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\textsubscript{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
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 $C_{\text{SENSE}}$ are in series and $C_{\text{SENSE}}$ 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

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.84</td>
</tr>
<tr>
<td>50</td>
<td>3.6</td>
</tr>
<tr>
<td>100</td>
<td>3.3</td>
</tr>
</tbody>
</table>

![SiCN Capacitive Pressure Sensor](image)

![Capacitance vs Pressure](image)
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
Circuit Simulations

Harmonic Balance Simulation

- 96.7 MHz 1st Harmonic
Oscillator Design

Circuit Simulations
To achieve oscillation stability
1) Phase must be zero at $f_0$
2) Loop gain must be greater than unity at $f_0$

Zero Phase at 96.7 MHz
Greater than unity at 96.7 MHz
Oscillator Design

Circuit Simulations

Harmonic Balance Simulation

P = 0 psi  \( f = 96.7 \text{ MHz} \)
P = 50 psi  \( f = 99.2 \text{ MHz} \)
P = 100 psi  \( f = 102.8 \text{ MHz} \)
Packaged wired prototype has the following characteristics

• Unpackaged Sensor System Size: 8 x 40 x 4 mm³ (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 mm³)
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.
Bench-Top Packaged System Characterization

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>96.88</td>
</tr>
<tr>
<td>100</td>
<td>102.79</td>
</tr>
<tr>
<td>200</td>
<td>109.54</td>
</tr>
<tr>
<td>300</td>
<td>116.77</td>
</tr>
<tr>
<td>350</td>
<td>119.86</td>
</tr>
</tbody>
</table>

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

\[ \frac{\Delta f}{\Delta P} = 6.57 \times 10^{-2} \, \text{MHz/psi} \]

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 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 x 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 $G_{\text{rms}}$
- 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.

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Temperature</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 psi</td>
<td>25°C</td>
<td>97.3 MHz</td>
</tr>
<tr>
<td>0 psi</td>
<td>520°C</td>
<td>96.5 MHz</td>
</tr>
<tr>
<td>342 psi</td>
<td>520°C</td>
<td>118.1 MHz</td>
</tr>
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</table>

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.
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
VIPR3

CST Aircraft / Communication Layout

*****Equipment positions are Approximate*****
VIPR3

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

BLD14 Failed Open Baseline Run

Pressure

Time (seconds past midnight)

5.55 5.6 5.65 5.7 5.75 5.8 5.85

x 10^4

P25
Ps3
Sporian

Max RPM
Ramp
Snap

Power Setting
Time

Idle RPM
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Transient Engine Test Profile

Sensor Output Data

BLD14 Failed Open During Ramp Accel

- P25
- Ps3
- Sporian

Power Setting

Time

Ramp

Idle

RPM

5.87 5.88 5.89 5.9 5.91 5.92 5.93 x 10^4

Time (seconds past midnight)
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Steady-State Engine Test Profile

Sensor output data

BLD25 Failed Open at Steady-State
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
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
Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

5.3 Grms random vibration profile