Thermo-mechanical Simulation of Guided Waves in Pipes Excited by Laser Pulses

Jung-Wuk Hong  Ph.D
Associate Professor

Hyeong Uk Lim
Graduate Student

Department of Civil & Environmental Engineering
Korea Advanced Institute of Science and Technology
Motivations

A giant oil spill in the Gulf of Mexico, 2010
Fukushima accident, 2011
Hydrofluoric acid gas leak in Korea, 2012
Current Challenges

- Fast scanning of pipes
- Enough information for inspection region
- Consideration of longitudinal damages
- Convenience for the excitation and sensing
- Exemption of bonding
Laser Ultrasonic Techniques in SHM

- Based on ultrasonic waves
  - Still using ultrasonic waves
  - Excitation of the pipe surface

- Convenience
  - Remote and non-contact
  - Fast scanning using laser beams and vibrometers

- Pros & Cons
  - Broadband, a wide range of frequencies (many modes)
  - Measurement of only radial displacement
Laser Ultrasonic in Pipes

- **Necessity**
  - Detection of defects in pipelines is a major concern in the petro-chemical and nuclear industries
  - Million kilometers of pipes are utilized worldwide

- **Excitation**
  - Using laser pulses - No need to install permanent distributed sensors

- **Sensing**
  - Using laser vibrometers, optical fibers, etc.
Numerical Simulation of Laser Ultrasonic

- Material: Aluminum
- Laser pulse energy: 10 mJ
- Absorptivity: $5.2 \times 10^{-2}$
- Pulse duration: 8 ns
- Flux: 9196 MW/m²
- Outer radius: 57.15 mm
- Laser source diameter: 3 mm
Formulation in MultiPhysics

Governing Equations

\[ \sigma_{ij,j} + f_i - \rho \ddot{u}_i = 0 \]  
Equation of motion

\[ T_0 \dot{s} + q_{i,i} = 0 \]  
Balance equation of entropy

Constitutive Equation

\[ \sigma_{ij} = C_{ijkl} \varepsilon_{kl} - \beta_{ij} \theta \]

\[ s = \beta_{ij} \varepsilon_{ij} + \frac{C_E}{T_0} \theta \]

\( \sigma_{ij} \): stresses  
\( f_i \): body force  
\( \rho \): density  
\( u_i \): displacements  
\( T_0 \): equilibrium temperature  
\( \dot{s} \): entropy rate per unit volume  
\( q_{i,i} \): thermal flux

\( C_{ijkl} \): elasticity tensor  
\( \varepsilon_{ij} \): strain tensor  
\( \beta_{ij} \): thermomechanical coupling tensor  
\( C_E \): specific heat capacity  
\( \theta \): temperature
Formulation (Cont’d)

- Virtual displacement and temperature
\[ \int_V \sigma_{ij,j} + f_i - \rho \ddot{u}_i \delta u_i \, dV = 0, \quad \int_V T_0 \dot{\delta} + q_{i,i} \delta \theta \, dV = 0 \]

- Discretization of displacement and temperature fields
\[ u = H_u U \quad \theta = H_\theta \Theta \]

- Finite element equations
\[ M\ddot{U} + K_{u\theta} \Theta + K_{uu} U = F \]
\[ C_{\theta u} \ddot{U} + C_{\theta\theta} \dot{\Theta} + K_{\theta\theta} \Theta = Q \]

Discretization for computation

- **Spatial discretization**
  - Discretize the entire domain into a thermo-mechanical region and a mechanical region
  - Reduce computational costs

- **Temporal discretization**
  - Explicit time integration for the mechanical dof’s
  - Implicit time integration for the thermal dof’s
Micro-scale modeling for obtaining the heat sources

- Model dimension: 2 μm x 2 μm x 100 μm
- Mesh size: 1 μm x 1 μm x 1 μm
- Heat flux value: 9196 MW/m²
FEM Simulation with FEAP

- Three dimensional configuration
- Large number of finite elements (1,728,000 elements)
- Impose the calculated temperature profile as an input
- Running time: approximately 16 hours

Mesh size: 1mm x 1.25mm x 1mm
Time step: $5 \times 10^{-10}$ for the first 40 steps
$1.5 \times 10^{-7}$ for the rest 1500 steps
For the numerical stabilities, the time step is determined smaller than the critical time step ($1.88 \times 10^{-7}$)
Wave Modes Excited by Laser Pulses in a Pipe

1. [0 ~ 1.5 MHz] 2. [1.6 ~ 1.9 MHz]

Ω (%) = \( \frac{A_S}{A_T} \times 100 \)

\( A_T \): the total area of all frequency bands
\( A_S \): the area of specific frequency bands

\( \Omega \): 7.71%
Wave Modes Excited by Laser Pulses in a Pipe with a Notch

Case 1: 1mm notch depth

RMSE: \(2.44 \times 10^{-11}\)  CC: 0.938

Ω: 8.22 %
Wave Modes Excited by Laser Pulses in a Pipe with a Notch

Case 2: 2mm notch depth

RMSE: $2.47 \times 10^{-11}$  CC: 0.935

Ω: 8.34 %
Wave Modes Excited by Laser Pulses in a Pipe with a Notch

Case 3: 3mm notch depth

RMSE: $3.53 \times 10^{-11}$  CC: 0.869

Ω: 8.37 %
Wave Modes Excited by Laser Pulses in a Pipe with a Notch

Case 4: 4mm notch depth

RMSE: $4.90 \times 10^{-11}$  CC: 0.729

$\Omega$: 9.33 %
Damage Detection based on Statistical Methods

- **Magnitude spectrum ratio**
  - Intact: 7.71%  
  - Case 1: 8.22%  
  - Case 2: 8.34%  
  - Case 3: 8.37%  
  - Case 4: 9.33%  
  - Area ratio of the frequency band to the entire frequency area [1.6 MHz, 1.9 MHz]  
  - Increases as the notch depth increases

- **RMSE (Root-mean-square-error)**
  - Case 1: 2.44 \times 10^{-11}  
  - Case 2: 2.47 \times 10^{-11}  
  - Case 3: 3.53 \times 10^{-11}  
  - Case 4: 4.90 \times 10^{-11}  
  - Increases as the notch depth increases

- **Cross-correlation (CC)**
  - Case 1: 0.938  
  - Case 2: 0.935  
  - Case 3: 0.869  
  - Case 4: 0.729  
  - Tangential displacement is used for the calculation of RMSE and CC  
  - Decrease as the notch depth increases
Multi-resolution Analysis using Wavelet Transform

$$WT_f(a,b) = \int_{-\infty}^{\infty} f(t) \cdot \overline{\psi}_{a,b}(t) dt = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} f(t) \cdot \overline{\psi}\left(\frac{t-b}{a}\right) dt$$

- $a$: the scaling parameter
- $b$: the translation parameter
- $\overline{\psi}_{a,b}$: the complex conjugate of the wavelet $\psi_{a,b}$

Intact case is used as a baseline
Mother wavelet function: Morlet

1.1 MHz is selected since the magnitude is large

Wavelet coefficients at 1.1 MHz
Multi-resolution Analysis using Wavelet Transform

Wavelet coefficients at 1.1 MHz

- Longitudinal damage detection
  - Magnitude of the wavelet coefficient decreases in the range from 90 to 100 μs
Conclusions & Future Work

- Simulate the wave propagation induced by laser pulses in a pipe (√)
- Use partitioning scheme and different integration scheme to accelerate the calculation (√)
- Find the presence of the notch in a pipe, using Fourier transformation and wavelet transformation (√)
- Simulation of more variety cases of damages
- Wave propagation in curved pipes
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Questions?