Passive Wireless Temperature Sensors and Pressure Sensors

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June 9, 2009
Outline

• Background and Motivation

• Passive Wireless Temperature Sensors
  – Battery powered wireless sensors
  – Colpitts oscillator – based passive wireless sensor
  – VCO – based passive wireless sensor
  – Meissner oscillator – based passive wireless sensor
  – RFID-based passive wireless sensor
  – Passive wireless integrated high temperature sensor

• Passive Wireless Pressure Sensor
  – Passive wireless integrated pressure sensor
  – Performance analysis and sensor design
  – Preliminary results

• Conclusions
Background and Motivation

• The information revolution has transformed our everyday lives forever by the always-on connectivity of the internet, but we still interact with two very separate worlds: the physical world in which we live and the online digital world of the web. Sensor technologies are the key to bridge the internet back to the physical world and promise to have profound impacts on our daily life.
Background and Motivation

• The primary objective of the proposed project is to conduct basic research into battery-free wireless sensing mechanism in order to develop prototypes of novel passive wireless sensor and sensor network for physical and chemical parameter monitoring in a harsh environment, which is critical to intelligent control of advanced power generation system, such as advanced gas turbine and advanced coal combustion applications.
Background and Motivation

- Rolling element bearings providing support and rotational freedom are critical mechanical components in virtually every type of equipment, included gas turbine.

- Due to the complex design and varying operation conditions, premature failure of individual bearings can occur at any time during its service.

- One of the leading causes of turbine engine failures is also directly related to roller element bearing failure.

- Temperature plays a vital role in the bearing health monitoring.
Cage temperature is a most sensitive parameter for bearing health monitoring

- The cage guiding the rolling elements is often the starting point of bearing damage.
- The bearing cage responds faster to an increase in heat input than other bearing component. This is due to:
  - Pure sliding motion between the rolling elements and the cage (great heat generation)
  - The mass of the cage is small
  - The cage is not in contact with heat dissipative elements
# Temperature Measuring on Different Parts of a Bearing

<table>
<thead>
<tr>
<th>Outer race</th>
<th>Standard instruments: Thermocouples, RTDs, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner race</td>
<td>Slip rings attached to the shaft in order to transmit the data to a stationary observer.</td>
</tr>
<tr>
<td>Cage</td>
<td>The motion of the cage is quite random since the cage is not attached or fixed to any of the bearing component. There is no way to directly monitor the temperature and vibration of the bearing cage. The size, weight and dynamics of the cage restrict the size of the sensor that can be installed on it without affecting its operation. Wireless micro-sensor can provide an effective solution to this problem. Battery-less operation is desirable.</td>
</tr>
</tbody>
</table>

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Cage Temperature Distribution
Battery-free Wireless Sensing Platform
Battery Powered Wireless Sensor

- The basic design of our first battery powered wireless sensor is called a Colpitts oscillator.
Battery Powered Wireless Sensor

- Based on Colpitts oscillator, the inductor $L_1$ and capacitors $C_1$ and $C_2$ form an oscillator tank. The frequency of the sensor is given by

\[
f = \frac{1}{2\pi} \sqrt{\frac{(C_1 + C_2)}{LC_1C_2}}
\]
Battery Powered Wireless Sensor

Battery Case

Inductor

Sensing Capacitor
RF Powering

- RF powering is based on the magnetic coupling between a transmitter (primary) coil driven by an alternating current, and a receiver coil. Both coils form a loosely coupled, coreless transformer. Coupling factor $K$ determines the received voltage in the secondary.

$$k = \frac{M}{\sqrt{L_t L_R}}$$
Passive Wireless Temperature Sensor

based on a Colpitts oscillator

Circuit diagram for RF powered wireless sensor

Temperature sensitive capacitors (C1 and C2) mounted on a bearing cage are integrated into Colpitts oscillator as frequency-controlling elements. The change in the value of the capacitor due to temperature variation translates into modulation of the oscillator frequency.
Passive Wireless Temperature Sensor

RF powered wireless temperature sensor using a Colpitts Oscillator
Passive Wireless Temperature Sensor

Power Coil

Transmitting Coil

Sensing Capacitor
Passive Wireless Temperature Sensor

RF-powered wireless temperature sensors based on Colpitts oscillator installed on a tapered roller bearing.
Passive Wireless Temperature Sensor

RF-powered wireless temperature sensor on a polyimide film
installed on a ball bearing

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Passive Wireless Temperature Sensor
based on a Voltage Controlled Oscillator

• Integrated Voltage Controlled Oscillator (VCO) is widely used in modern wireless systems

• A VCO based passive wireless temperature sensor is to use voltage output of an IC temperature sensor as input of VCO to realize wireless temperature monitoring

• IC temperature sensor gives a voltage as a function of the temperature fluctuation

• IC temperature sensors have very small size, very low power consumption and very high linearity.
Passive and Wireless Temperature Sensor

based on a Voltage Controlled Oscillator

Schematic diagram for RF-powered wireless temperature sensor based on a Voltage Controlled Oscillator.
Passive and Wireless Temperature Sensor
based on a Voltage Controlled Oscillator

RF powered wireless temperature sensor using a Voltage Controlled Oscillator and an IC temperature sensor
Integrated Passive and Wireless Temperature Sensor
based on a Meissner Oscillator

Principle of a passive wireless integrated sensor system

The advantages of this design are simplicity, low cost, absence of biasing resistor that reduce the quality factor and reduced number of active device generating noise etc.
Integrated Passive and Wireless Temperature Sensor
based on a Meissner Oscillator

- The natural frequency of the Meissner oscillator is given by

\[ f = \frac{1}{\sqrt{LC}} \]

- The capacitance changes in the resonator due to the changes in the bearing temperature vary the natural frequency of the LC tank, so, the frequency of the circuit is a function of the measured temperature.
Integrated Passive and Wireless Temperature Sensor
based on a Meissner Oscillator
RFID Technology

• Radio Frequency Identification (RFID) is a technology used to identify an object, with a RFID tag, contact less and without line of sight. The id of the object, which is a serial number in form of radio waves, is sent wireless to a reader. RFID can be used as an Automatic Identification and Data Capture (AIDC) System. These AIDC systems are used to track and monitor physical objects wirelessly, without human interaction the system perceives, thinks and does everything by itself.
Integrated Passive and Wireless Temperature Sensor

based on RFID Principle

• This approach is based on the Radio Frequency Identification RFID principle and therefore widely available on the marked.

• The main components of an RFID system are the reader and sensor unit. The reader transmits a continuous RF carrier signal. When a sensor unit enters the RF field of the reader, the sensor receives energy to operate. Once the sensor is energized by the transmitter, it modulates the carrier signal according to the data to be sent.

• Its main advantage is that the antenna used to transmit power is also used to receive information from the sensor.
Integrated Passive and Wireless Temperature Sensor
based on RFID Principle

• Sensing element: IC temperature sensor.

• The transducer output is digitized for enabling the backscattering modulation of the temperature data to the power-transmitting/reception unit.

• The class-E power amplifier was used to generate the RF carrier signal and to energize the sensing circuit. Furthermore to receive the modulated signal.
**Integrated Passive and Wireless Temperature Sensor**

**based on RFID Principle**

- Sensing element: IC temperature sensor.
- The transducer output is digitized for enabling the backscattering modulation of the temperature data to the power-transmitting/reception unit.
- This digitization is done by a V-F converter: 5 kHz to 10 kHz.
- The class-E power amplifier was used to generate the RF carrier signal and to energize the sensing circuit. Furthermore to receive the modulated signal.
Integrated Passive and Wireless Temperature Sensor
based on RFID Principle
Sensor Calibration Setup

[Diagram showing a setup with labeled components: Thermocouple Meter, Single-loop Antenna, Sensing Element, Glass Jar, Oil, Hot Plate (20°C to 450°C), LC Sensor, DAC, Function Generator, LC Sensor Reader, Oscilloscope.]
Calibration Results

Wireless temperature sensor based on a Colpitts oscillator

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Calibration Results

Wireless temperature sensor based on a VCO

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Calibration Results

Wireless temperature sensor based on a Meissner oscillator

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Calibration Results: Summary

<table>
<thead>
<tr>
<th>Sensor principle</th>
<th>Transducer type</th>
<th>Temperature range</th>
<th>Frequency range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colpitts Oscillator</td>
<td>Capacitive</td>
<td>20°C to 85°C</td>
<td>1.16 MHz to 2 MHz</td>
<td>15.7 kHz /°C</td>
</tr>
<tr>
<td>VCO</td>
<td>IC-temperature sensor</td>
<td>0°C to 125°C</td>
<td>53 MHz to 56 MHz</td>
<td>35.5 kHz /°C</td>
</tr>
<tr>
<td>Meissner Oscillator</td>
<td>Capacitive</td>
<td>20°C to 80°C</td>
<td>9 MHz to 21 MHz</td>
<td>180 kHz /°C</td>
</tr>
<tr>
<td>RFID</td>
<td>IC-temperature sensor</td>
<td>0°C to 125°C</td>
<td>5.6 kHz to 15 kHz</td>
<td>61.4 Hz /°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor principle</th>
<th>Data receiving antenna</th>
<th>Capture range of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colpitts Oscillator</td>
<td>Ferrite core AM radio coil</td>
<td>Up to 5 cm.</td>
</tr>
<tr>
<td>VCO</td>
<td>Loop wire</td>
<td>Up to 8 cm</td>
</tr>
<tr>
<td>Meissner Oscillator</td>
<td>Loop wire</td>
<td>Up to 1 cm</td>
</tr>
<tr>
<td>RFID</td>
<td>Loop wire (used also to transmit power)</td>
<td>same as the powering range (3 cm to 5 cm)</td>
</tr>
</tbody>
</table>
Experimental Setup

![Experimental Setup Image]

- Oscilloscope
- Spectral analyzer
- Spindle
- Power transmitter
- Instrumented bearing
- Antenna
- Load shaft

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Experimental results

1200 rpm with 25 pounds of load

1200 rpm with 45 pounds of load
Experimental results

1550 rpm with 25 pounds of load

1550 rpm with 45 pounds of load
Integrated Passive Wireless Temperature Sensor for Harsh Environment

- Passive wireless sensors presented above only operate under temperature 125 °C for bearing health monitoring.

- For a critical turbine engine environment, roller element bearings experience an oil wash within a temperature of 250 to 300 °C.

- There is a need to develop high temperature passive wireless sensors, which can monitor the bearing cage temperature up to 350 °C or more.
Passive Wireless Integrated Temperature Sensor

Passive Wireless Temperature Sensor
Structure of LTCC Passive Wireless Sensor

Integrated passive wireless temperature sensor
Passive Wireless Integrated Temperature Sensor

\[ C_S(T) = \frac{\varepsilon_0 \varepsilon_r(T) A}{t} \]

\[ L_S \approx \mu_0 R \left[ \ln \left( \frac{8R}{a} \right) - 1.75 \right] \]

\[ f_r = \frac{1}{2\pi \sqrt{L_s C_s}} \]
Sensor Performance Analysis

Equivalent Circuit Diagram of Wireless Telemetry System

\[ Z_R = j\omega L_R + R_R + \frac{1}{j\omega C_R} \]

\[ Z'_S = \frac{(\omega M)^2}{j\omega L_S + R_S + \frac{1}{j\omega C_S}} = -\frac{\omega^2 k^2 L_R L_S}{j\omega L_S + R_S + \frac{1}{j\omega C_S}} \]

\[ k = \frac{M}{\sqrt{L_R L_S}} \]

\[ \Delta Z'_S = \frac{\omega^2 k^2 L_R L_S}{j\omega L_S + R_S + \frac{1}{j\omega(C_S + \Delta C_S)}} \]

\[ Z_i = j\omega L_S + R_R + \frac{1}{j\omega C_R} + \frac{\omega^2 k^2 L_R L_S}{j\omega L_S + R_S + \frac{1}{j\omega(C_S + \Delta C_S)}} \]
## Sensor Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader Inductance $L_R$</td>
<td>1.5 µH</td>
</tr>
<tr>
<td>Sensor Inductance $L_S$</td>
<td>0.68 µH</td>
</tr>
<tr>
<td>Sensor Total Resistance $R_L$</td>
<td>6 ohm</td>
</tr>
<tr>
<td>Sensor Nominal Capacitance $C_S$ at 20°C</td>
<td>0.24 nF</td>
</tr>
<tr>
<td>Nominal Coupling Factor $k$</td>
<td>0.4</td>
</tr>
<tr>
<td>Reader Radius $r_R$</td>
<td>30cm</td>
</tr>
<tr>
<td>Inductor Radius $r_S$</td>
<td>28.5cm</td>
</tr>
<tr>
<td>Coupling Distance $d$</td>
<td>2.5cm</td>
</tr>
</tbody>
</table>
Sensor Performance Analysis

Impedance vs Sweep Frequency

Increasing Temperature

Impedance (ohm)

Frequency (MHz)
Sensor Performance Analysis

Voltage vs. Sweep Frequency

- $r=50\,\text{ohm}$ (blue solid line)
- $r=100\,\text{ohm}$ (green solid line)
- $r=500\,\text{ohm}$ (red dashed line)
- $r=1000\,\text{ohm}$ (cyan dotted line)

Sweep Frequency (MHz)
Temperature Sensor Prototypes

Sensing Element embedded
Experiment Setup

[Diagram showing experimental setup with labeled components: Single-loop Antenna, Sensing Element, LC Sensor, Glass Jar, Oil, Hot Plate, 20°C - 450°C, Thermocouple Meter, DAQ, Function Generator, LC Sensor Reader, Oscilloscope.]
Experiment Setup
Calibration result

Frequency vs. Temperature

Capacitance vs. Temperature
Passive Wireless Pressure Sensor

\[ C_p = \frac{\varepsilon_r(P)A}{d} \]
Pressure Sensor Design

![Diagram of a pressure sensor design with labeled components: Inductor Coil, Dielectric, Metal Plates, Stainless Steel Plates. Dimensions are indicated in millimeters (Unit:mm)].
Pressure Sensor Design Parameters

<table>
<thead>
<tr>
<th></th>
<th>Polyurethane</th>
<th>PDMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>17mm</td>
<td>17mm</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>17mm</td>
<td>17mm</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>2mm</td>
<td>2mm</td>
</tr>
<tr>
<td><strong>Young Modulus</strong></td>
<td>67Kpa</td>
<td>750Kpa</td>
</tr>
<tr>
<td><strong>Relative Permittivity</strong></td>
<td>4.33</td>
<td>2.65</td>
</tr>
<tr>
<td><strong>Number of Turns</strong></td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td><strong>Diameter of the Circular Coil</strong></td>
<td>50mm</td>
<td>50mm</td>
</tr>
<tr>
<td><strong>Diameter of Coil Wire</strong></td>
<td>0.4mm</td>
<td>0.4mm</td>
</tr>
</tbody>
</table>
# Sensor Electrical Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Polyurethane</th>
<th>PDMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Nominal Capacitance</td>
<td>Cs</td>
<td>5.53 pF</td>
<td>3.39 pF</td>
</tr>
<tr>
<td>Sensor Inductance</td>
<td>Ls</td>
<td>33.9μH</td>
<td>33.9μH</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>fo</td>
<td>11.62Mhz</td>
<td>14.84Mhz</td>
</tr>
<tr>
<td>Sensor Resistance</td>
<td>Rs</td>
<td>6 ohm</td>
<td>6 ohm</td>
</tr>
<tr>
<td>Reader Inductance</td>
<td>Lr</td>
<td>28 μH</td>
<td>28 μH</td>
</tr>
<tr>
<td>Reader Radius</td>
<td>R</td>
<td>7.5cm</td>
<td>7.5cm</td>
</tr>
<tr>
<td>Radius of Antenna Coil</td>
<td>r</td>
<td>2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>Coupling Distance</td>
<td>d</td>
<td>2.5cm</td>
<td>2.5cm</td>
</tr>
</tbody>
</table>
Sensor Performance Analysis

![Graphs showing frequency vs impedance for Polyurethane and PDMS]
Sensor Fabrication

1. Bond terminals
2. Apply Rubber
3. Place top plate
4. Apply adhesive layer
5. Place Stainless Steel Plates
6. Wind insulated Wire & bond both terminals

Copper Layers

Release for 2 hours
Pressure Sensor Prototype
Experimental Setup
Experimental Setup
Preliminary Results

![Pressure vs Frequency Graph]

- **Frequency (Mhz)**
  - 10.2
  - 10
  - 9.8
  - 9.6
  - 9.4
  - 9.2
  - 9

- **Pressure (Kpa)**
  - 0
  - 50
  - 100
  - 150
  - 200

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Preliminary Results

![Graph showing pressure vs frequency for PDMS and Polyurethane materials.](image)

**Pressure vs Frequency**

- **Frequency (MHz):** 13 to 7
- **Pressure (Kpa):** 0 to 140

Legend:
- PDMS
- Polyurethane
Summary

• Six different passive wireless integrated temperature sensors have been developed.
• Overall weight of two component sensor is only about 1.5 grams.
• Experimental results confirmed that the maximum temperature of our high temperature sensor has been reached to 225 °C.
• A prototype of the passive wireless integrated pressure sensor has been also developed with pressure range of 0-130 Kpa.
Thanks!

Question?