Packaged Capacitive Pressure Sensor System for Aircraft Engine Health Monitoring

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Introduction

- *Sensing systems for harsh environments:*

High temperature electronics and sensors

Three Major Industries

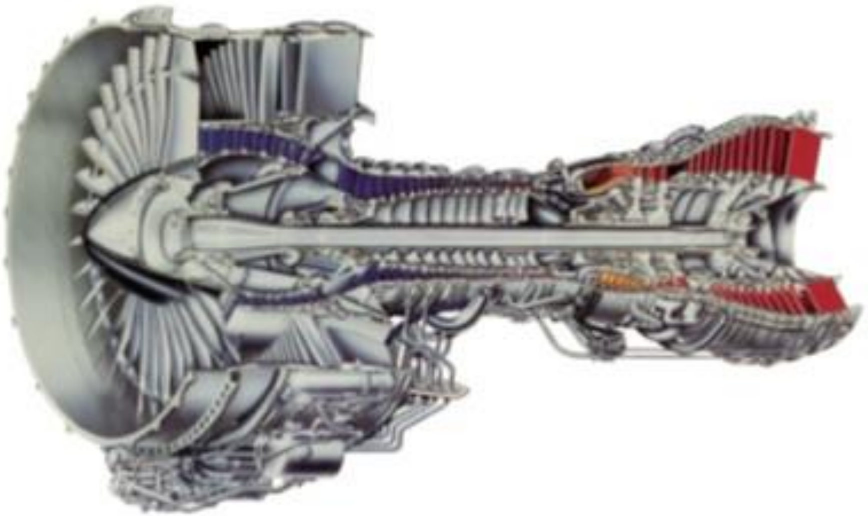
- Downhole Oil and Gas
  - Drilling operations were limited 150 to 175°C for reserves in easily accessible wells
  - Declining reserves force deeper wells, which increase drilling temperatures to 300°C
- Automobile
  - Cylinder pressures temperature: 300°C
  - Exhaust sensing temperature: 850°C
- Aerospace
  - Monitoring the health of aircraft engines at temperatures above 300°C (emissions, temperature, blade tip clearance and pressure)
  - Atmospheric and surface conditions of Venus (480°C)

Introduction

Develop a SiC-based MEMs capacitive pressure sensor system that can be used to monitor the pressure of a conventional gas turbofan engine.

Operating Conditions:

Temperature: 25 to 500°C
Pressure: 0 to 300 psi
Vibration: up to 5.3 G_{rms}



System Design

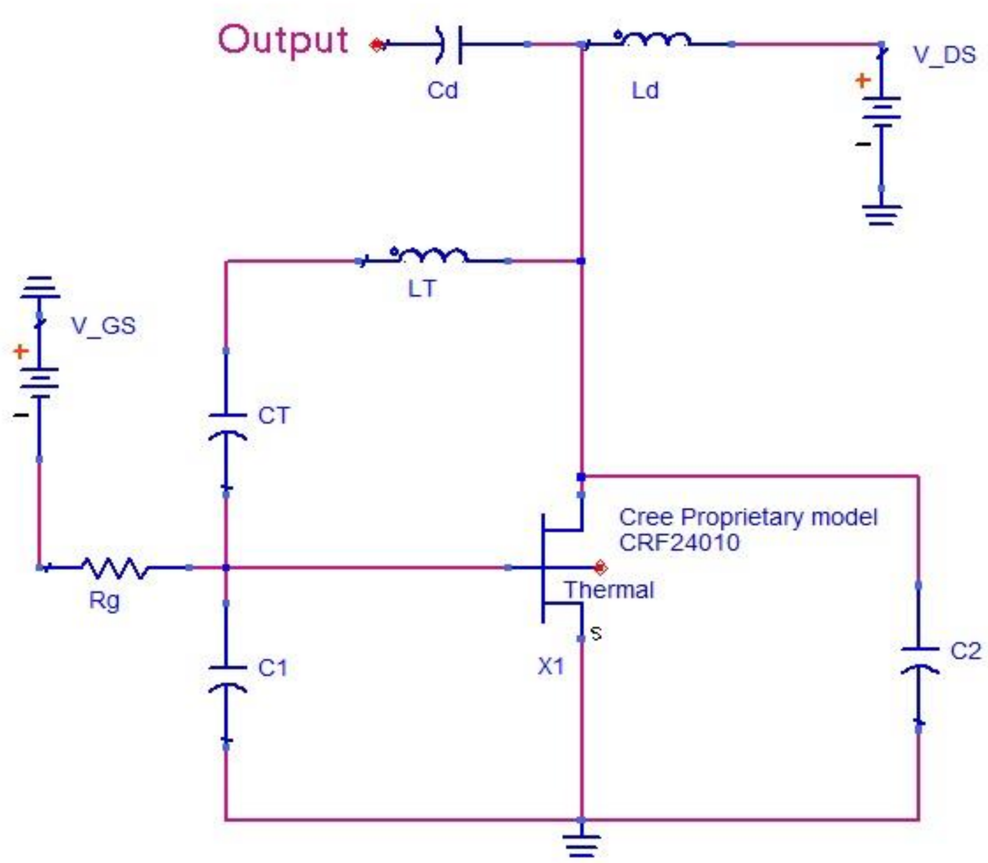
The system is realized by integrating the following components on a common, high temperature substrate

1. A novel SiCN MEMS capacitive pressure sensor
2. 6H-SiC MESFET as active device
3. MIM capacitors, wirewound inductors, thick film resistors
4. Low form factor packaging
5. Borescope plug adaptor

Electronics Design

The proposed system uses a Clapp-Type Oscillator Design

- The integrated system uses a Clapp-type oscillator with capacitive pressure sensor located in LC tank circuit
- As pressure increases, pressure sensor capacitance decreases, which causes the operational frequency to increase
- Cree SiC MESFET used for driving circuit into oscillation



Electronics Design

Clapp-Type Oscillator vs Colpitts Oscillator

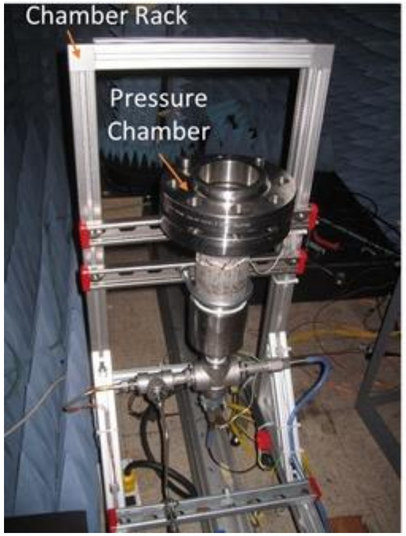
- The proposed Clapp oscillator requires one inductor, three capacitors and one MESFET. Requires fewer components vs. Colpitts oscillator design
  - Increases system efficiency
  - Increases system reliability under harsh environment conditions
- L_T and C_{SENSE} are in series and C_{SENSE} is used to set the operational frequency
- C_1 and C_2 are used to control the gain conditions
- This arrangement increases frequency stability, making it more frequency stable than the Colpitts design.

Pressure Sensor Testing

High Temperature and Pressure Chamber

System Key Features

- Pressure range: 0 to 100 psi
- Temperature range: 25 to 500°C
- LabVIEW control program
- Power source
- Multiple thermocouple
- Multiple feedthroughs
- Sight glass for signal transmission

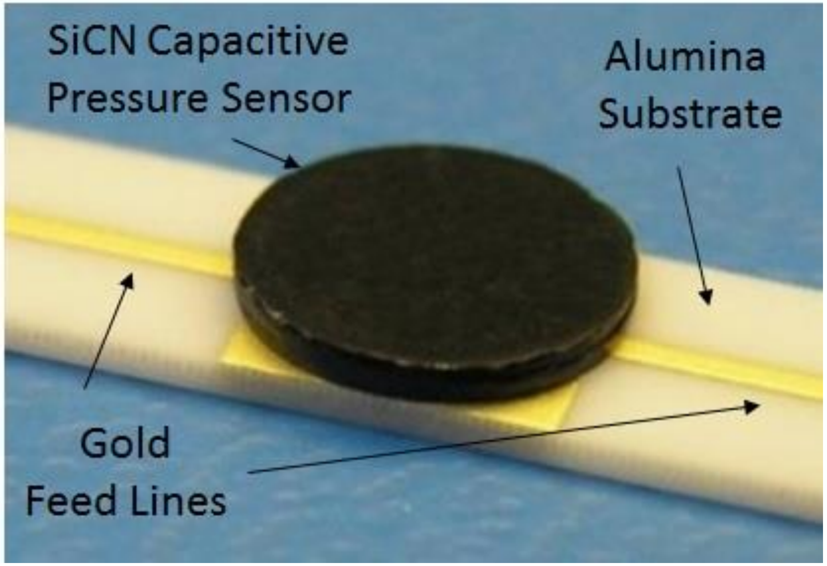


Pressure Sensor

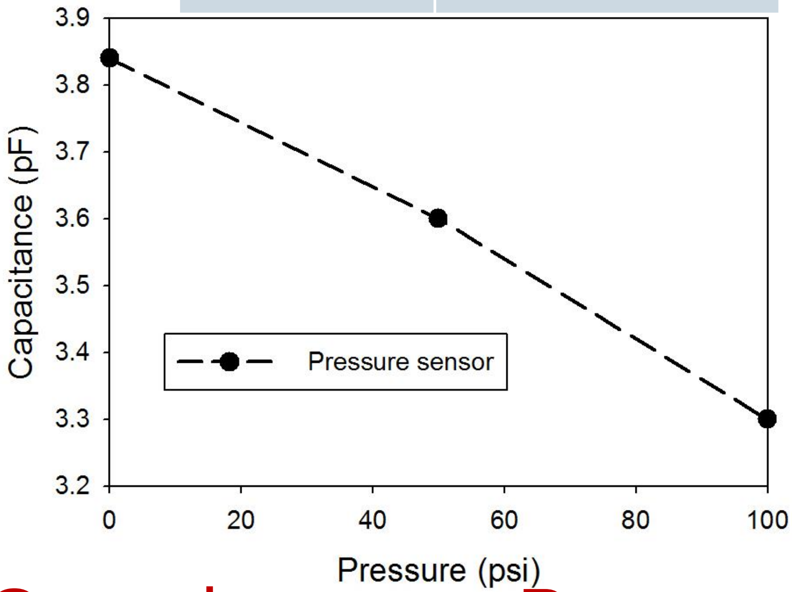
Sporian SiCN Capacitive Pressure Sensor

- Parallel plate capacitor model
- SiCN membrane
- Temperature range: up to 1000°C
- Pressure range: 0 to 400 psi

Pressure (psi)	Capacitance (pF)
0	3.84
50	3.6
100	3.3



SiCN pressure sensor



Capacitance vs Pressure

Oscillator Design

Circuit Simulations

Keysight's Advanced Design System (ADS) Software suite

CT =3.84 pF
LT = 780 nH
C1 = 14 pF
C2 = 41 pF
RG = 10KΩ
LD = 390 nH
CD = 188 pF

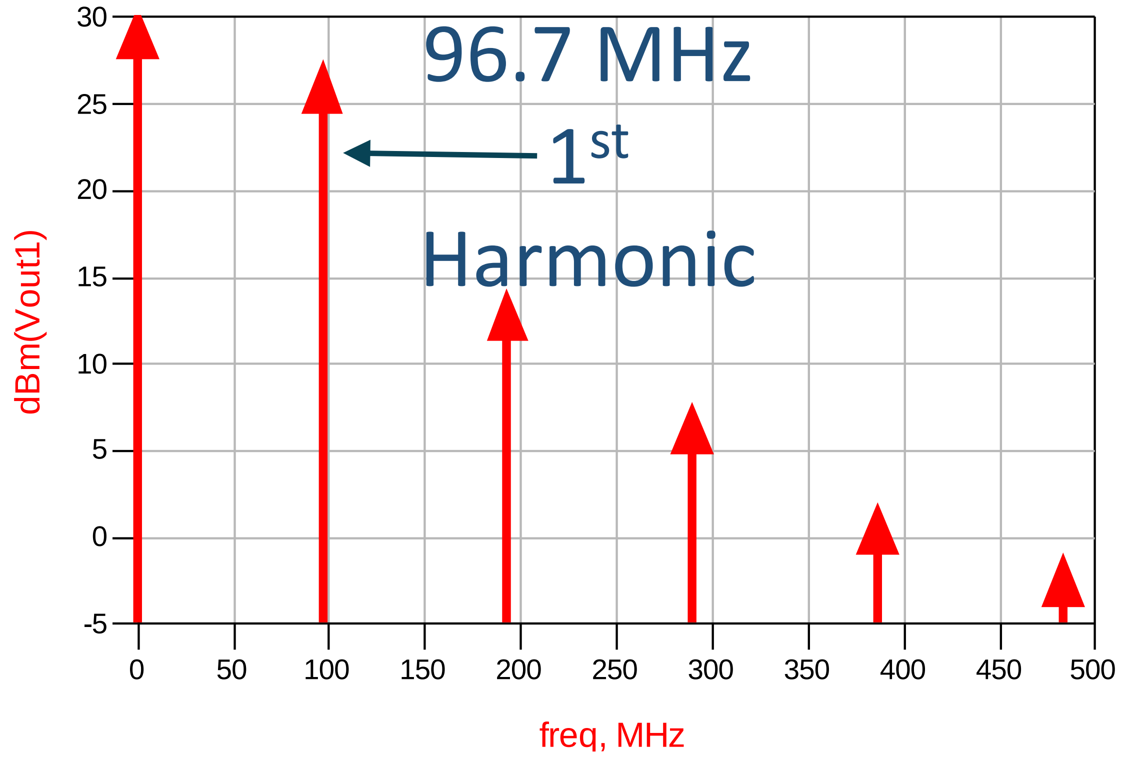
Cree SiC MESFET model

Oscillation Frequency 96.7 MHz

Oscillator Design

Circuit Simulations

Harmonic Balance Simulation



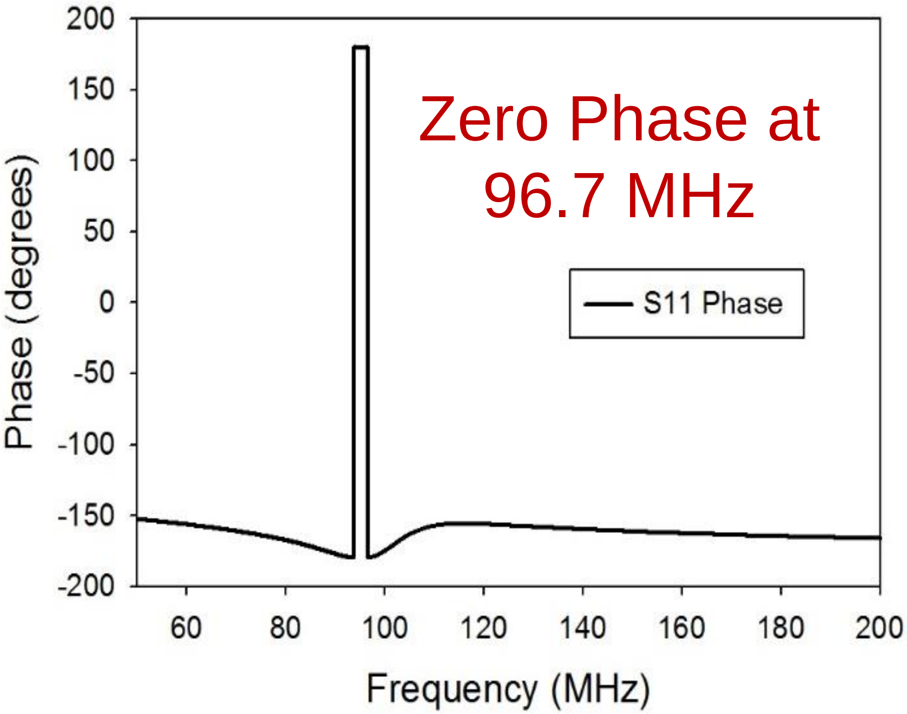
Oscillator Design

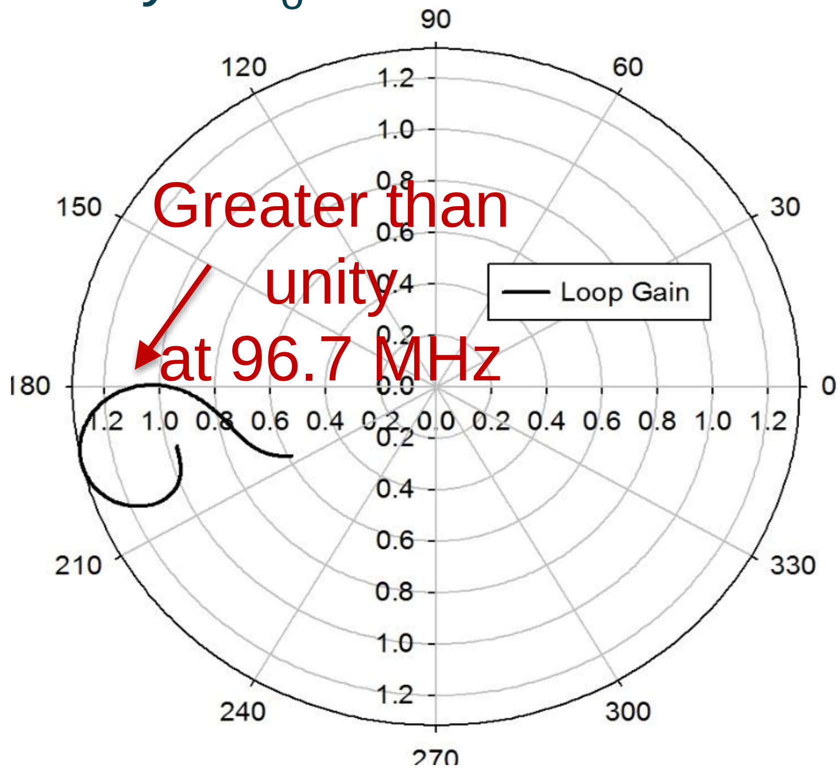
Circuit Simulations

To achieve oscillation stability

1) Phase must be zero at f_o

2) Loop gain must be greater than unity at f_o





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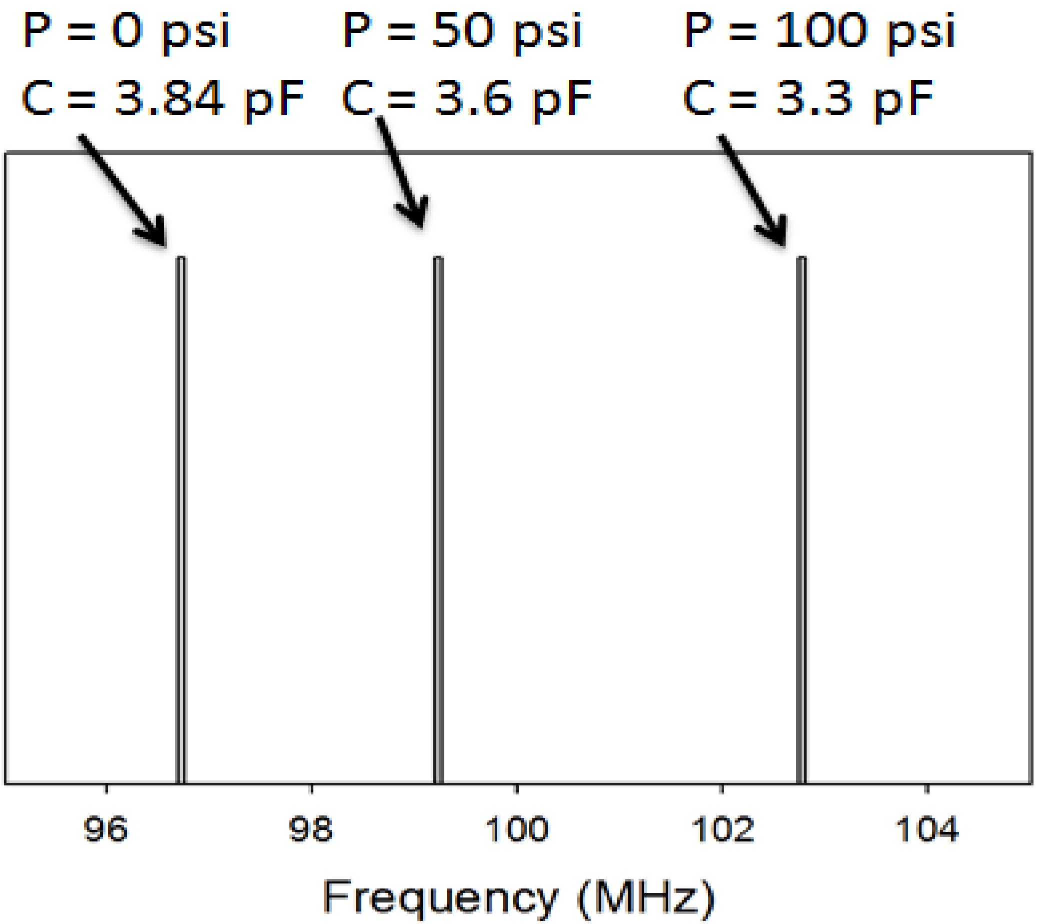
Oscillator Design

Circuit Simulations

Harmonic Balance Simulation

P = 0 psi f = 96.7 MHz
P = 50 psi f = 99.2 MHz
P =100 psi f = 102.8 MHz



Engine Testing

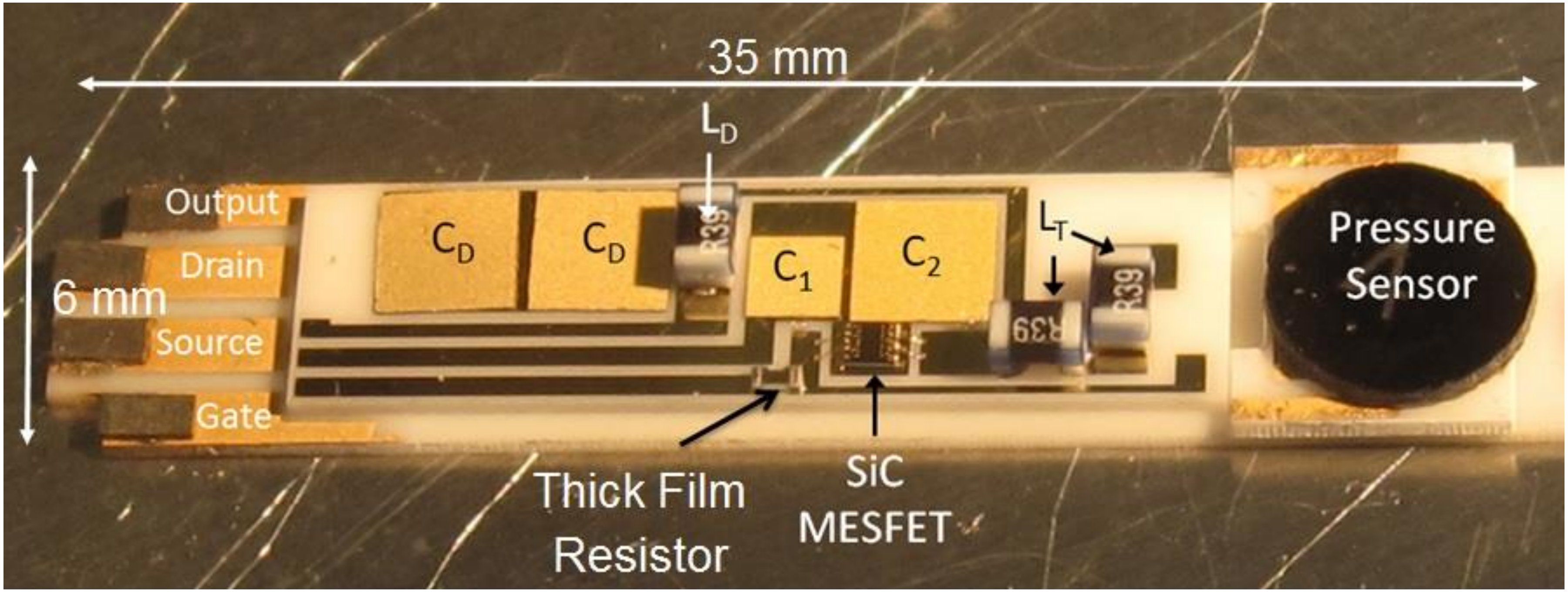
Packaged wired prototype has the following characteristics

- *Unpackaged Sensor System Size: 8 x 40 x 4 mm^3 (including on-board DC bias circuits)*
- *Form Factor: Packaged sensor equipped with borescope adaptor for a borescope plug on engine*
- *Maximum Operational Temperature: 500°C for 1 hour at tip of borescope adaptor*
- *Maximum Vibration: 5.3 G_{rms} along X-, Y- and Z-axis for 20 min*

Pressure Sensor System

Entire circuit assembled on a single alumina substrate

(6 x 35 x 2 mm^3)

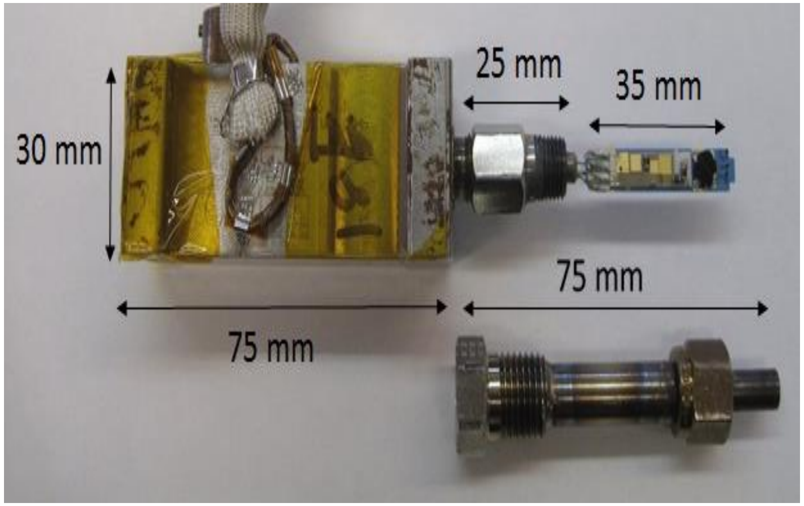


Pressure Sensor System

Packaged Sensor System Assembly

Key Features

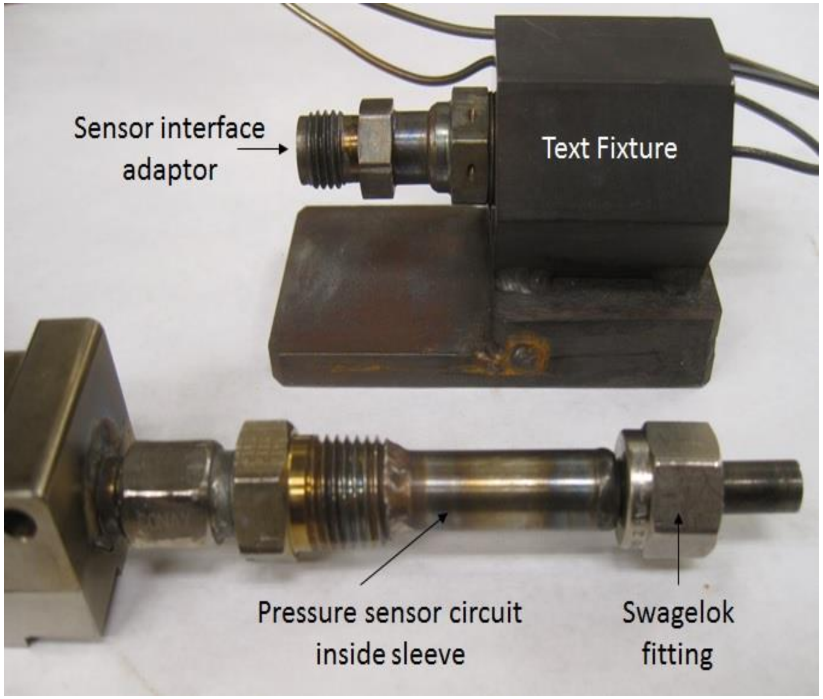
- Stainless steal packaging
- Thermo couples
- Custom connector/cable from package to facilitate input power and output signal
- Borescope plug adaptor
- Size: 30 x 150 mm



Pressure Sensor System

Bench-Top Acceptance Testing

- Custom-in-house pressurized fixture
- Packaged sensor is attached to quasi-borescope adaptor
- Thermocouple inside fixture to emulate inner engine temperature

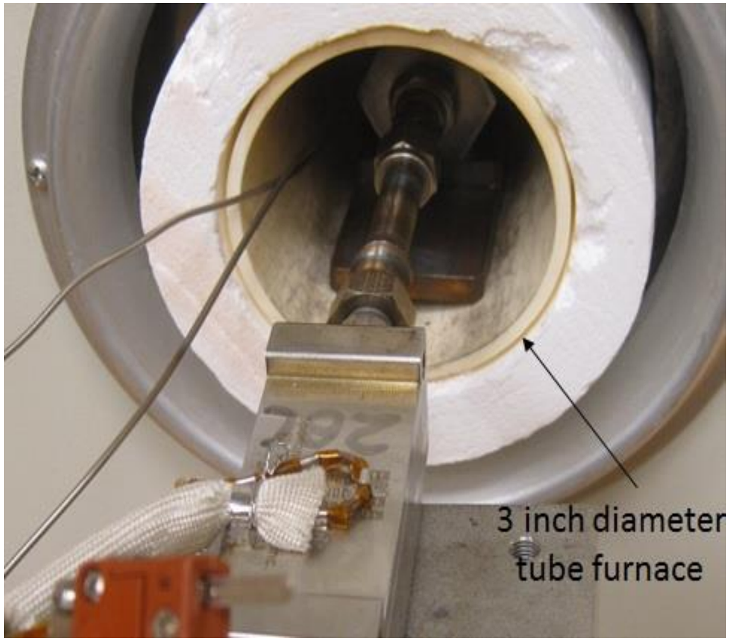


Pressure Sensor System

Bench-Top Packaged System Characterization

To emulate actual jet turbofan engine conditions the packaged sensor was heated to over 500°C and the pressure was increased from 0 to 300 psi.

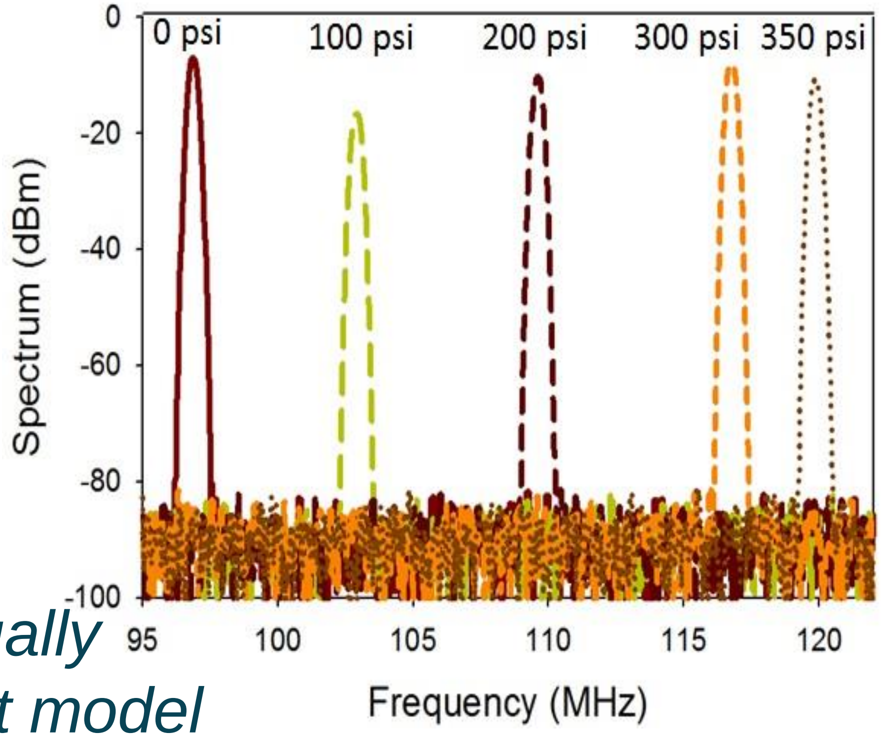
Note: The temperature recorded on the metal sleeve was ≈ 400°C, which is assumed to be the steady-state temperature of the system



Pressure Sensor System

Bench-Top Packaged System Characterization

0 psi	→ 96.88 MHz
100 psi	→ 102.79 MHz
200 psi	→ 109.54 MHz
300 psi	→ 116.77 MHz
350 psi	→ 119.86 MHz



Note: Simulated and measured response at 0 and 100 psi are virtually identical: Incredibly accurate circuit model

6.57×10^{-2} $\Delta f / \Delta P$ MHz/psi
Percent difference = 21.2%

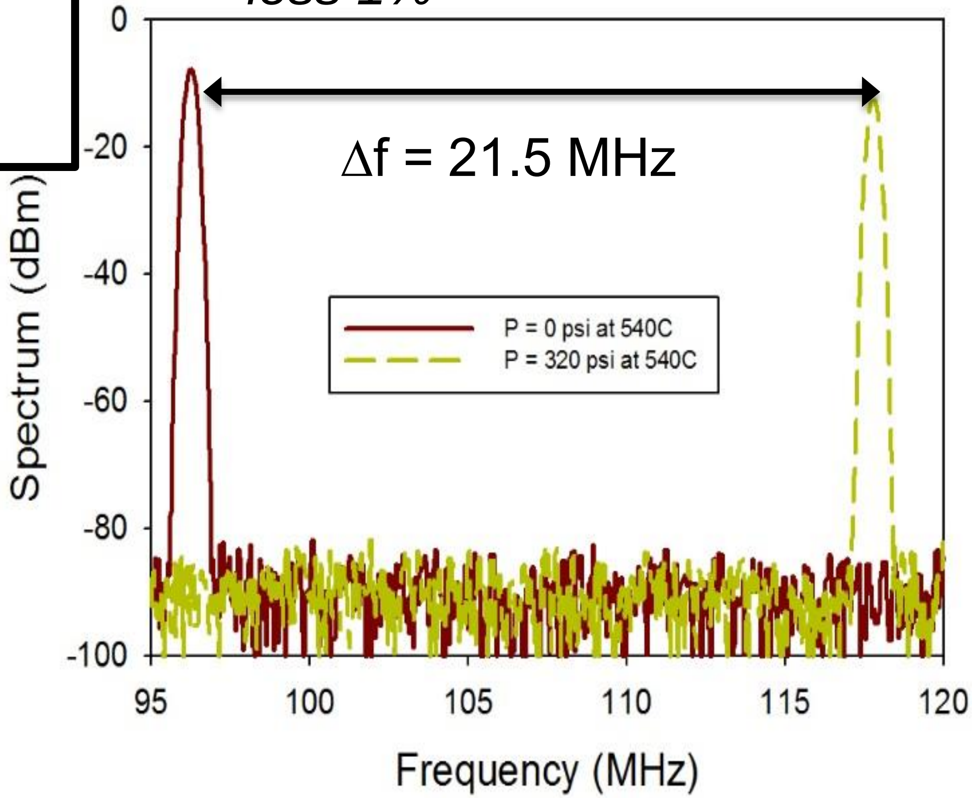
Spectrum response of packaged pressure sensor from 0 to 350 psi at 25°C

Pressure Sensor System

Bench-Top System Characterization

The temperature at the tip of the sensor inside the pressurized is fixture is 540°C
(≈ 400°C at the sleeve)

The change in frequency at 25 and 540°C at 0 psi is less 1%



0 psi → 96.3 MHz
320 psi → 117.8 MHz

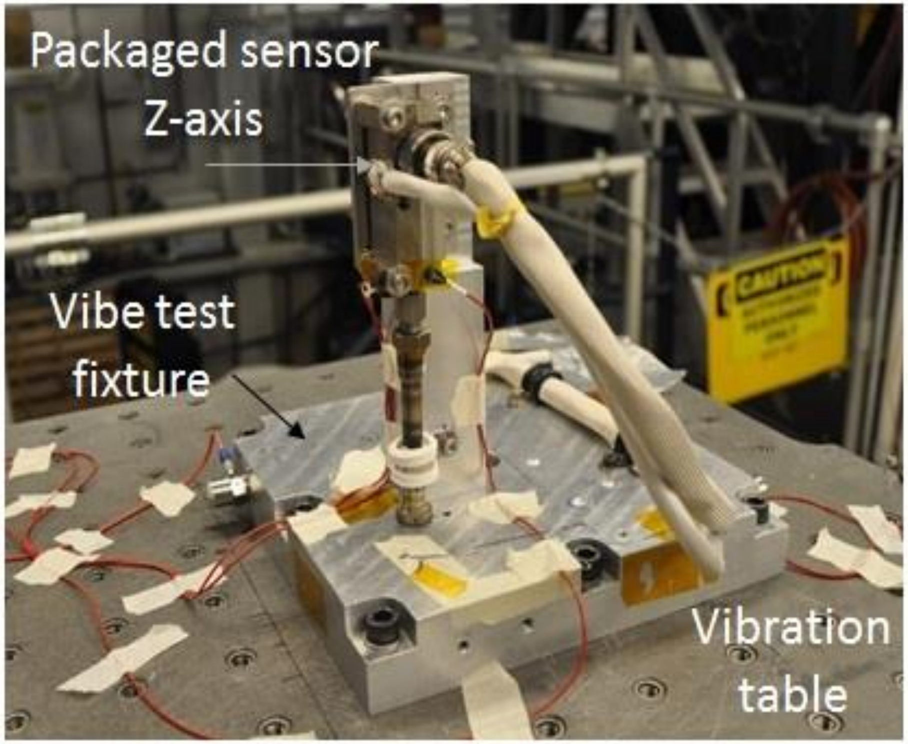
6.8×10^{-2} Δf/ΔP MHz/psi
Percent difference = 20 %

Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

- Emulate on engine testing
- Sine wave sweeps
- Random vibration
- Maximum vibration 5.3 G_{rms}
- X-, Y- and Z-axis testing
- Resonate frequency recorded at the beginning and end of each axis test. NO change!!

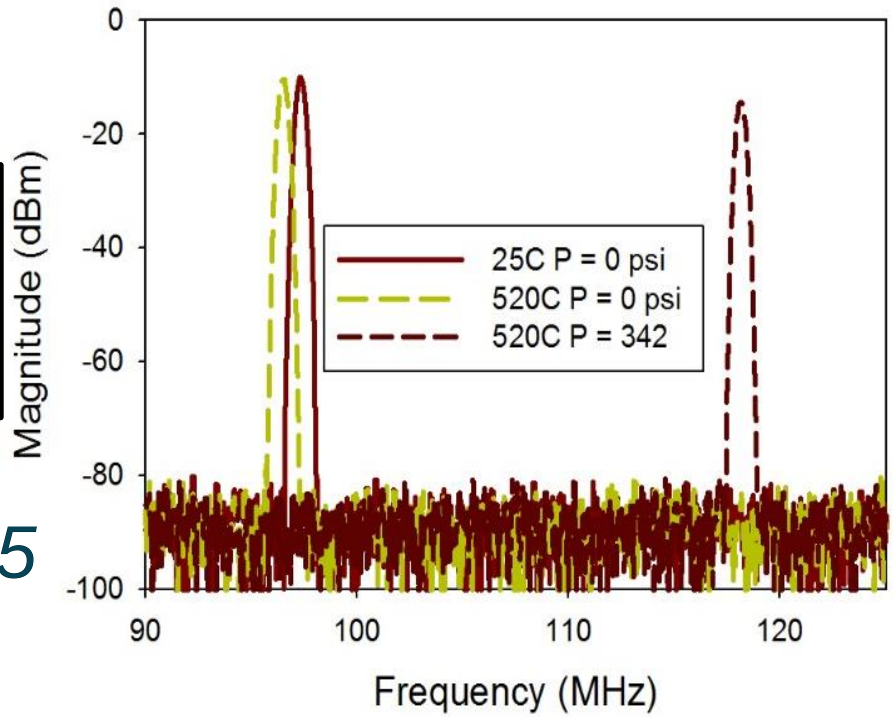


Pressure Sensor System

Bench-Top Packaged System Characterization

The packaged sensor system was again measured after structural dynamic testing.

0 psi → 25°C → 97.3 MHz
0 psi → 520°C → 96.5 MHz
342 psi → 520°C → 118.1 MHz



The change in frequency at 25 and 540°C at 0 psi is less 1%

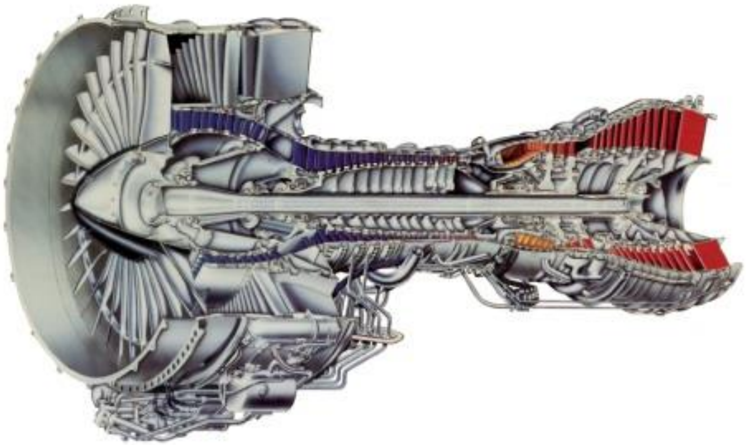
Vehicle Integrated Propulsion (VIPR)

VIPR was a series of ground-based on-wing engine demonstrations to mature aircraft engine health management technologies

Test vehicle was a U.S. Air Force C-17 aircraft equipped with Pratt & Whitney F117 engines

VIPR partners include NASA, U.S. Air Force, Pratt & Whitney, GE, Rolls Royce, Boeing, FAA, USGS, and other external organizations

Boeing C-17 Globemaster III



Pratt & Whitney F117 Turbofan Engine

VIPR3

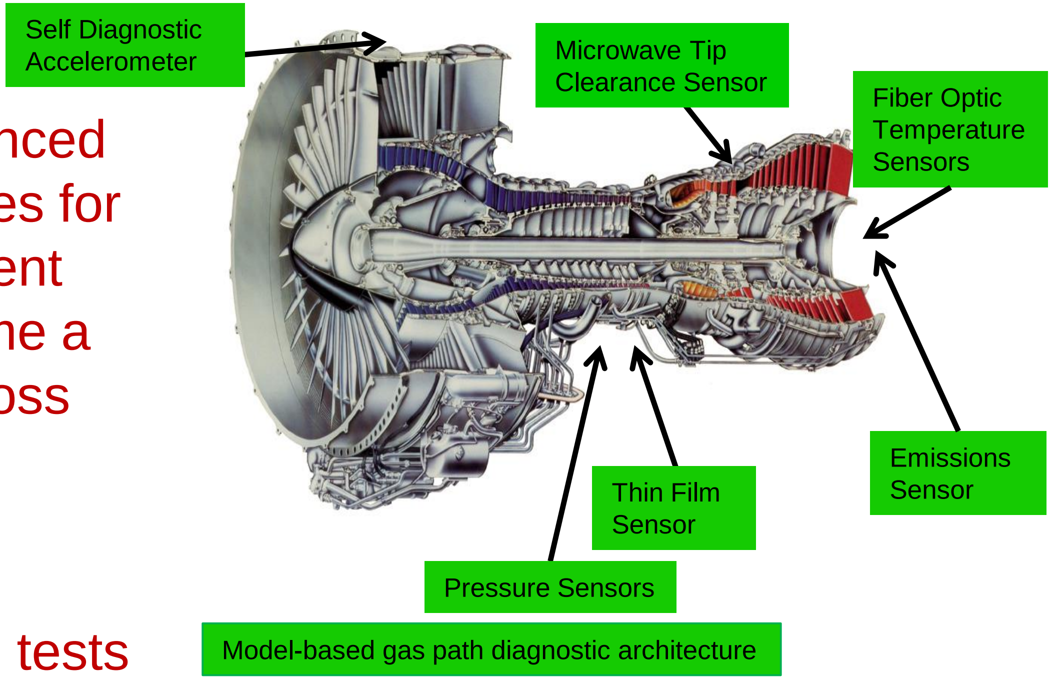
Test Objectives:

Demonstrate capability of advanced health management technologies for detecting and diagnosing incipient engine faults before they become a safety impact and to minimize loss of capability

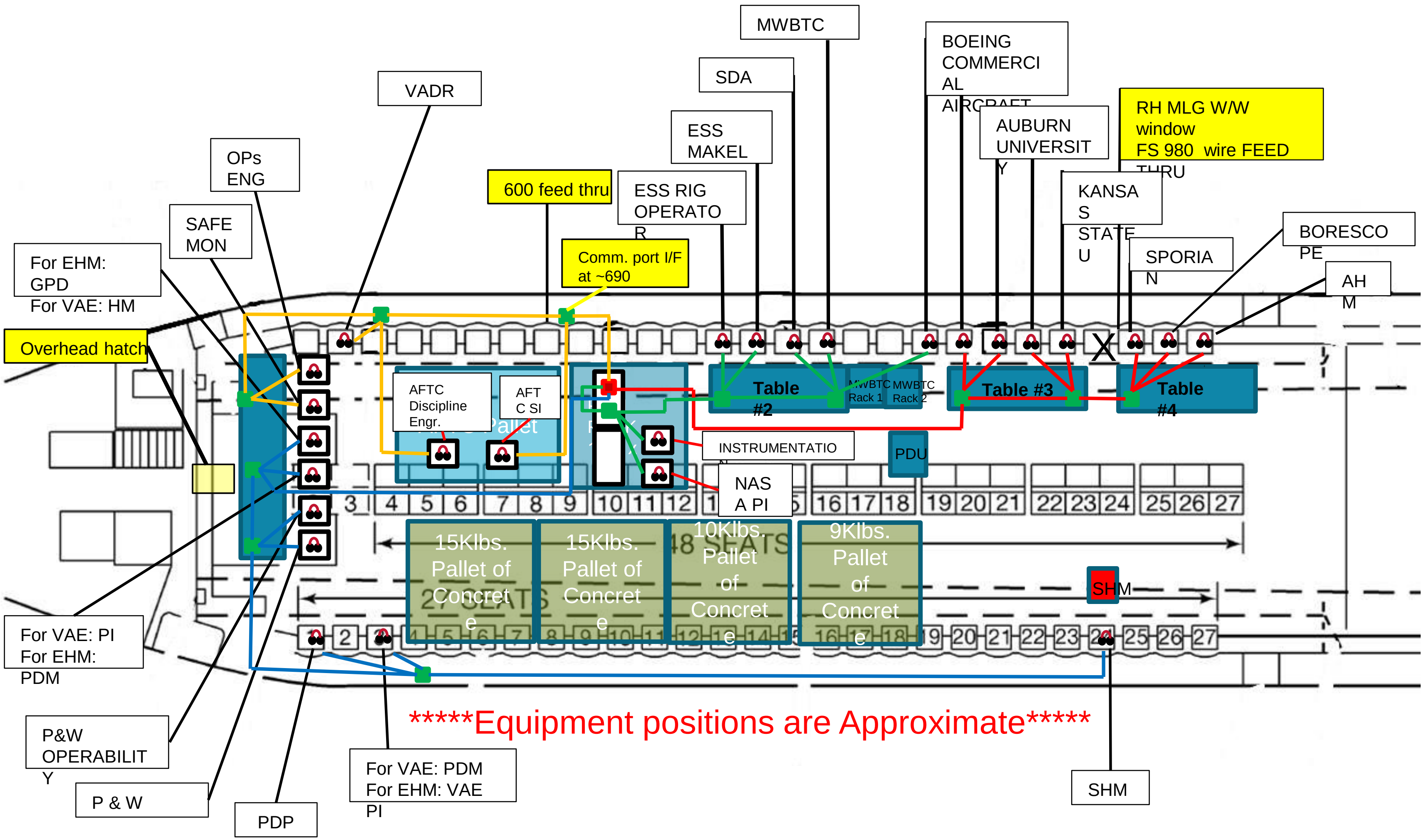
Approach:

Perform on wing engine ground tests

- Normal engine operations
- Seeded mechanical faults
- Seeded gas path faults
- Accelerated engine life degradation through volcanic ash ingestion testing



CST Aircraft / Communication Layout



*****Equipment positions are Approximate*****

Aircraft Research Station Layout

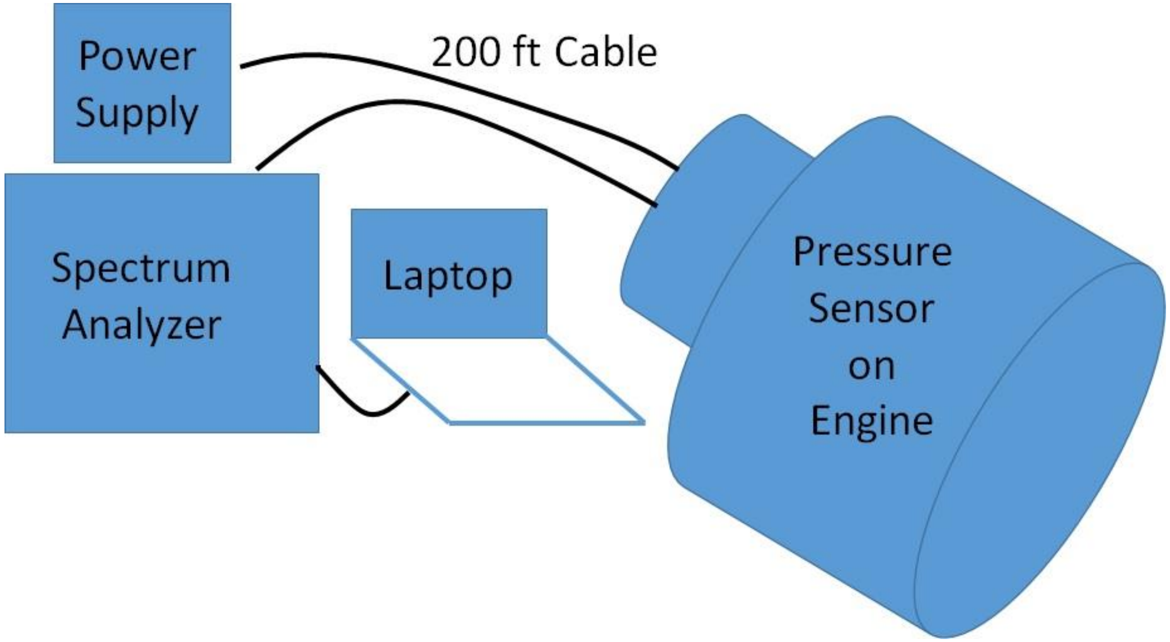
VIPR3

Aircraft Research Station Layout

VIPR3

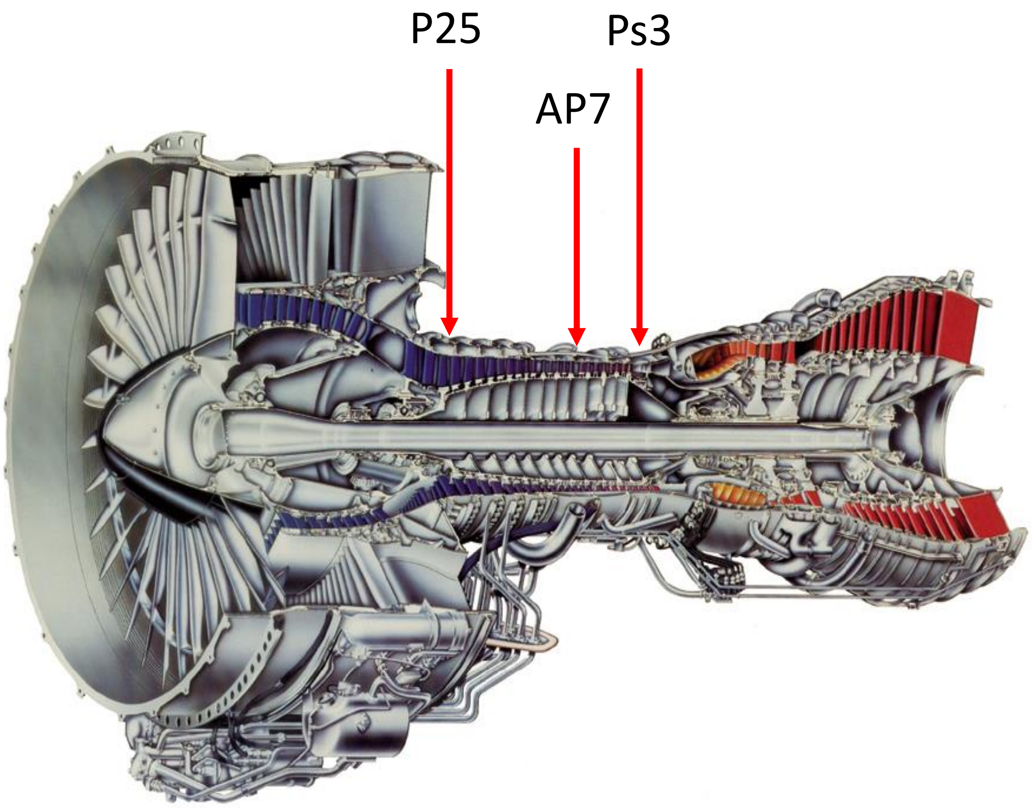
Measurement setup in fuselage to sensor on the engine attached to the wing

- Spectrum analyzer
- Power supply
- Laptop
- Labview program to record measurements
- 200 ft cable going from equipment to sensor on engine



Vehicle Integrated Propulsion (VIPR)

Sensed Pressure Locations



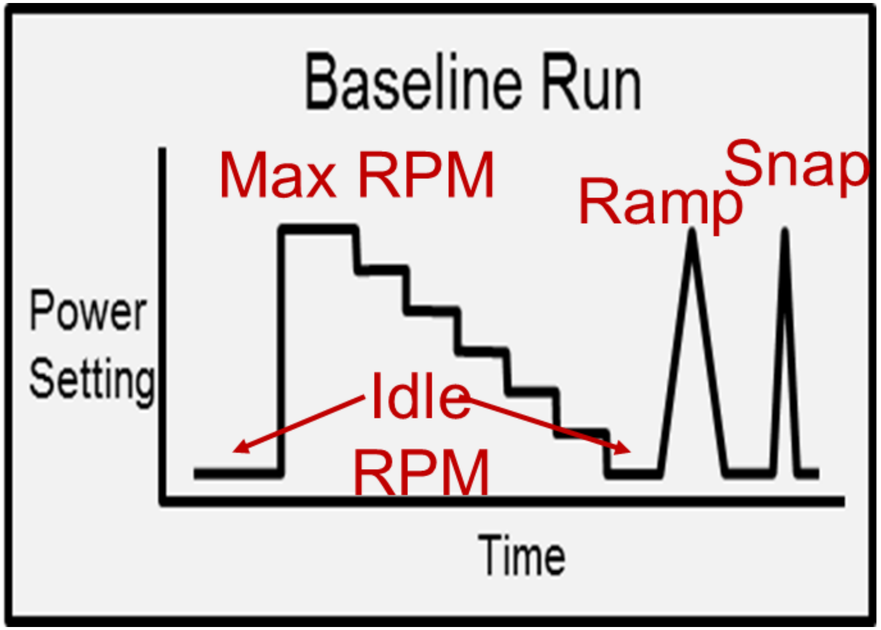
AP7:

High temp capacitive pressure sensor system

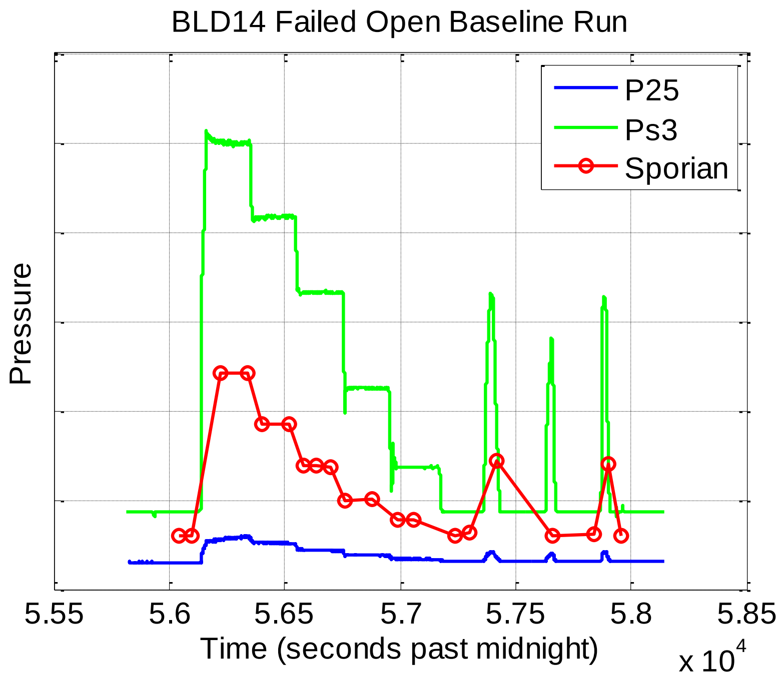
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Baseline Engine Test Profile



Sensor Output Data



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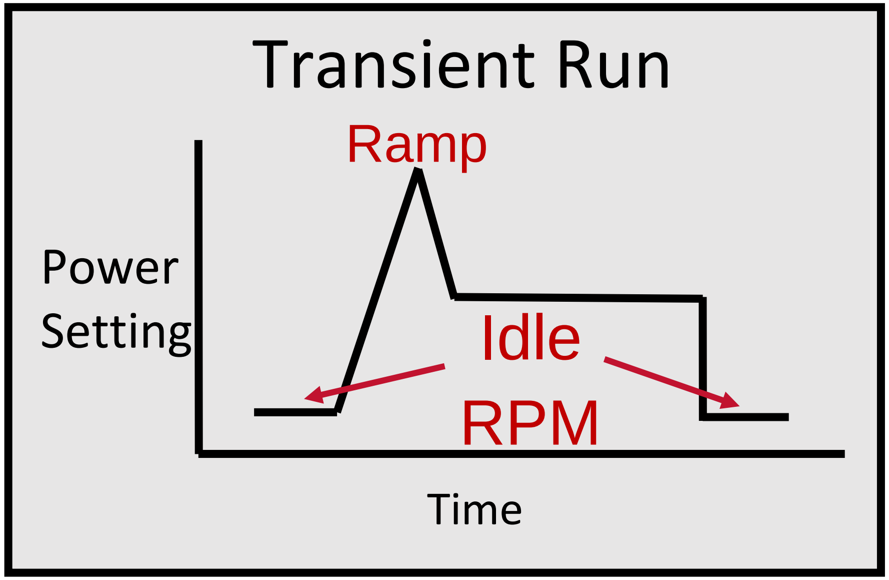
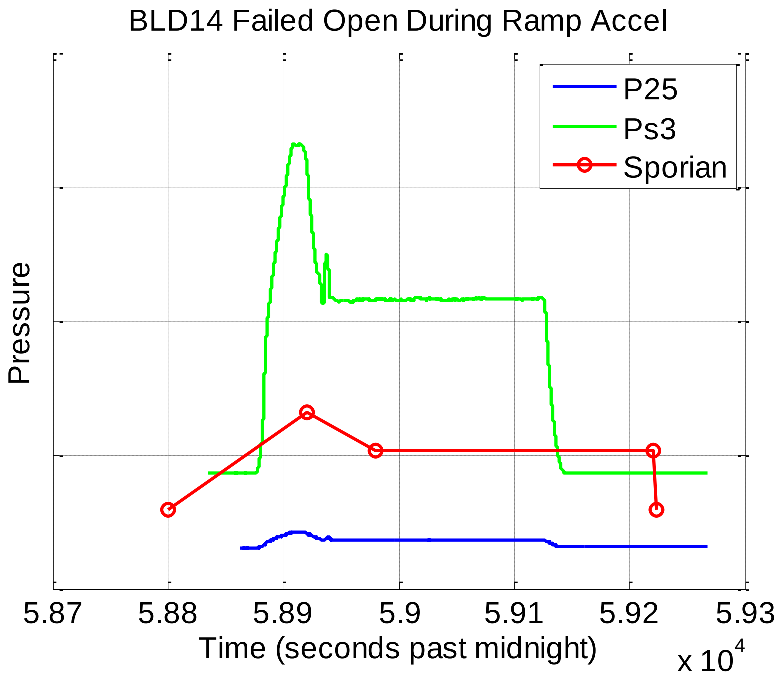
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Transient Engine Test Profile



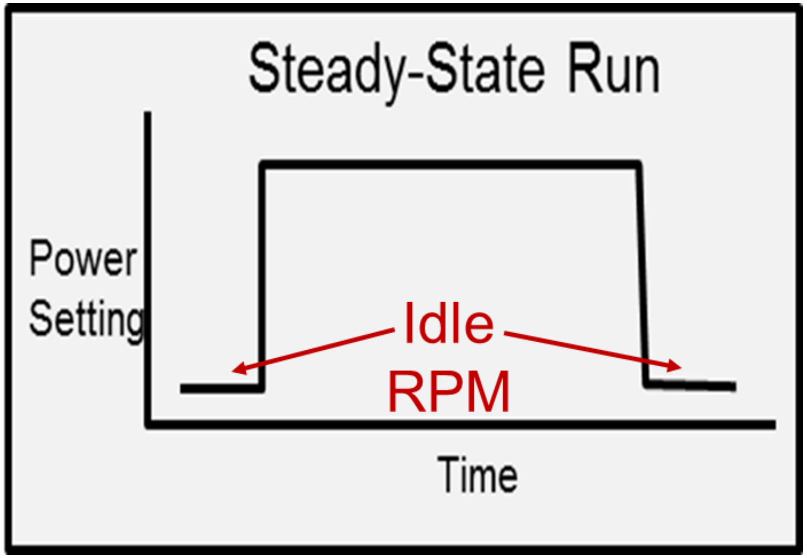
Sensor Output Data



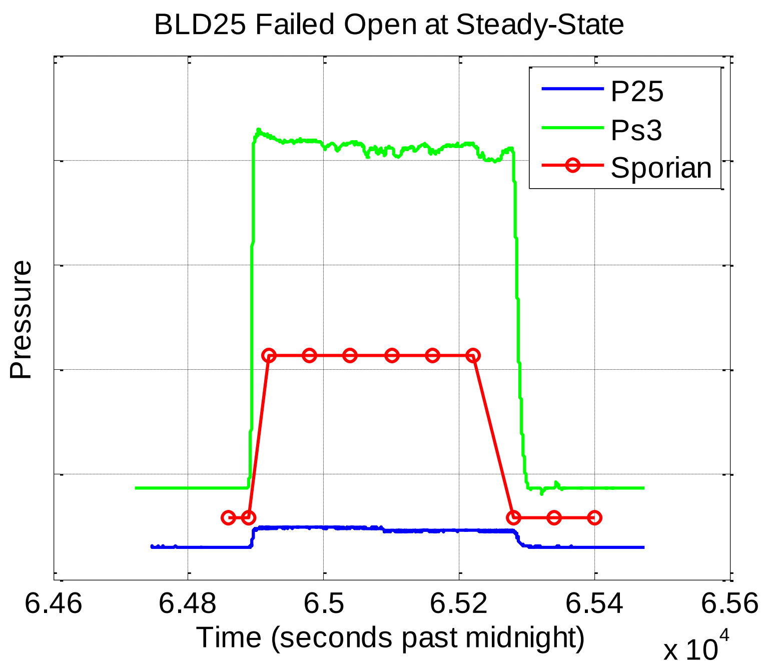
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Steady-State Engine Test Profile



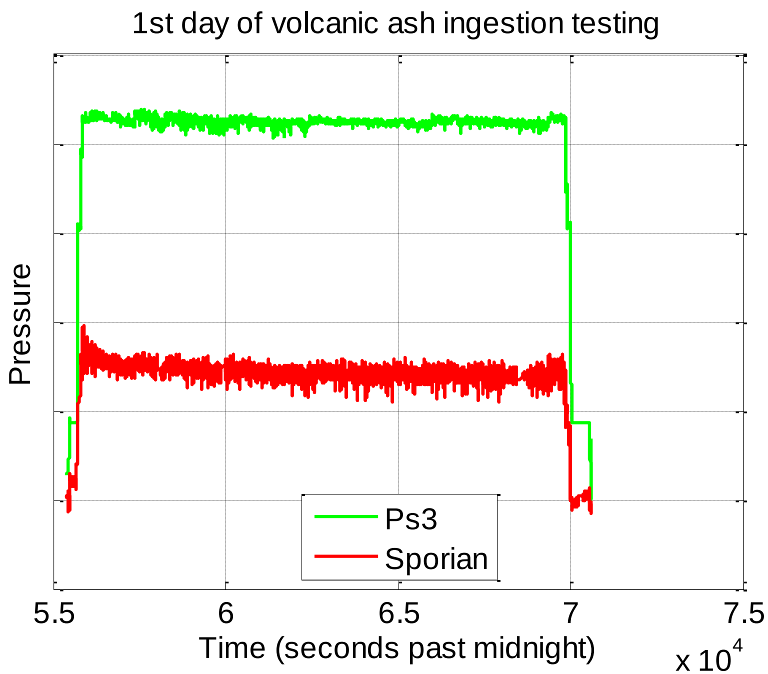
Sensor output data



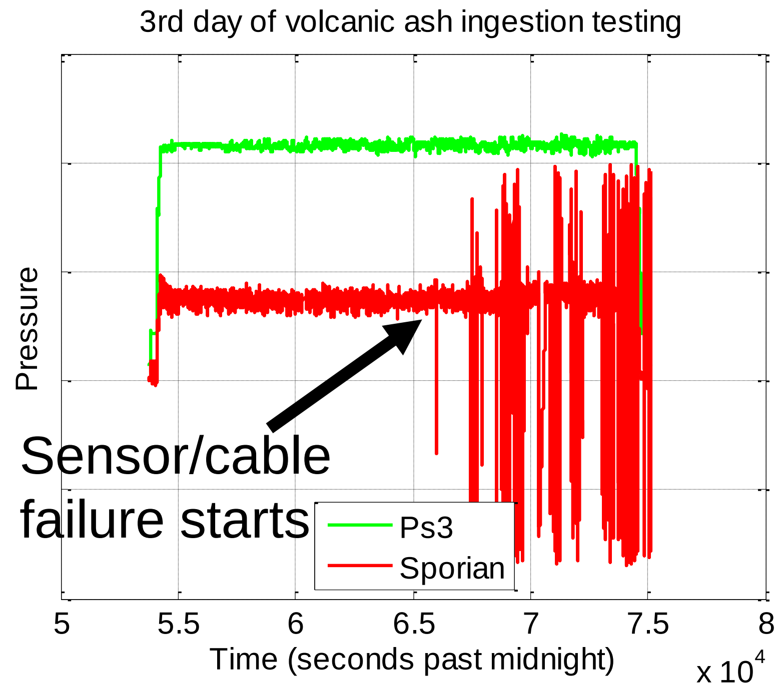
Packaged Sensor On-Engine

Volcanic Ash Testing

1st day of low flow volcanic ash ingestion testing



3rd day of low flow volcanic ash ingestion testing



14 hours low rate
ash testing 1 mg/cu meter

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Summary

- Simulated Clapp-type oscillator to prove concept
- Developed a packaged pressure sensor system
- Demonstrated accuracy of simulations vs. measured
- Performed pressure, temperature and vibration acceptance testing
- Successfully demonstrated sensor system tracking engine performance

Acknowledgements

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Thank you

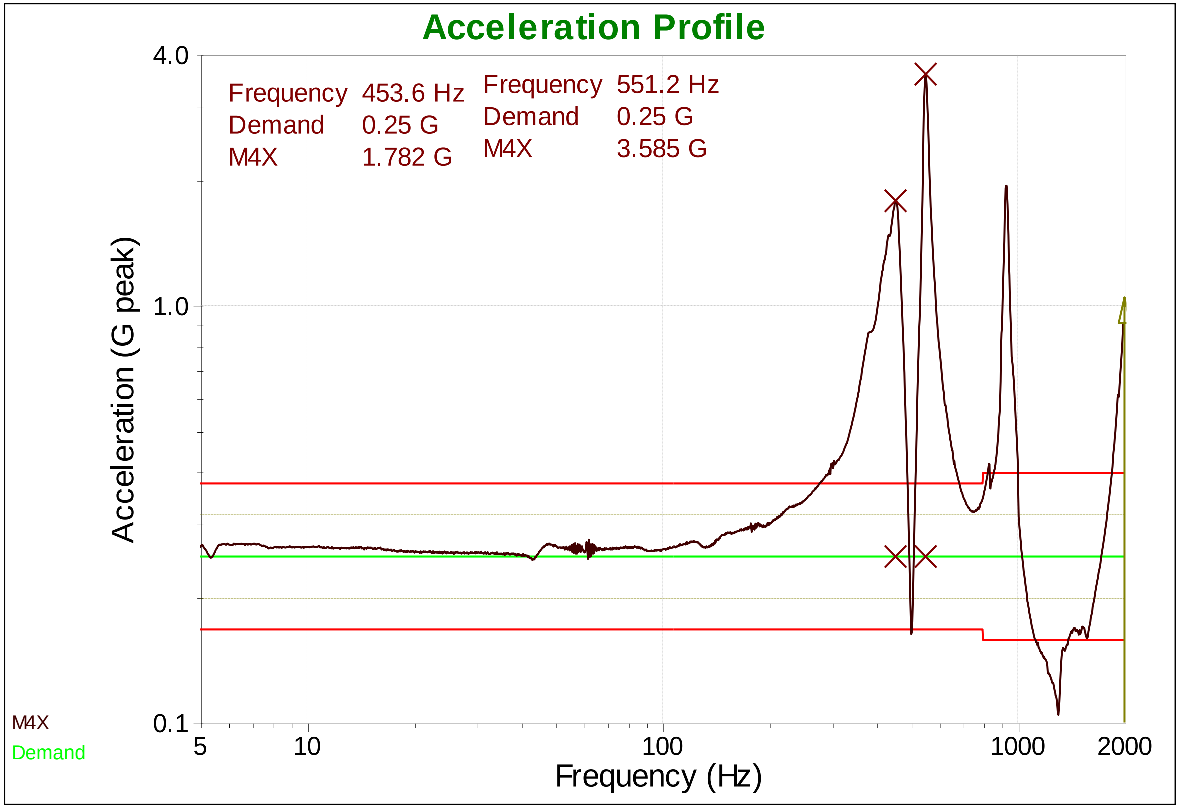
Appendix Slides

Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

1.4 g sinusoidal sweep profile



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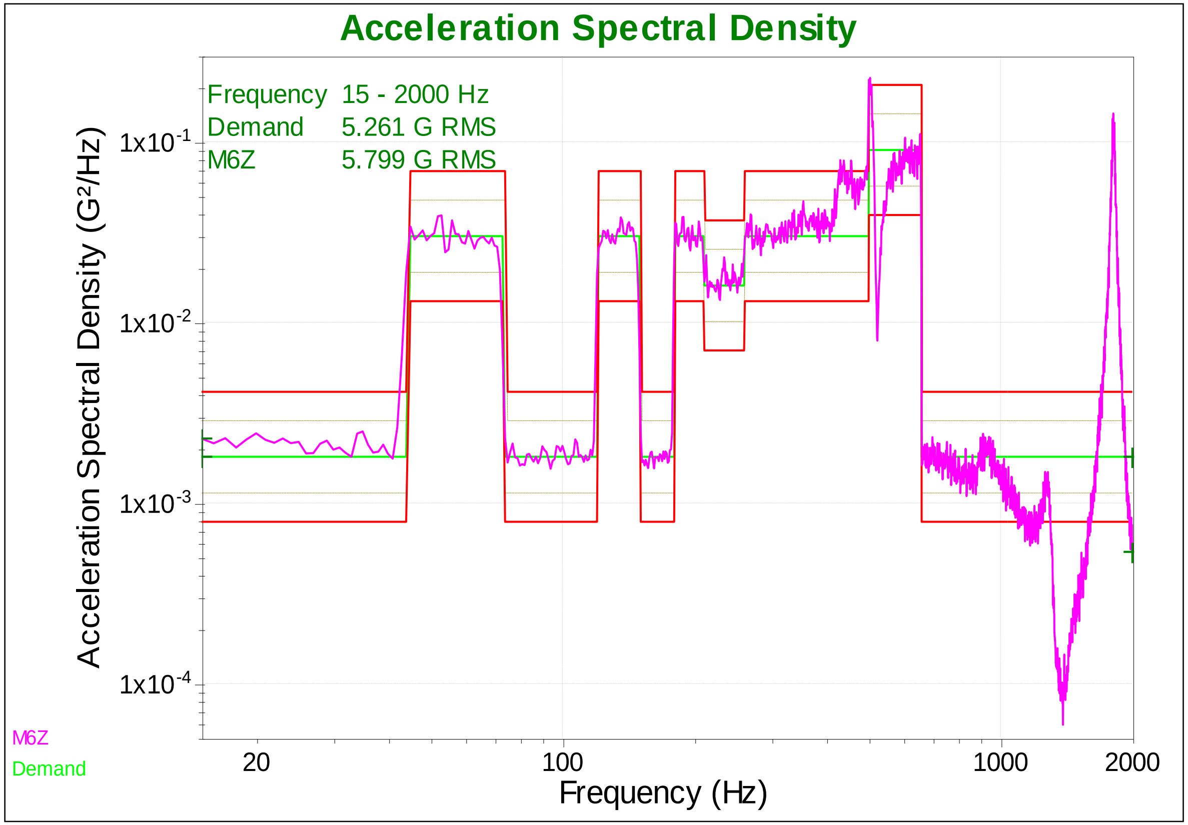
Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

5.3 Grms random vibration profile



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