Systems and Structures Health Management Technical Group

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Optical Fiber Pressure Sensor for Nuclear Power Plant Monitoring

• Sponsor: EPRI

• Problem: Degradation of electronics due to exposure to nuclear radiation, often limits the life of monitoring system components in nuclear power plant applications

• Solution: Utilize optical fiber based sensors – high sensitivity and signal-to-noise ratio allows longer standoff distances without the need for transmitter electronics
Optical Fiber Pressure Sensor for Nuclear Power Plant Monitoring

- Pressure (single-ended or differential) induces strain in an optical fiber Bragg grating sensor.
- Pressure-induced strain is read using commercial optical fiber Bragg grating interrogator.
- Remote interrogation of optical fiber transducer eliminates extends life of sensor in radiation environment.
- Sensor has undergone environmental and operational testing.
Pressure sensor installation in PSU Steam Plant

- Pressure sensor was installed and operated successfully for 72 days across boiler feed water valve to demonstrate performance in a relevant environment.
**Sponsor:** US Army TARDEC

**Background:**
- Expeditionary fluid delivery systems allow the establishment of temporary pipelines for the delivery of fuel or water.
- Pipelines consist of a series of diesel engine driven pump stations connected by rigid pipe or flexible hose.
- A 50 mile pipeline may contain from 10-20 pump stations.
- Manual control of pump station operations and preventive maintenance checks and services drive manning reqs.
Autonomous Monitoring and Control of Expeditionary Fluid Delivery Systems

• Goals: demonstrate next-generation capability in the monitoring and control system.
  - The control system must support manual, local automatic and remote automatic modes.
  - Support remote control and monitoring from a common command center
  - The monitoring system will reduce the need for traditional preventive maintenance checks and services

• The combination of monitoring and control enables the ability to autonomously respond to degraded operating conditions and machinery failures.
Monitoring & Control Architecture

- Controller Inputs
- Sensor Data Controller Output
- Pump Controller
- Control Signals
- Auxiliary Sensors
- Diesel-driven Pump

Monitoring & Control Supervisor

Command and Control Node

- Comms
- Status Report:
  - Digital ID Tag
  - Engine Oil Pressure
  - Fuel Level
  - Fuel Tank Temperature
  - Engine Oil Temperature
  - Engine Coolant Temperature
  - Pump Suction Pressure
  - Pump Discharge Pressure
  - Voltage
  - Current
  - Operating Mode
  - Pump Operating Condition (GYR)
  - Diag/Prog Information
  - Maintenance Report

- Set Pressure Set Point
- Set Operating Mode
- Request status report
- Request Maintenance Report
- Set Monitoring thresholds

Automated Pump Station
OVERVIEW

Purpose: Develop nonlinear ultrasonics methods for nondestructive characterization of microstructural evolution in a metal alloy to enable life prediction modeling.

Objectives: The project aims to characterize the microstructure mechanisms activated in Alloy 617 by mechanical loading and dwell times at elevated temperature. The acoustic harmonic generation method will be researched for microstructural characterization. It is a nonlinear ultrasonics method with excellent potential for nondestructive evaluation, and even online continuous monitoring once high temperature sensors become available. It is unique because it has the ability to quantitatively characterize microstructural features well before macroscale defects (e.g., cracks) form. The nonlinear acoustics beta parameter will be correlated to microstructural evolution using a systematic approach to handle the complexity of multiaxial creep-fatigue and creep-ratcheting deformation. Thorough microscopy is required and will be conducted to correlate the beta parameter with individual microstructure mechanisms.

IMPACT

Logical Path: Correlate nonlinear ultrasonics with results from microstructure evaluation of mechanically loaded specimens.

Outcomes: A highly sought after nondestructive characterization capability will be developed for NGNP materials, providing an early indication of structural damage in high temperature piping. Results will enable improvement of the ASME-NH code with regard to Alloy 617. Moreover, four Ph.D. students will be trained for careers in the field of nuclear energy.

DETAILS

Principal Investigator: Cliff Lissenden
Institution: Penn State
Collaborators: North Carolina State & Tuskegee
Duration: 3 years
Total Funding Level: $1,000,000
TPOC: David Hurley
Federal Manager: Susan Lusica
Workscope: G4A-3
PICSNE Workpackage #: NEUP Project number 102946

RESULTS

Results: Thermal aging, tensile creep, and combined loading experiments have been conducted. Samples have been viewed with optical microscopy, SEM, and TEM. Nonlinear ultrasonic guided waves theory, simulation, and experiments have advanced the nondestructive characterization capabilities for plate and pipe geometries.


Accomplishments: Nonlinear guided wave propagation in pipes has been modeled to enable mode/frequency selection. Third harmonic generation experiments in Alloy 617 pipes have been correlated with microstructure evolution. An application for a provisional patent on nonlinear acoustic guided wave spectroscopy was submitted.
**OVERVIEW**

**Purpose:** Develop ultrasonic transducers and methods for online condition monitoring of LWR (up to 400°C) and NGNP (up to 950°C) components. Online monitoring of structural damage and precursors to damage will improve safety and operations of nuclear plants.

**Objectives:** The sensory system, monitoring methodology, data acquisition, and damage characterization algorithm that comprise a condition monitoring system will be researched. The objectives of this research are to: (1) assess the concept viability of spray-on piezoelectric coatings to generate ultrasonic guided waves that are sensitive to microstructure evolution, (2) provide a detailed technology gap analysis, and (3) create a comprehensive technology development roadmap.

**IMPACT**

Logical Path: is shown in the flowchart below

**Outcomes:** The much-desired ability to perform online condition monitoring in high temperature environments will be achieved through research and development of high temperature piezoelectric transducers and ultrasonic guided waves. The technology gap will be assessed and a roadmap developed.

**RESULTS**

**Results:** PZT/bismuth titanate and bismuth titanate/lithium niobate transducers were spray-deposited using sol-gels and powders. Electrodes were patterned using laser ablation to create comb transducers for preferential excitation of axisymmetric guided wave modes in pipes. Procedures were developed to deposit and process these transducers in the field on large structural components. Nonlinear guided waves for characterization of microstructure evolution associated with incipient material degradation were analyzed. Primary wave modes that generate strong higher harmonics were identified and a nonlinear guided wave spectroscopy method based on mixing waves to generate nonlinear interactions was developed. Journal articles include:


**Accomplishments:** Guided wave signals have been demonstrated for spray-on PZT/BiTi transducers on stainless steel pipe. A provisional patent application has been submitted for nonlinear acoustic guided wave spectroscopy.
Cliff Lissenden, Penn State Engineering Science and Mechanics
Arthur Motta, Penn State Nuclear Engineering
Igor Jovanovic, Penn State Nuclear Engineering
Sean Brennan, Penn State Mechanical Engineering
Karl Reichard, Penn State Applied Research Lab
John Popovics, Illinois Civil Engineering
Travis Knight, South Carolina Nuclear Engineering

Crack detection in barely accessible harsh environments

Advisory Board: Dwight Clayton, ORNL; John Wagner, ORNL; Ryan Meyer, PNNL; Harold Adkins, PNNL; Jeremy Renshaw, EPRI; Laszlo Zsidai, Holtec
TPOC: Steve Marschman, INL
Overall Goal: develop and demonstrate robotic multi-sensor inspection systems for monitoring dry cask storage canisters (detection of cracks and detection of SCC-inducing salts) and concrete overpacks (microcracks)

Hope Creek ISFSI

U.S. ISFSIs, Curie.ornl.gov
IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks

- **Canister Types**: sensing systems for welded stainless canisters, delivery system for MPC/HI-STORM, steel-clad and exposed concrete overpack
- **Access**: LIBS via optical fiber and multiple EMAT heads will be delivered via the HI-STORM ventilation system
- **Size Constraints**: robotic multi-sensor system will navigate to and operate in gap between full-length guide channels in HI-STORM overpack
- **Operational Implementation**: robotic multi-sensor system will be operated from outside the cask and follow ALARA
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Operational Implementation: robotic multi-sensor system will be operated from outside the cask and follow ALARA.
Environmental Requirements: the electronics and materials of the sensing equipment will survive 280 F (137 C) with a gamma dose of $2.7 \times 10^4$ Rad/h (270 Gy/h) for at least a few hours; The time to perform partial and full monitoring of the welds will be estimated.

Environmental Requirements: modeling effort will use COBRA-SFS and MCNP6.1 to calculate temperature and radiation field at various locations inside and on the cask surface.

Environmental Requirements: the robotic system will be designed to not damage the cask surfaces and be retrievable with a tether.

Material Compatibility: organic materials, cobalt, and Teflon will be avoided.

Gamma-ray irradiation at Penn State RSEC

IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks
Localization: the robotic system will be able to trace its position to within 2” (50 mm)

Measurements: LIBS Detection of deposited salts; demonstrate ability to detect 0.05-10 g/m² of NaCl deposited on stainless steel; quantitative benchmarking will be performed and detection limits explored

Measurements: ultrasound detection of cracks in canister; arbitrarily oriented semi-elliptical cracks 0.21x0.42” (5x10 mm); start with EDM notches and later demonstrate capability for realistic stress corrosion cracks

Measurements: noncontact ultrasound monitoring of exposed concrete overpack for microcracking; steel-clad concrete will also be inspected for voids and major disbonds
Measurements: radiation detection and temperature measurement for calibration of the models will be performed as part of the multi-sensor robotic system.

Data Acquisition and Management: DAQ system located outside the cask will acquire, process, and fuse data from the sensing systems; open file formats will facilitate collaboration in analysis of results.

Validation: systems will be demonstrated first on table-top experiments and later tried on partial and full mockups; the sensitivity of the robotic and sensing systems both to radiation and to thermal/humidity conditions will be demonstrated separately.

Validation: reproducibility of results will be demonstrated.
Sensor Layout for Inspection

Unrolled view of HI-STORM
Sensor Layout for Inspection

Unrolled view of HI-STORM
The second prototype is primarily to test the geometric constraints of the robot and the cask.
The second prototype is primarily to test the geometric constraints of the robot and the cask.
The curvature of the cask limits the robot height to less than 1.77 inches, and the width to less than 7.99 inches.
Navigation of the 90° bends limits the length of each robot section.
Health Monitoring Methods for Joints in Rotorcraft Composite Structures

B Ren, CJ Lissenden, JL Rose

Vertical Lift Research Center of Excellence (Army, Navy, NASA)

http://www.sikorsky.com/

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PVDF Array Receiver:
- broad-banded (0.2-3 MHz)
- conformable to curved surfaces
- low profile (0.3 mm thick)
- low mass (3 g)
- inexpensive (25 USD)

Damage Detection Via Mode Conversion
HIGHER HARMONIC ULTRASONIC GUIDED WAVES FOR STRUCTURAL INTEGRITY ASSESSMENT OF INFRASTRUCTURE

CJ Lissenden, G Choi, V Chillara, H Cho

National Science Foundation, Structural Mechanics and Materials, Sensors and Sensing Systems, Hazard Mitigation and Structural Engineering
Need to decrease the detectable damage threshold and shift to the left along service life axis. Fatigue for example...

However, **Shift Left** using the same methods means POD ↓ and false calls ↑

Therefore, we need a different method!
Need to decrease the detectable damage threshold and shift to the left along service life axis. Fatigue for example…

What methods are sensitive to microstructure?

- microstructural feature, e.g., PSBs
- minimum detectable crack size
- macrocrack initiation

What methods are sensitive to microstructure?
Wave mixing has unique advantages for sensitive SHM:
1. combinational harmonics at frequencies that are not integer multiples of the excitation frequency.

\[
\begin{align*}
T_1 & \quad \text{Mode A}_0 \text{ at } f_1 \\
T_2 & \quad \text{Mode S}_1 \text{ at } f_2
\end{align*}
\]

\[f_1 = 1.67 \text{ MHz}\]
\[f_2 = 0.83 \text{ MHz}\]

**Combinational Harmonics**
- Second Order: \(f_1 + f_2, f_2 - f_1\)
- Third Order: \(f_1 + 2f_2, 2f_1 + f_2, 2f_1 - f_2, \text{etc.}\)

Amplitude (a.u.)
\[
\begin{align*}
\text{Frequency (MHz)} & \quad 0 & 1 & 2 & 3 & 4 & 5 & 6 \\
\text{Amplitude} & \quad 0 & 0.5 & 1 & 0 & 0.5 & 1 & 0
\end{align*}
\]

Frequencies and modes must be carefully selected!
Wave mixing has unique advantages for sensitive SHM:

1. combinational harmonics at frequencies that are not integer multiples of the excitation frequency.

### A few examples...

<table>
<thead>
<tr>
<th>Mode pair</th>
<th>Wave field</th>
<th>Frequency (MHz)</th>
<th>(C_p) (mm/(\mu)s)</th>
<th>Wavelength (mm)</th>
<th>Wavenumber</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Primary modes</td>
<td>A0</td>
<td>0.58</td>
<td>2.429</td>
<td>4.1879</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>S1</td>
<td>1.60</td>
<td>6.708</td>
<td>4.1925</td>
<td>1.49</td>
</tr>
<tr>
<td>Sum harmonics</td>
<td>A1</td>
<td>2.18</td>
<td>4.5612</td>
<td>2.09229</td>
<td>3.00</td>
</tr>
<tr>
<td>2 Primary modes</td>
<td>A0</td>
<td>3.76</td>
<td>2.9328</td>
<td>0.78</td>
<td>8.05</td>
</tr>
<tr>
<td></td>
<td>S1</td>
<td>2.40</td>
<td>5.709</td>
<td>2.3785</td>
<td>2.63</td>
</tr>
<tr>
<td>Sum harmonics</td>
<td>A2</td>
<td>6.16</td>
<td>3.6212</td>
<td>0.588</td>
<td>10.68</td>
</tr>
<tr>
<td>3 Primary modes</td>
<td>SH2</td>
<td>1.78</td>
<td>6.30</td>
<td>3.54</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>SH4</td>
<td>3.56</td>
<td>6.30</td>
<td>1.77</td>
<td>3.55</td>
</tr>
<tr>
<td>Diff harmonics</td>
<td>S1</td>
<td>1.78</td>
<td>6.30</td>
<td>3.54</td>
<td>1.77</td>
</tr>
</tbody>
</table>

**Combinational Harmonics**
- Second Order: \(f_1+f_2, f_2-f_1\)
- Third Order: \(f_1+2f_2, 2f_1+f_2, 2f_1-f_2, \) etc.
Wave mixing has unique advantages for sensitive SHM:
1. **Localized degradation** can be characterized by scanning the domain using time delays.

---

**Diagram:**
- Interaction Point
- T1
- T2
- Transmitter #1
- Transmitter #2
- A1 Sum harmonic from A0@0.58 MHz and S1@1.60MHz

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**Graph:**
- $\varepsilon$ (Sum harmonic increment)
- Position (mm)

---
Wave mixing has unique advantages for sensitive SHM:

3. historical baseline can conceivably be replaced by a spatial baseline.

The spectral amplitude of the received higher harmonic is a function of material nonlinearity and propagation distance (cumulative higher harmonic, diffraction, attenuation)
Localized degradation, for example in a pipe, can be scanned and a tomogram created.

Sum harmonic from $T(0,1)@0.7\; MHz$ and $L(0,2)@1\; MHz$