U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle System

Advanced Sensors and Instrumentation Annual Webinar

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Project Overview

- Goal and Objective

To develop and evaluate high temperature embedded/integrated sensor systems (HiTEISs) for applications in reactor and fuel cycle systems.

- Participants (2019)

Xiaoning Jiang, PI, North Carolina State University

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Leigh Winfrey, Co-PI, Pennsylvania State University

- Schedule

Task 1: HiTEIS design and development (Year 1 & 2)

Task 2: HiTEIS Integration and characterization (Year 2 & 3)

Task 3: Development of embedded sensors and laser ultrasound (Year 2 & 3)

Accomplishments

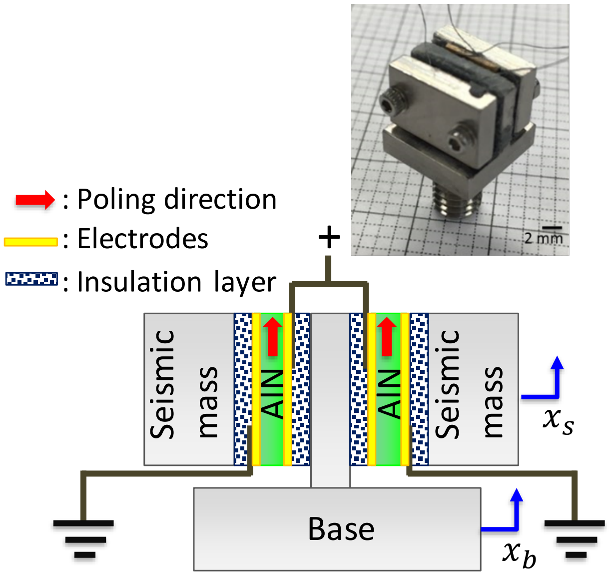
<u>Accomplishment 1:</u> HT vibration sensor and characterization

<u>Purpose:</u>

- To develop and characterize a HT vibration sensor for nuclear power plant application

<u>Methods:</u>

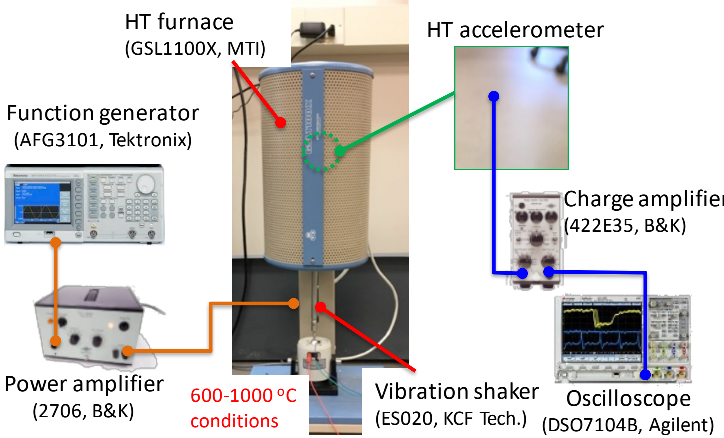
A. Sensor design and fabrication



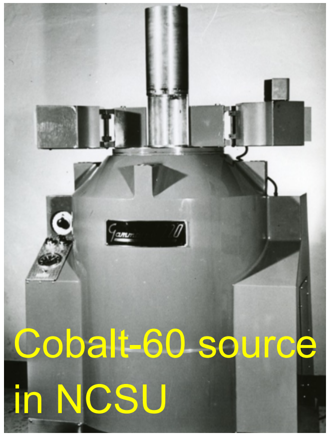
AlN based shear-type accelerometer

B. Characterization

1. HT (~1000 °C) test



2. Radiation (9 kGy) test

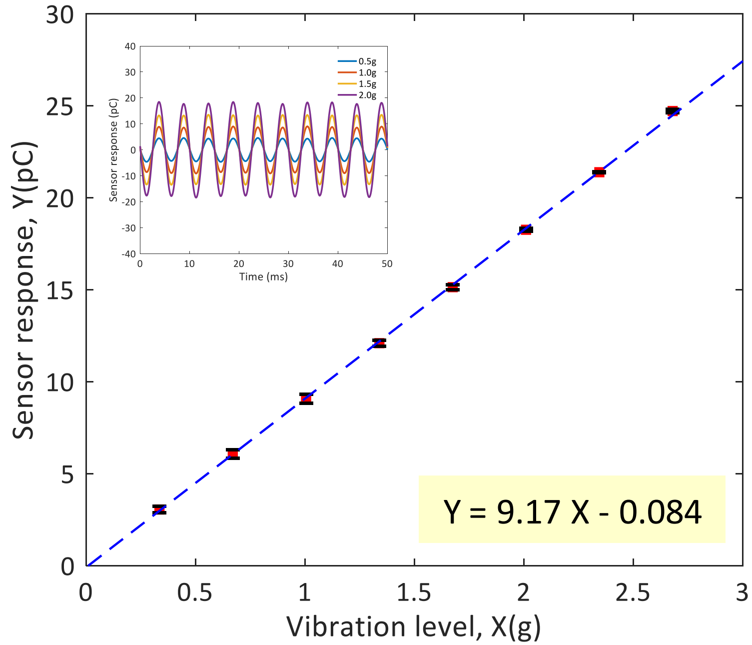


Sensor validation under HT and radiation fluence

Accomplishments

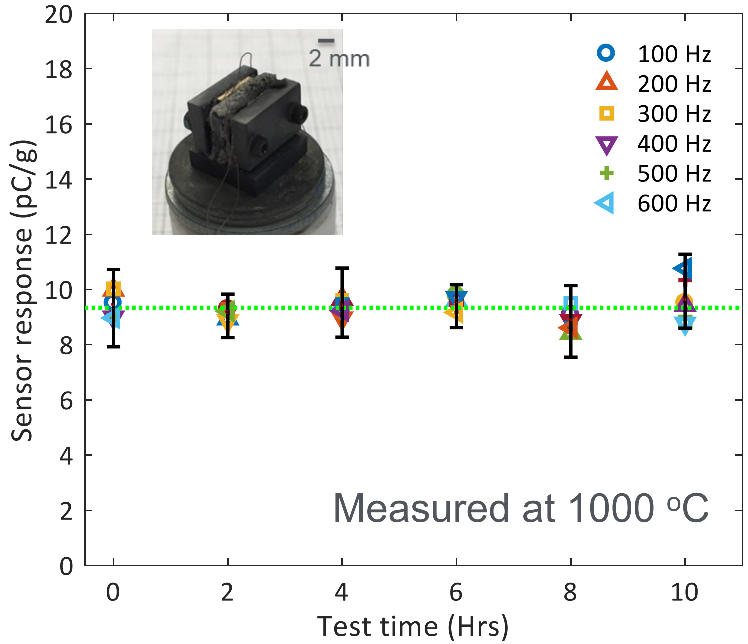
Results:

A. Sensitivity



Sensitivity ~ 9.2 pC/g
(greater than the previous YCOB sensor (+60%))

B. HT endurance



No significant damage or crack under HT
Stable sensor performance

Conclusions:

- Developed a vibration sensor performing under HT condition (~ 1000 °C)
- Radiation effect (9 kGy (kilogray)) of the sensor is currently being tested.

Accomplishments

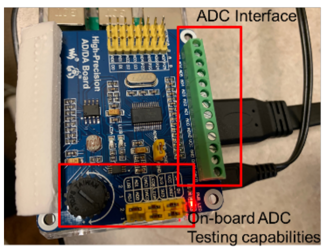
<u>Accomplishment 2:</u> HT Vibration Sensor Development and Characterization

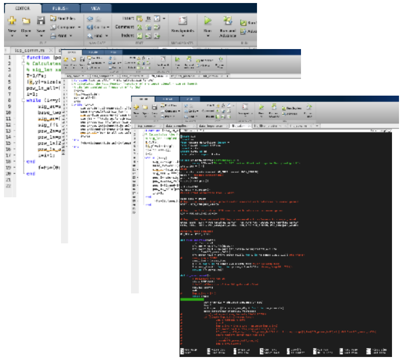
<u>Purpose:</u>

- To develop the wireless communication system for the HiTEIS

<u>Methods:</u>

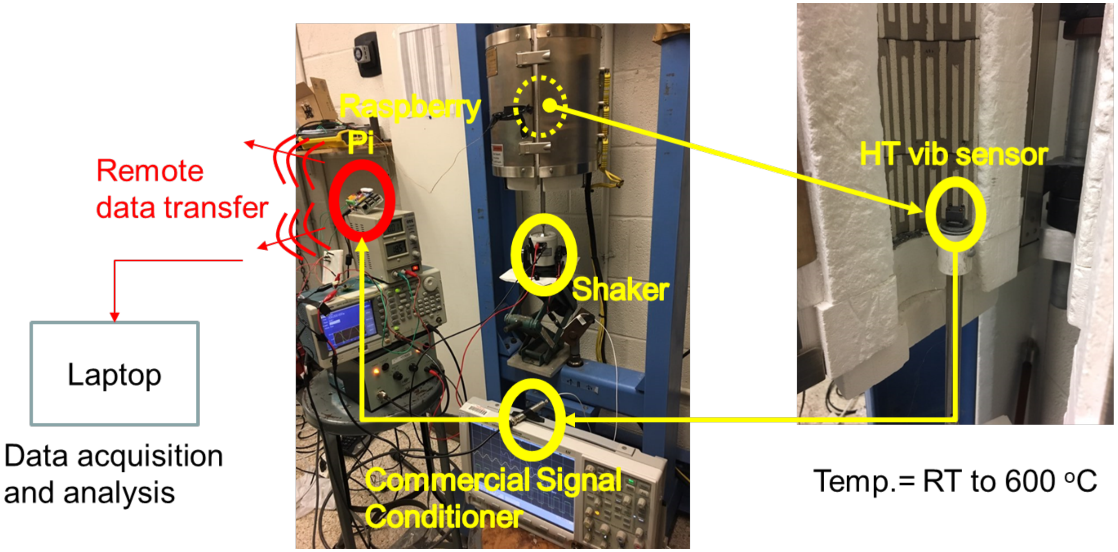
A. Data communication system





Software/hardware development

B. System validation

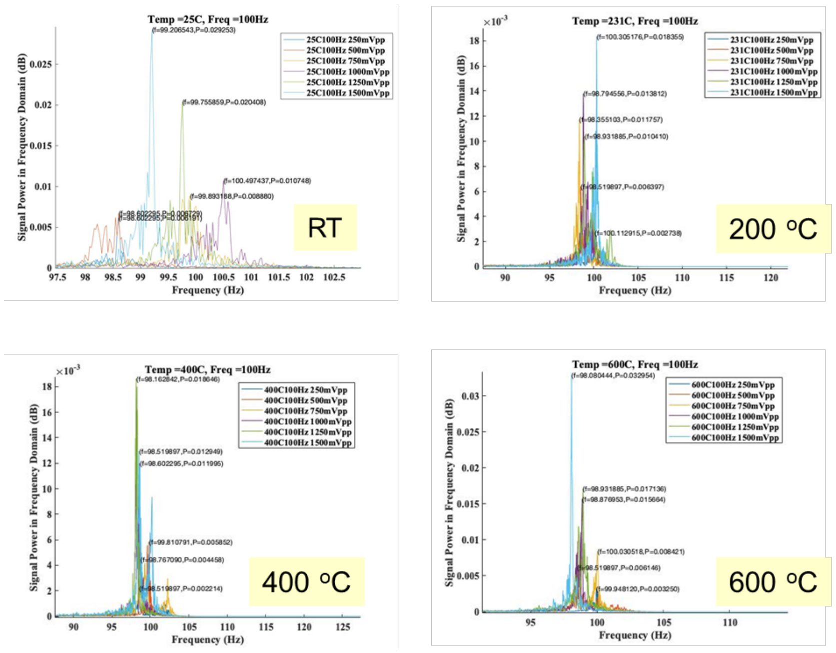


Sensor data from the HT vibration sensor (~ 600 °C)
Remote data transmission

Accomplishments

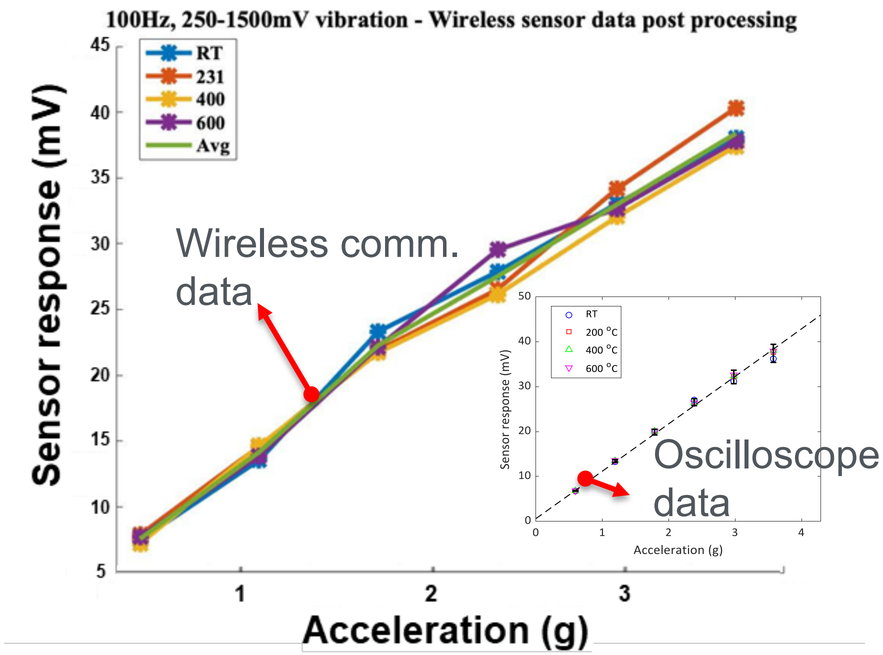
Results:

A. Wireless data acquisition/storage



Change in the peak value of the frequency spectrum by changing the vibrational level of the sensor

B. Reliability



Reliable agreement with the directly connected oscilloscope data

Conclusions:

- Demonstrated a wireless communication system for HiTEIS

Accomplishments

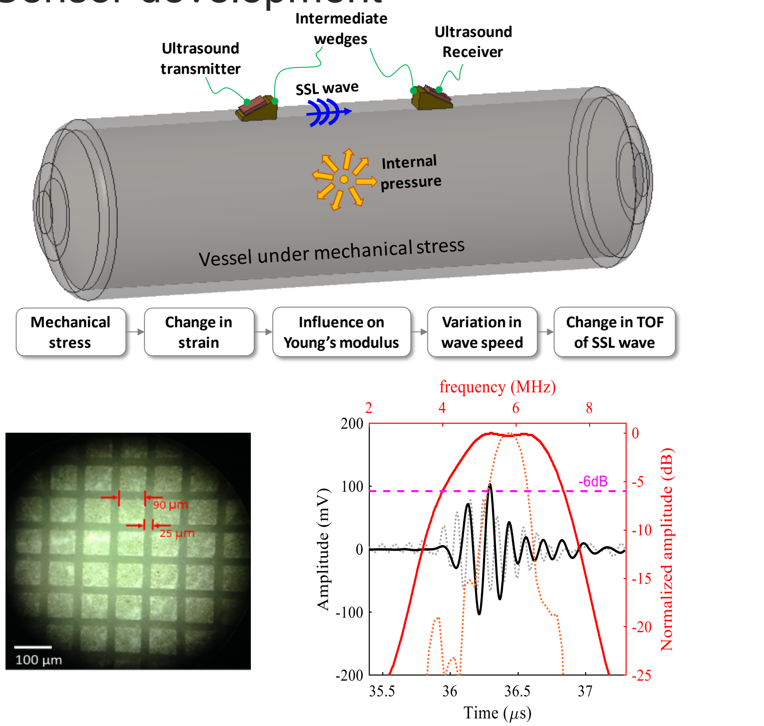
Accomplishment 3: Stress Measuring Technique and Temperature Compensation Method

Purpose:

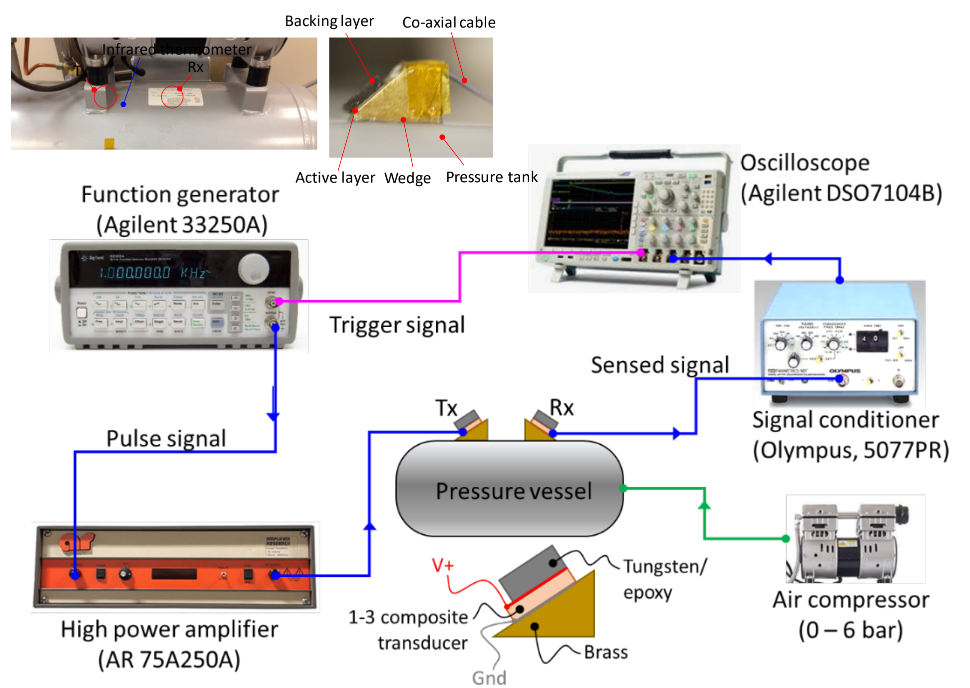
- To investigate a wave-based stress sensing method

Methods:

A. Sensor development



B. Characterization

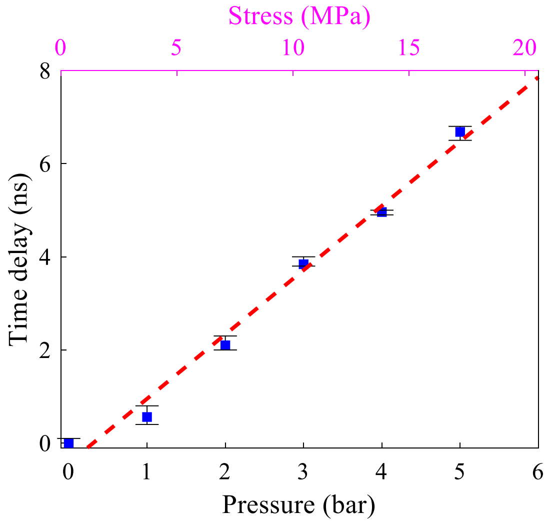


Stress measurement under temperature variation

Accomplishments

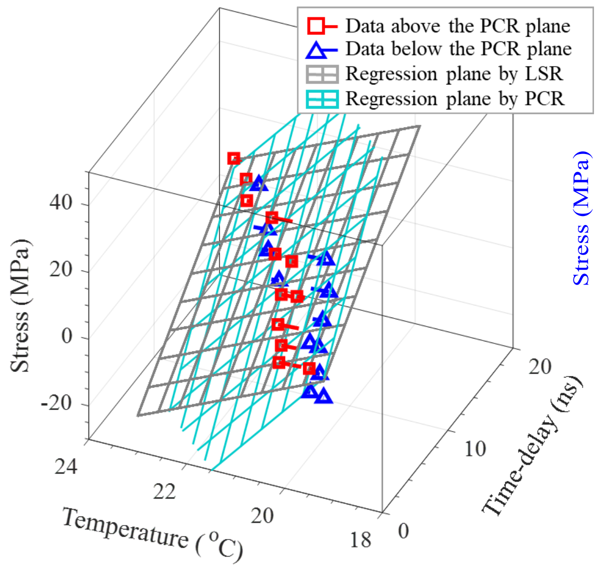
Results:

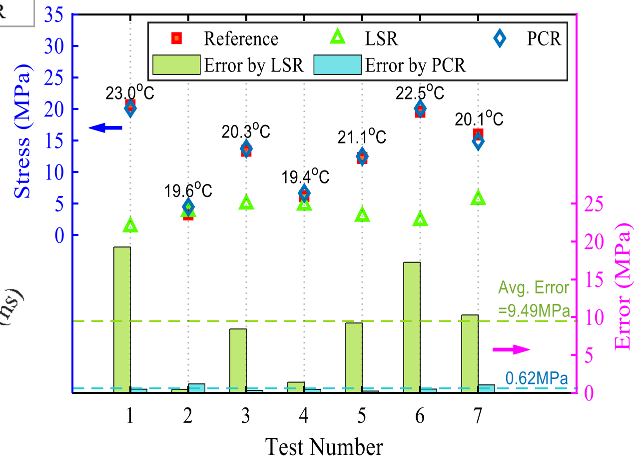
A. Sensitivity



Linear relationship between the time-delay and the stress level

B. Temperature compensation





Temperature compensation by principal component regression
Accurate regression than the least square regression

Conclusions:

- Demonstrated a stress sensing method using 1-3 composite piezo sensors

Accomplishments

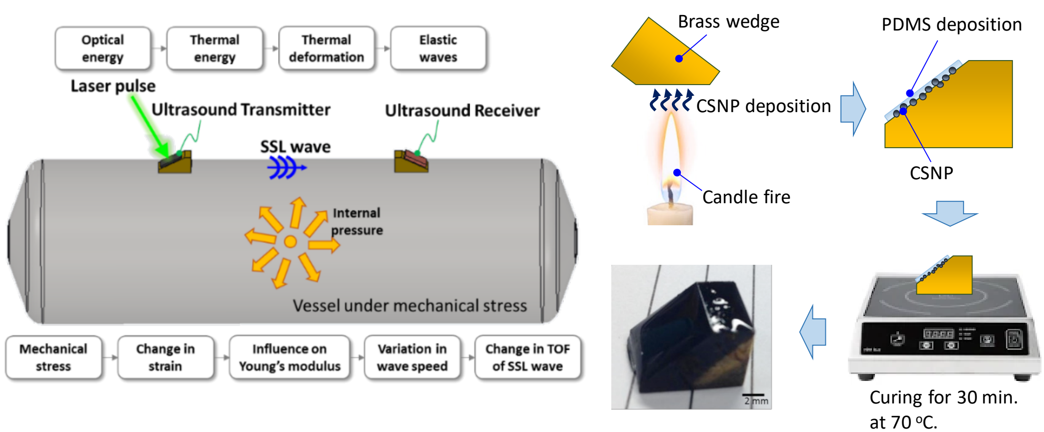
Accomplishment 4: Laser stress sensor and characterization

Purpose:

- To develop a laser assisted stress sensor and to characterize it

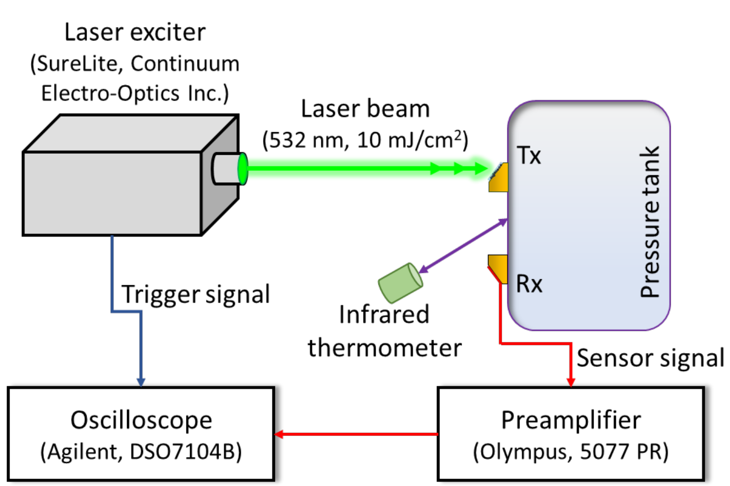
Methods:

A. Sensor development



Laser generated ultrasound for the stress sensing
Candle-soot nanoparticle (CSNP) composite for the intensified photoacoustic conversion

B. Characterization

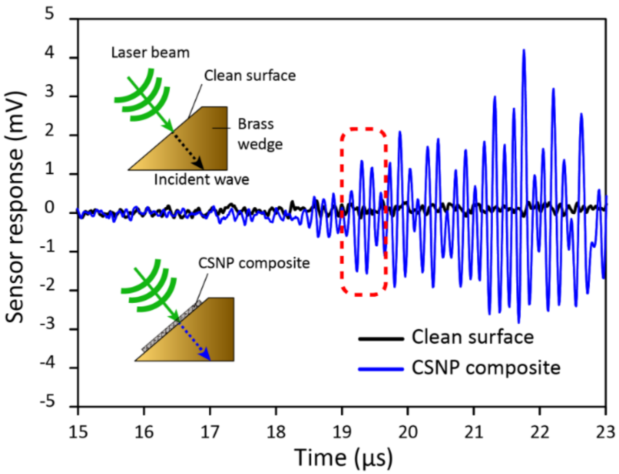


Stress measurement with the laser generated ultrasound and the piezoelectric sensor

Accomplishments

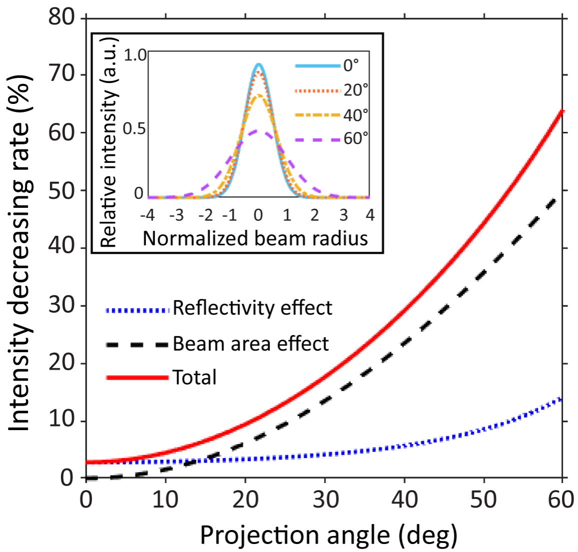
Results:

A. Efficacy of the CSNP



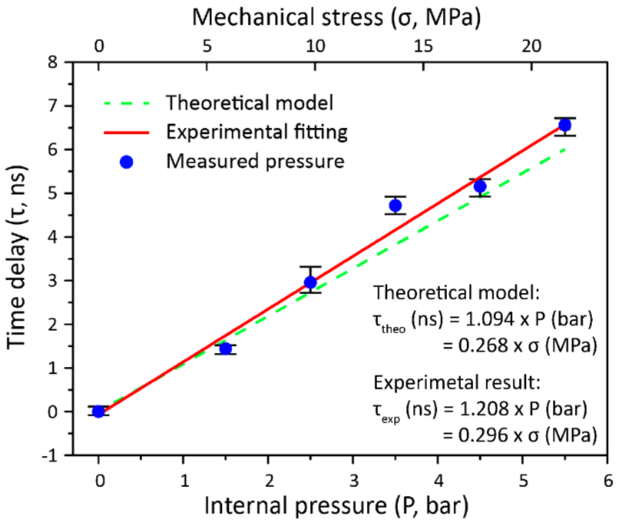
CSNP material intensifies the photoacoustic (PA) effect

B. Angular dependency of the laser generated ultrasound



Laser projection angle is important in the PA conversion rate (normal projection is preferred)

C. Sensitivity



Linear relationship between the stress and the time-delay

Conclusions:

- Developed a stress sensing method using the laser generated ultrasound
- Carbon-soot nanoparticle aids to intensifies the photoacoustic conversion

Accomplishments

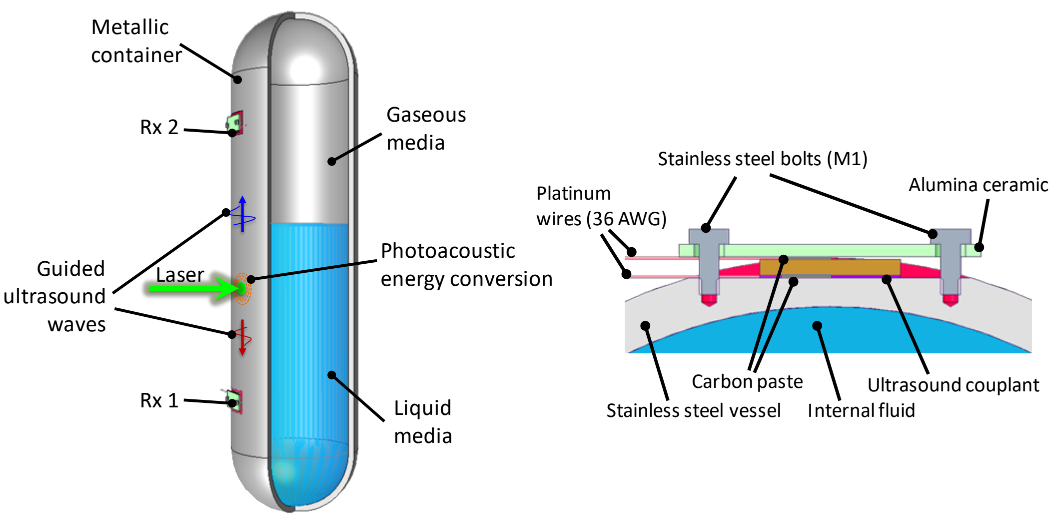
<u>Accomplishment 5:</u> Liquid level sensor and characterization

Purpose:

- To develop a nonintrusive liquid level sensor using a laser power

Methods:

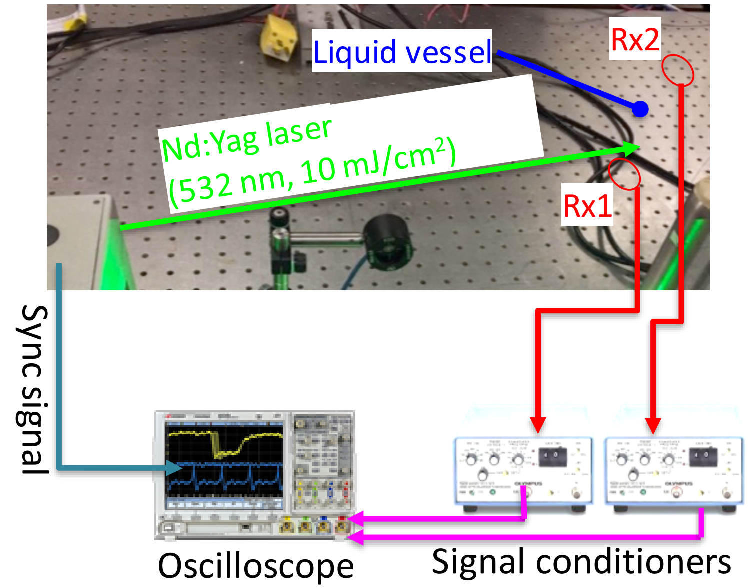
A. Sensor development



The intensity laser generated ultrasound varies w.r.t the liquid level sensor due to the leaky guided wave

HT sensor embedding method on a test structure

B. Characterization

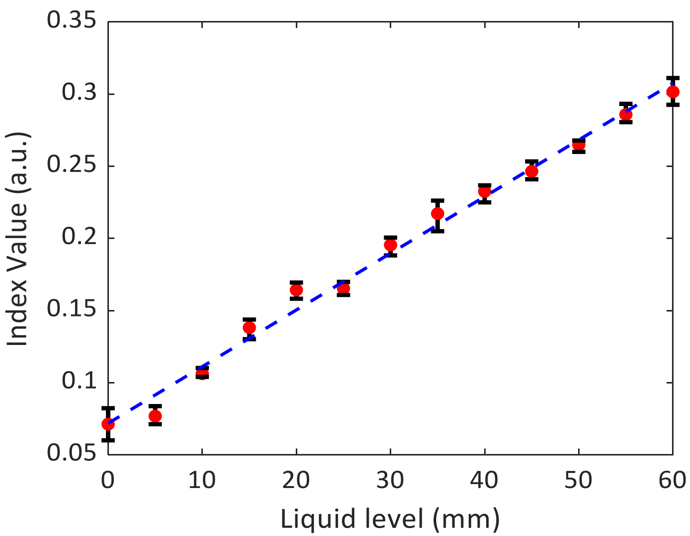


Liquid level measurement, varying the liquid temperature

Accomplishments

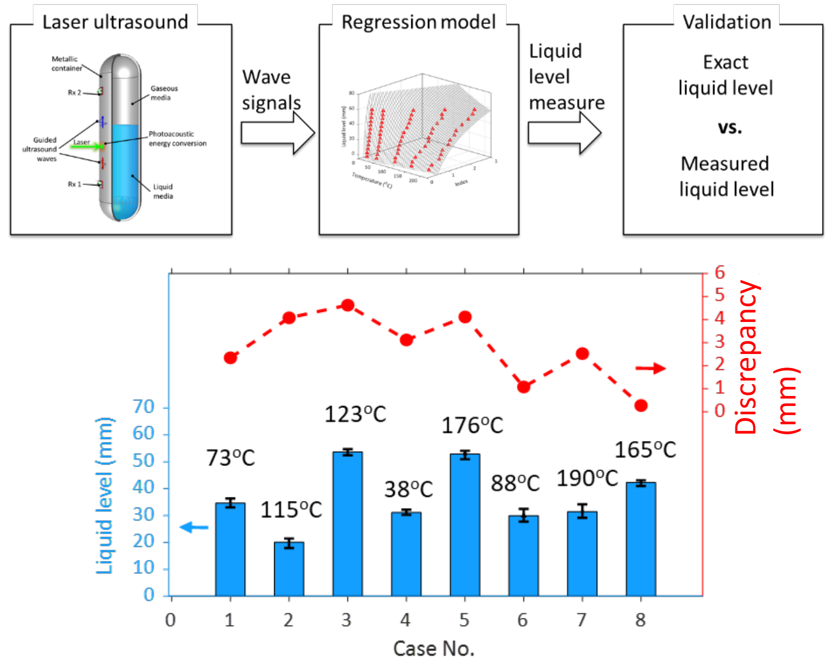
Results:

A. Sensitivity at RT



Linear response of the level sensor at the RT condition

B. Sensor regression model for the varying temperature



Nonlinear behavior of the sensor at the HT condition

Logarithmic regression model

Accuracy within 5% / Repeatability within 4.98 mm

Conclusions:

- Developed a laser assisted liquid level sensor with the HT sensors
- Sensor calibration in elevated temperature conditions (~ 200 °C)

Accomplishments

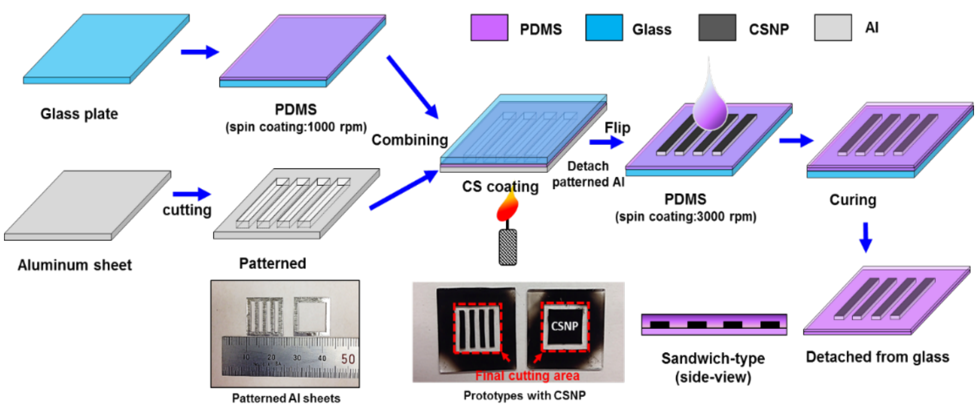
<u>Accomplishment 6:</u> Laser Generated Lamb Wave for NDT sensor

<u>Purpose:</u>

- To develop a photoacoustic transducer for the narrowband Lamb wave generation

<u>Methods:</u>

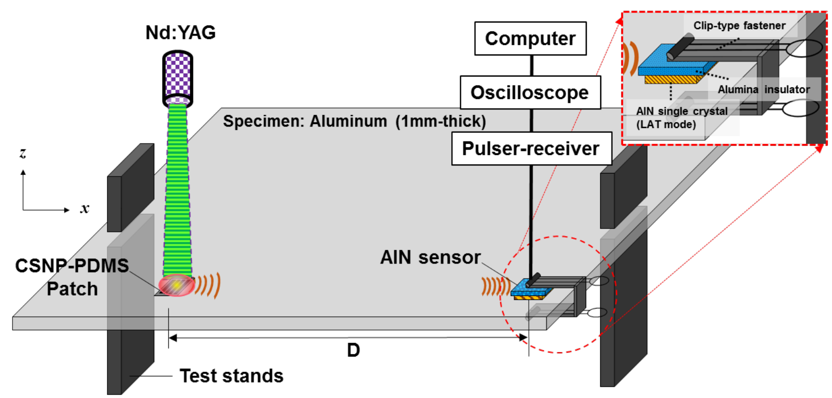
A. Transducer development



A line-arrayed patch made with a candle soot nanoparticle-polydimethylsiloxane (CSNP-PDMS)

The spacing of the array determines the wavelength of the guided wave.

B. Transducer validation

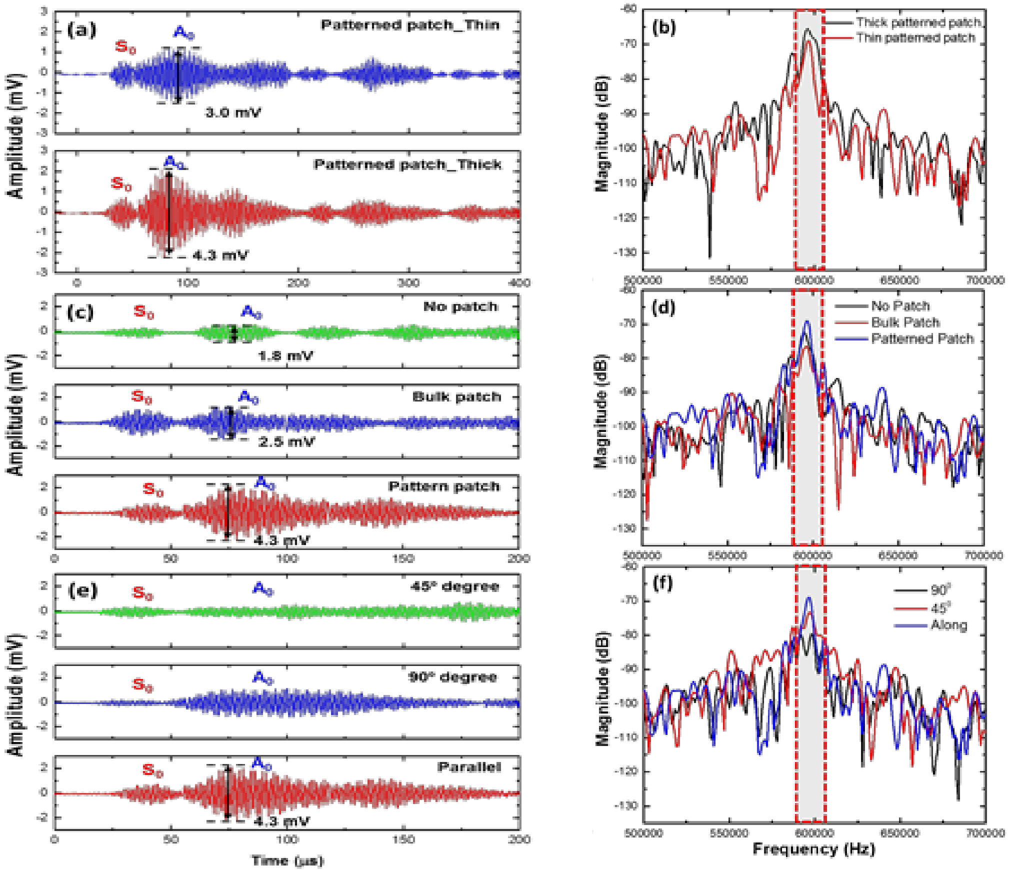


Laser-generated ultrasound on the CSNP-PDMS patch

Signal capture by the AlN sensor

Accomplishments

Results:



- **Thick patch** for the effective photoacoustic energy conversion
- **Pattern in the patch** intensifies the guided ultrasound on the plate
- Variation of the laser ultrasound w.r.t. the **pattern direction**

Conclusions:

- Developed a laser ultrasound transducer to capture the narrowband Lamb wave signal

Accomplishments

Publications:

A. Journal papers (5)

[1] T. Kim, J. Kim, and X. Jiang, "AlN Ultrasound Sensor for Photoacoustic Lamb Wave Detection in a High-Temperature Environment," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 65, No. 8, pp. 1444-1451, 2018.

[2] J. Kim, H. Kim, W. Y. Chang, W. Huang, X. Jiang, and P. A. Dayton, "Candle-Soot Carbon Nanoparticles in Photoacoustics: Advantages and Challenges for Laser Ultrasound Transmitters," *IEEE Nanotechnology Magazine*, Vol. 13, No. 3, pp. 13-28, 2019.

[3] T. Kim, W. Y. Chang, H. Kim, and X. Jiang, "Narrow Band Photoacoustic Lamb Wave Generation for Nondestructive Testing Using Candle Soot Nanoparticle Patches," *Applied Physics Letters*, Vol. 115, No. 10, 102902, 2019.

[4] H. Kim, T. Kim, D. Morrow, X. Jiang, "Stress Measurement of a Pressurized Vessel Using Ultrasonic Subsurface Longitudinal Wave with 1-3 Composite Transducers," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Controls*, in press, 2019.

[5] H. Kim, W. Y. Chang, T. Kim, and X. Jiang, "Stress Sensing Method via Laser-Generated Ultrasound Wave Using Carbon Soot Nanoparticle Composite," *IEEE Sensors Journal*, submitted for publication, 2019.

B. Conference papers (3)

[1] H. W. Kim, W. Y. Chang, T. Kim, S. Huang, and X. Jiang, X. "Stress Measurement of a Pressurized Vessel Using Candle Soot Nanocomposite Based Photoacoustic Excitation," *SPIE Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XIII*, Denver, CO, Vol. 10971, pp. 109710G, 2019.

[2] H. W. Kim, T. Kim, D. Morrow, X. Jiang, "Stress Sensing Technique via Subsurface Longitudinal Wave with Composite Trasducer," *The 11th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies*, Orlando, FL, 2019.

[3] B. Balagopal, S. Kerrigan, H. Kim, M. Y. Chow, M. Bourham, X. Jiang "A Smart Sensor Prototype for Vibration Sensing in Nuclear Power Plants," *The 28th International Symposium on Industrial Electronics (IEEE-ISIE)*, Vancouver, Canada, 2019.

Technology Impact

- *Advances the state of the art for nuclear application*

  Nonintrusive monitoring of structural integrity under harsh environmental conditions such as HT and radiation

- *Supports the DOE-NE research mission*

  In-service monitoring data of the nuclear structures, guaranteeing the sustainable nuclear energy usage with the reliable lifetime prediction.

- *Impacts the nuclear industry*

  Nonintrusive HiTEIS and wireless communication system enable more frequent and thorough inspection while excluding human operator from the nuclear environments.

- *Will be commercialized*

  Some inventions (e.g., laser assisted liquid level sensor), achieved from the project, will be disclosed through technical patents.

Conclusion

1. A HT vibration sensor was developed and characterized under 1000 ^{o}C. The radiation effect of the sensor is, currently, being tested using Cobalt source.
2. A wireless data transmitting system was designed and validated by using the HT vibration sensor placed in a hot furnace.
3. Ultrasound based stress sensors were investigated using the composite piezoelectric sensor and the photoacoustic transducer, respectively.
4. Nonintrusive HT liquid level sensor was studied using the laser generated ultrasound.
5. Narrowband Lamb wave generator was investigated using the candlesoot nanoparticle composites.
6. In the future works, the developed HiTEIS will be embedded in a miniaturized reactor mock-up for more tests. In addition, more laser ultrasound sensors will be studied.

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