Detection of Micron-Scale Flaws through Nonlinear Wave Mixing

Topic: NDE Techniques for Pressure Vessels

Project ID: IN014

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LUNA

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LUNA | Overview

Timeline

- Project Start Date: 08/19/2019
- Project End Date: 08/18/2021

Barriers Addressed

E. Gaseous Hydrogen Storage and Tube Delivery Costs

K. Safety, Codes and Standards, Permitting

Budget

- Total Contract Value: $1,048,000
- FY19 Funding: $524,000
- Planned FY20 Funding: $524,000
- Total DOE Funds Spent*: $301,516

*As of 04/30/2020

Partners

- Innerspec Technologies
- Sandia National Laboratory
- Murray State University

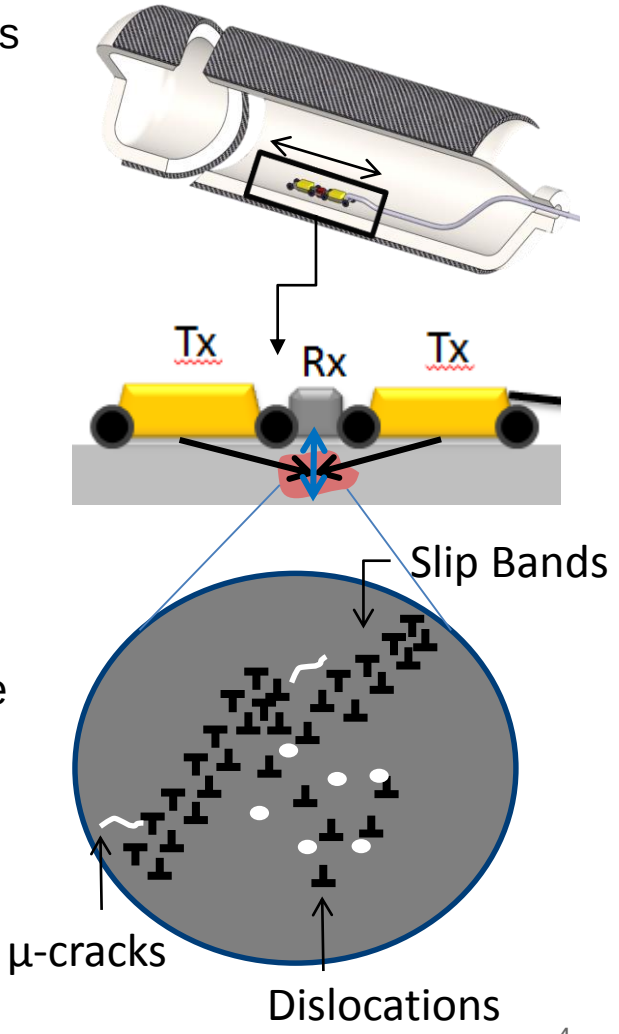
LUNA | Relevance

Objective: Develop NDE technology that improves the resolution to micrometer-scale flaws in hydrogen storage vessels and allows more accurate estimates of remaining useful life.

Barrier from 2015 MYRDDP	Relevant Targets	Project Impact
Gaseous Hydrogen Storage and Tube Trailer Delivery Costs	Stationary Gaseous H_2 Tanks: - Purchase Capital Cost of Type II Pressure Vessel: $450/kg - Lifetime: >30yrs	Gaseous storage tank costs are driven by replacement timelines. Improved damage assessment may enable re-certification of tanks after nominal design lives are exceeded while improved manufacturing inspections enable extended design lives prior to retirement.
Safety, Codes and Standards, Permitting	N/A	As part of the NDE development effort, this project is exploring methods for incorporating early-stage damage and micron-scale flaw detection into standards to affect system design and operational lives.

LUNA | Approach

- Leverage nonlinear ultrasonic wave mixing to sense µm-scale flaws in hydrogen storage vessels that impact tank lifetimes
  - Applied in manufacturing environment – to extend *design life*
  - Applied in field inspections – to extend *operational life*
- Design tailored hardware for field and manufacturing inspections without direct contact with specimen surface
  - Reduces effect of surface condition on measurement results
  - Eliminates need for couplant fluids that could contaminate surfaces and limit scanning capability
- Develop understanding of response to early-stage damage development in pressurized hydrogen environment
  - Exploring sample populations with damage seeded in air and hydrogen to allow estimate of remaining useful life in the field



LUNA | Approach – Planned Milestones

Milestone/Task Planned For FY19	Status
Demonstrate feasibility of using nonlinear wave mixing with non-contact transducers	100%
Identify tank suppliers and hydrogen-material interaction expertise for collaboration	100%
Identify system requirements and standards relevant to tank manufacturing and life extension	100%

Milestone/Task Planned For FY20	Status
Develop relevant sample population for optimizing measurement approach	75%
Establish modeling framework to evaluate response to varying damage types and severities	75%
Assemble inspection hardware and tune inspection processes	75%
Design sensing head for tank wave-mixing measurements	50%

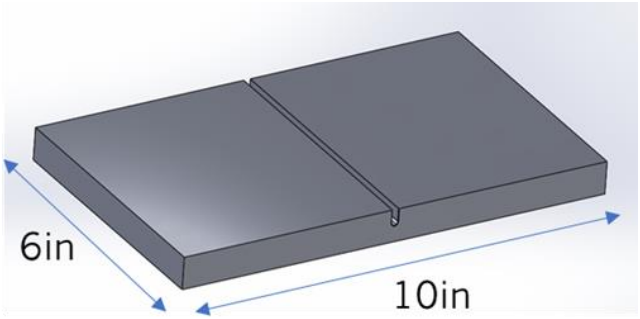
Milestone/Task Planned For FY21	Status
Relate Microstructural Damage Development in Hydrogen to Tank Useful Life	25%
Construct Prototype System for Conducting Tank Inspections	10%
Evaluate System Performance on Retired Tank Test Articles	0%

Accomplishments: Specimen Population Development

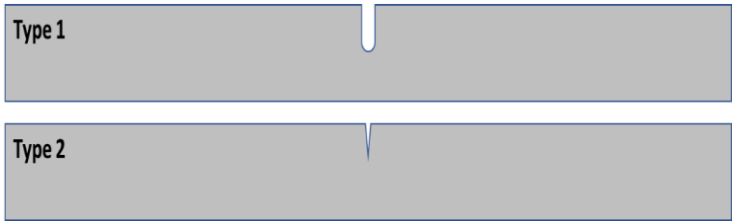
- Specimens designed and seeded with two damage scenarios
  - Microstructural Damage – U-notched specimens subjected to pre-cracking fatigue
  - Microcracking – V-notched specimens with fatigued until crack nucleation

- Progress:
  - Bar specimens of 4140 steel designed, fabricated, and loaded to seed damage
  - Plate specimens fabricated and custom fixture for plate fatigue designed and built

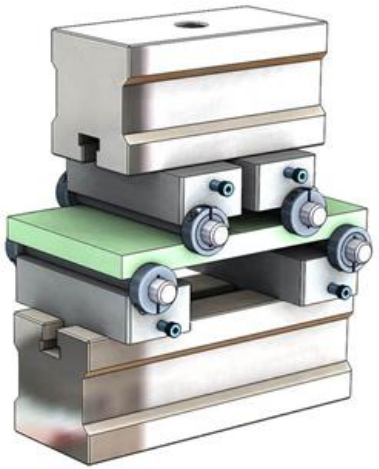
Plate specimens for surface scans



Bar specimens for point inspection and line scans



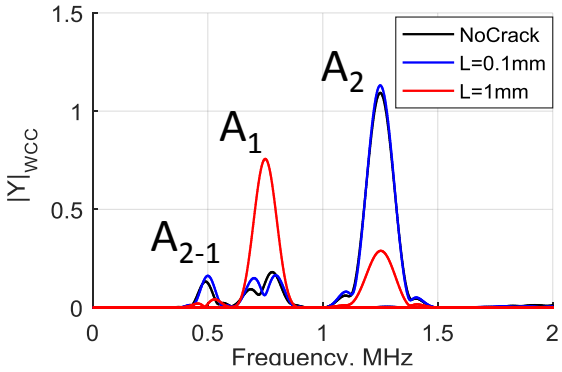
Material testing fixture designed for plate fatigue



Accomplishments: Establish Modeling Framework

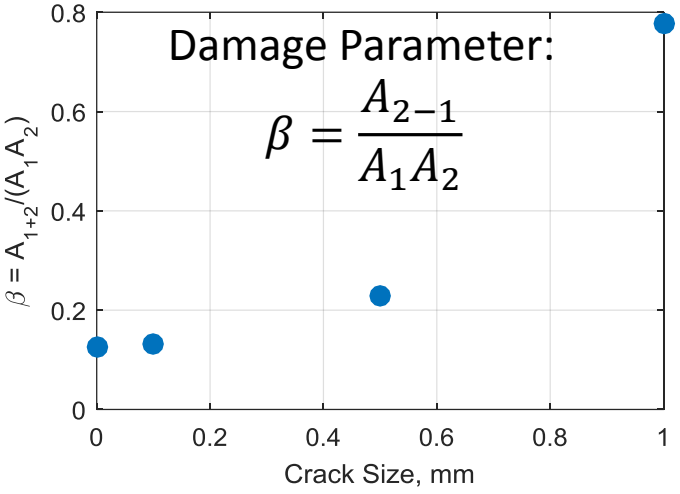
- Finite element modeling framework developed to study wave mixing physics
  - Modeling surface wave mixing in regions with microcracking and microstructural damage

Left Transducer

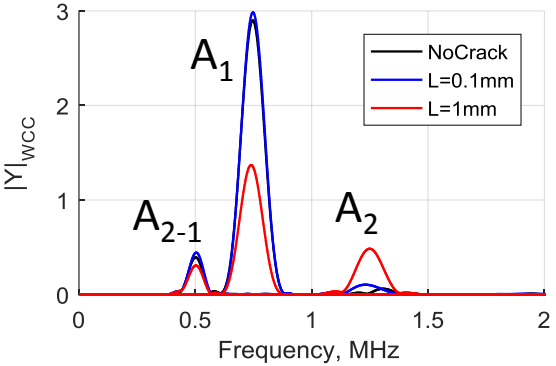


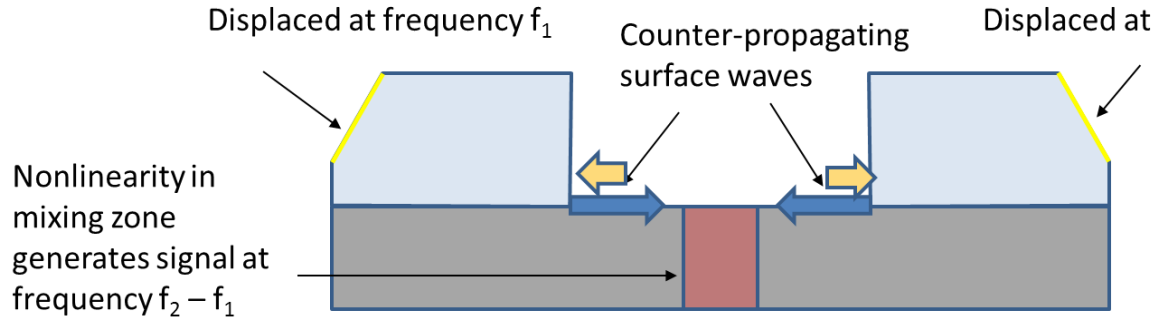
Damage Parameter:

$$\beta = \frac{A_{2-1}}{A_1 A_2}$$



Right Transducer



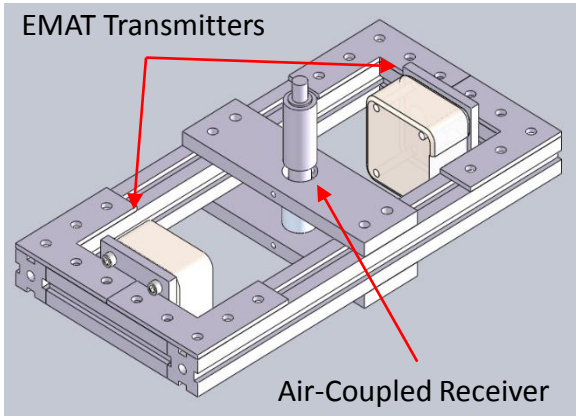


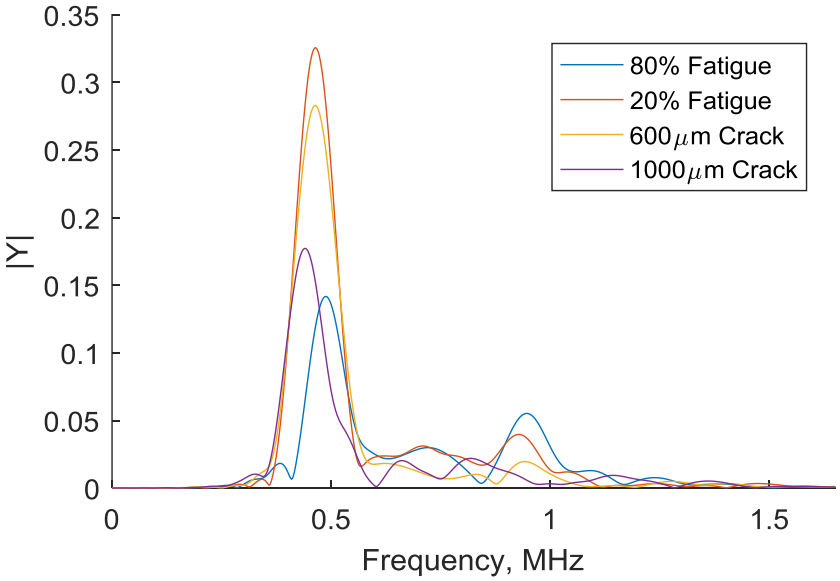
FEA models of surface wave mixing shows sensitivity to microcracks as small as 100µm

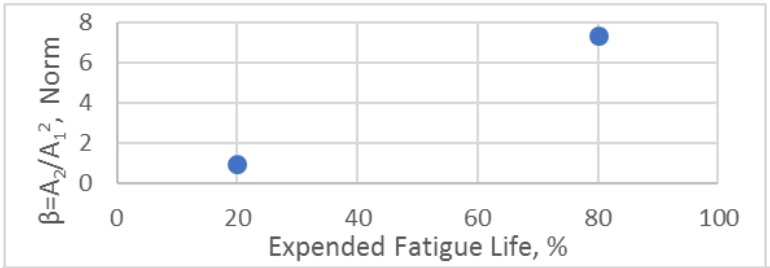
Accomplishments: Development of EMAT Wave Mixing Sensor

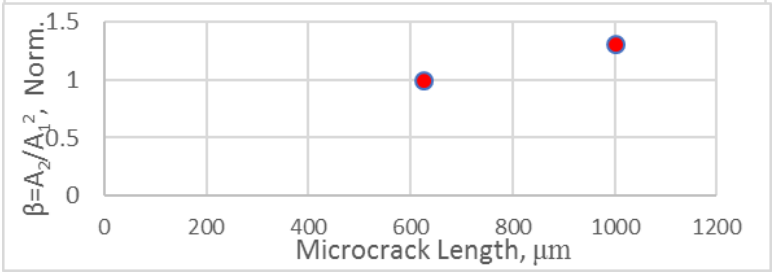
- Electromagnetic Acoustic Transducer (EMAT) mixing approach refined through bar testing
- Packaged sensor head currently under development at Innerspec Technologies for plate and tank scanning

Laboratory Experimental Setup









EMAT wave mixing experiments are being optimized on bar specimen sets and will be applied to custom tank scanning hardware

Proposed Future Work

- Remaining in FY 2020
  - Finalize design of tailored measurement head and verify performance
  - Seed damage in plate specimens to enable optimization of damage mapping in a 2D surface
  - Optimize measurement techniques in immersion scanning environments relevant to tank manufacturing
- Proposed in FY 2021
  - Explore sensor response to damage developed in pressurized hydrogen environment
  - Design and build tank scanning system and validate performance in retired tank test articles
  - Identify transition paths and contacts within the tank manufacturing community

Remaining Challenges and Barriers

1. Developing understanding of effects of tank wall residual stress on measurement approach
   - Planned Resolution: Working to develop sample population cut from representative tanks to verify performance

2. Understanding differences in damage progression in hydrogen vs. air environment
   - Planned Resolution: Working with Sandia National Lab to study early-stage (pre-cracking) fatigue damage in hydrogen and air environments. Testing of this sample population will allow correction factors for sensor calibration for improved remaining life prediction.

3. Identifying usage cases in manufacturing environments
   - Planned Resolution: Working with commercial partners and identified tank manufacturers to understand how to modify quality control processes to incorporate micron-scale flaw detection into design life estimates

LUNA | Collaborations

- Innerspec Technologies
  - Providing guidance and design effort on non-contact Electromagnetic Acoustic Transducers (EMAT) for conducting wave-mixing measurements in the field
- Sandia National Laboratory
  - Providing guidance on relevant hydrogen-material interactions and mechanical testing in ambient and pressurized H_2 environments for study of acoustic response under each condition
- Murray State University
  - Aiding in measurement optimization with a focus on immersion methods that will be leveraged in hydrogen tank manufacturing environments

Technology Transfer Activities

- Continuing to work with commercial partners at Innerspec Technologies to identify strategies for integrating novel test methods into their existing measurement hardware

- Abstract submitted to the ASME Annual Review of Progress in Quantitative NDE (QNDE) covering aspects of the nonlinear ultrasonic measurement approaches
  - Provides visibility to broader NDE community and greater acceptance of this type of emergent measurement approach

- Market analysis conducted leveraging DOE TABA funding. Goals of analysis include identifying user communities and early adopters for the developed NDE system. Users will be contacted over the next year to identify transition opportunities and market access points.

- Potential Future Funding:
  - DOE SBIR Phase IIA – Focusing on expanding technology development with integration into field-portable units developed by commercial partners at Innerspec.

Reviewer Comments

- This project was not reviewed last year

LUNA | Summary

Objective	Develop tailored non-destructive evaluation techniques for hydrogen storage vessels for improved manufacturing and potential tank re-certification in the field
Relevance	Advanced NDE provides knowledge of material damage required for life extension and cost targets for hydrogen storage and delivery infrastructure
Approach	- Applying nonlinear ultrasonic techniques in non-contact form-factor to enable use on hydrogen storage vessels for identifying micron-scale flaws and early stages of fatigue damage - Develop an understanding of the relationship between vessel-specific damage mechanisms and sensor response for estimating remaining life in fielded infrastructure
Accomplishments	- Developed (and continue to develop) a specimen population for optimizing measurement approaches demonstrated during Phase I. - Established a modeling framework to explore wave mixing physics. - Applied wave mixing to experiments on fatigued bar specimens with seeded microstructural damage and microcracking - Completed initial designs for custom wave mixing sensing head
Collaborations	Innerspec Technologies (sensor development), Sandia National Laboratory (hydrogen