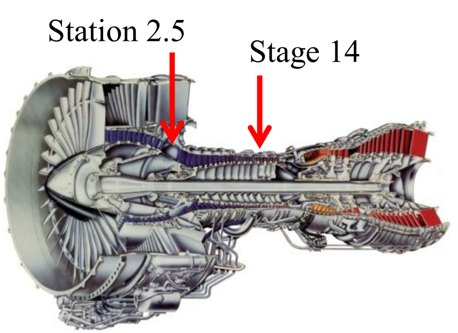
- Station 2.5 bleed failed full-open
- Station 2.5 bleed schedule biased +10% open
- Stage 14 bleed failed full-open

Next Steps:

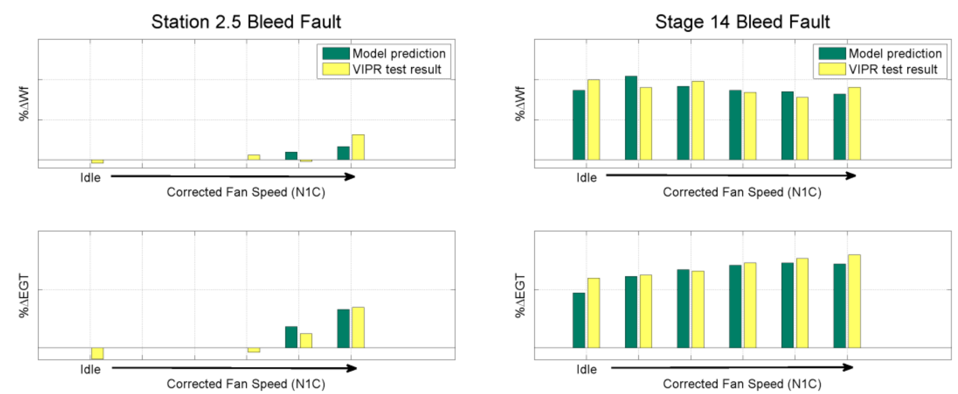
- Continue post-test data analysis
- Improve model transient and low power accuracy



Event Test Sequence



F117 engine – bleed fault locations



Station 2.5 and Stage 14 bleed fault signatures

VIPR I Post-Test Data Analysis
(*Preliminary Results*)

- Model-based performance estimation and diagnostics
  - Steady-state measurement residuals (faulty vs. nominal baseline) found to be in good agreement with model predictions for each fault type.
  - Model-based diagnostic architecture trained on a single baseline run and then used to analyze remaining runs. With training:
    - Model-engine residuals reduced on subsequent baseline runs.
    - Model-engine residuals exhibit increases on fault runs.
  - Future steps will be taken to:
    - Improve model accuracy at specific power settings and during engine transients.
    - Evaluate the effectiveness of different machine learning techniques applied to capture engine-model mismatch.

VIPR I Post-Test Data Analysis
(*Preliminary Results - continued*)

- Emission Sensor System (ESS)
  - Baseline emission levels established.
  - Discernable change in emissions observed during preservation oil burn-off.
  - Demonstrated system under nominal and seeded fault conditions. The ESS system in general tracked a wide range of varying engine conditions.

- Microwave blade timing / tip clearance sensor
  - Successfully passed electro-magnetic interference (EMI) / electro-magnetic compatibility (EMC) checkout.
  - Cleared for actual on-engine use for future VIPR tests at DFRC.

- Self-diagnostic accelerometer (SDA)
  - Four SDAs, attached at engine B-flange and gearbox, successfully completed first-ever demonstration in engine environment.
  - SDA able to successfully detect un-torquing (loosening) of accelerometer connection.

Future Test Plans (VIPR 2 and VIPR 3)

- VIPR 2 Test Objectives (2013)
  - Advanced sensors
  - Gas path diagnostic technologies
  - Miss-scheduled turbine case cooling
  - Fan response research

- VIPR 3 Test Objectives (~2014)
  - Initial steps toward EHM sensor fusion with Advanced Sensors
  - Volcanic ash ingestion testing
  - Run engine to end of life