Two-dimensional analysis of subharmonic ultrasound generation at closed cracks by damped double nodes

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Content of this talk

• Background
  “Why high depth resolution is required for nonlinear imaging methods”
• New simulation method for nonlinear ultrasound
• Effect of amplitude, incidence angle and residual stress
• Comparison with Experiments
• Conclusion
Background

Important structures such as nuclear power plant is degraded by cracks including

- Fatigue Crack
- Stress Corrosion Crack (SCC)

To solve this, accurate crack depth measurement is essential.

Problem

If the crack is closed by (residual stress, oxide film)

Underestimation of crack
Example of crack sizing error in atomic power plant in Japan (worst case)

<table>
<thead>
<tr>
<th>Real depth (mm)</th>
<th>Estimated depth by UT (mm)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>2</td>
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<td>10</td>
<td>12</td>
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<td>12</td>
<td>14</td>
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</table>

Report on Primary Loop Recirculation piping
Feb 26, 2003  Japanese Government organization
6 - 1   p13.

『UT : 1.0mm ⇒ Real depth: 8.5mm』
Onagawa No1 Plant Miyagi (near Sendai)
Nonlinear Ultrasound

Small Amplitude

Large Amplitude

Transmission

Generation of Nonlinear Ultrasound

Superharmonics $2\omega, 3\omega, \ldots \approxeq [1]

Subharmonics $\omega/2, \omega/3, \ldots \approxeq [2-4]

Contact Vibration (Opening and Closing)

Crack Plane

Possible to detect closed cracks


Selectivity of closed cracks

Superharmonics $<$ Subharmonics

Source

Closed Cracks, Transducer, Couplant

Closed Cracks

Accurate imaging of closed cracks with high selectivity
1D oscillator model


\[
\text{COD}(x(t) - a \sin \omega t)
\]

\[
\{a = 5.1, z_s = -3, k_c = 0.2\}
\]

Short burst of even a few cycles can show subharmonics.

Configuration of crack and probe can not be expressed in detail.
**Subharmonic Phased Array for Crack Evaluation (SPACE)**

![Diagram of the Subharmonic Phased Array for Crack Evaluation (SPACE)]

- **Signal Generator**
- **Gated Amplifier**
- **Phased Array**
- **Load**
- **Digital Filter**

**Practical thick specimen (40 mm)**

- **LiNbO₃ single crystal**
- **Polyimide**
- **Array sensor (32 elements)**

The diagram illustrates the setup for crack evaluation using a subharmonic phased array. The signal generator feeds into the gated amplifier, which is connected to the phased array that is loaded. The array is filtered by a digital filter. The practical thick specimen is 40 mm in length.
Experiments on a closed fatigue crack in Al alloy

- **Load**: \( p \)
- **Amplitude**: \( 0 \text{kgf} \)
- **Reflection echo from slit**: \( 0 \text{kgf} \)
- **Lateral wave**: \( 150 \text{kgf} \)
- **Tip diffraction echo**: \( \Delta p = 10 \text{kgf} \)
- **Reflection echo from slit**: \( \Delta p = -10 \text{kgf} \)

**Diagram**:
- Crack Tip
- 10 \( \mu \)m
- Magnification

**Graph**:
- Time (\( \mu \)s)
- Amplitude

**Notes**:
- \( P \) force applied
- \( \Delta p \) change in load

**Image**:
- Microscope image of crack tip with scale
Sample A \( (K_{\text{max}}=17, K_{\text{min}}=2 \text{ kgf/mm}^{3/2}) \)

Sample B \( (K_{\text{max}}=14, K_{\text{min}}=2 \text{ kgf/mm}^{3/2}) \)

Image of open and closed crack in aluminum alloy (A7075)
Dependence of Crack Images on Crack Closure Stress

- Imaging of the change in crack state with varying closure stress
- Subharmonic images always gave an accurate crack depth
- Imaging of various parts of crack as well as crack tip
- The boundary between the open and closed region at B became ambiguous → The linear scattering source diminished
- Closure stress of more than 100MPa

Load
29MPa (2kN)

84MPa (9kN)

112MPa (12kN)

- 29 MPa
- 84 MPa
- 112 MPa
Measurement accuracy of crack depth measured with SPACE

Fundamental images  →  Underestimation
Subharmonic images  →  Accurate crack depths with a measurement accuracy of approximately 1 mm


New simulation method for nonlinear ultrasound

Damped double node (DDN) model to reproduce subharmonic generation in bulk material

Applied to finite difference time domain (FDTD) simulation
**Finite difference time domain (FDTD) method**

Assuming cubic crystal and $U_y=0$, we apply Hooke’s law

$$\frac{\partial T_1}{\partial t} = c_{11} \frac{\partial u}{\partial x} + c_{13} \frac{\partial w}{\partial z}, \quad \frac{\partial T_3}{\partial t} = c_{13} \frac{\partial u}{\partial x} + c_{33} \frac{\partial w}{\partial z},$$

$$\frac{\partial T_5}{\partial t} = c_{55} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)$$

And Newton’s second law, alternatively

$$\rho \frac{\partial \dot{w}}{\partial t} = \frac{\partial T_3}{\partial z} + \frac{\partial T_5}{\partial x}, \quad \rho \frac{\partial \dot{u}}{\partial t} = \frac{\partial T_1}{\partial x} + \frac{\partial T_5}{\partial z}$$

For example, particle velocity $w$,

$$\dot{w}_{i+1/2,j}^{k+1} = \dot{w}_{i+1/2,j}^k + \frac{\Delta t}{\rho \Delta z} \left( T_{3,i+1/2,j+1/2}^k - T_{3,i+1/2,j-1/2}^k \right)$$

$$+ \frac{\Delta t}{\rho \Delta x} \left( T_{5,i+1,j}^k - T_{5,i,j}^k \right)$$

The density of particle velocity node at free boundary is made proportional to the number of the stress node connected to it. (M. Sato, 2007)
Damped double node (DDN) model

**Closed crack**

```
\begin{align*}
\text{if } & (i - \frac{1}{2}, j) \quad \text{then} \\
& T^{k+1}_{i+1,j} = \frac{1}{2} \left( T^{k+1}_{i+1,j+1} + T^{k+1}_{i+1,j-1} \right) \\
\end{align*}
```

- If \( T_{3M} \leq T_{th} \), the crack continues to be closed state.
- If \( T_{3M} > T_{th} \), the crack becomes open.

**Open crack**

```
\begin{align*}
\text{if } & (i - \frac{1}{2}, j) \quad \text{then} \\
& T^{k+1}_{i+1,j} = \frac{1}{2} \left( T^{k+1}_{i+1,j+1} + T^{k+1}_{i+1,j-1} \right) \\
\end{align*}
```

**Criteria of crack opening/closing**

- Tensile stress \( T_{3M} > T_{th} \) 100 MPa
- Crack opening displacement \( \Delta w \leq 0 \)
- The grid is separated to dual nodes, and the viscous damping is proportional to the particle velocity difference between \( w^{-} \) and \( w^{+} \).

\[
\dot{w}^{+}_{i+\frac{1}{2},j} = \dot{w}^{k}_{i+\frac{1}{2},j} + 2V_{PL} T^{k}_{i+\frac{1}{2},j+\frac{1}{2}} - \gamma (\dot{w}^{+}_{i+\frac{1}{2},j} - \dot{w}^{k}_{i+\frac{1}{2},j+1})
\]

\[
\Delta w^{k+1}_{i+\frac{1}{2},j} = w^{k+1}_{i+\frac{1}{2},j} - w^{-k}_{i+\frac{1}{2},j}
\]

- If \( \Delta w > 0 \), the crack continues to be open.
- If \( \Delta w \leq 0 \), the crack becomes closed.
Effect of amplitude, incidence angle and residual stress
Normal incidence

# of element 32 centered at (0, 150)
Frequency 8MHz; time step 2 ns
Wavelength $\lambda=0.69$ mm; node step 0.02mm
Crack depth $d = 3$ mm; $d/\lambda=4.4$ (deep crack)
Incident angle $0^\circ$
Particle displacement 20, 40 and 80 nm
Focus position (150, 1200)
Compression stress 100 MPa
Spectral analysis of small amplitude incident wave

Low amplitude input wave 40nm

No COD

Wgain=-1.86=40nm  Γ=0.7
Spectral analysis of large amplitude incident wave

High amplitude input wave 80nm

\[ W_{\text{gain}} = -3.68 = 80 \text{ nm} \quad \Gamma = 0.7 \]

Clear subharmonics in transmission side

Finite COD

W + (dB)

W - (dB)

Frequency f (MHz)

Time t (us)
We succeeded in reproducing the subharmonic waves by the 2D model of closed cracks with compression residual stress.
Effect of compression stress

No compression stress $T_{zz} = 0$

COD when 40nm input

Envelop detection, mechanical diode (DC effect)

40nm incident wave

Wgain = 40nm, $\Gamma = 0.7$

Clear superharmonics with unclear subharmonics

COD, $\Delta W$, $W^+$, $W^-$

Frequency $f$ (MHz), COD (dB), $W^+$ (dB), $W^-$ (dB)

Time $t$ (us), $T_{zz} = 0$

40nm incident wave
Oblique incidence

20μm/grid

Crack length: 200

Amplitude dependence

Amp 20nm

Amp 80nm
Closed crack at the center

Amp 160nm

# of element 32 centered at (0, 150)
Frequency 8MHz; time step 2 ns
Wavelength λ=0.69 mm; node step 0.02mm
Crack depth d= 3mm ; d/λ=4.4
Incident angle 56.3°
Particle displacement  20nm, 80nm, 160nm
Focus position (150, 1200)
Compression stress 100 MPa
Subharmonic components were observed more clearly in the oblique incidence than in the normal incidence.
Effect of damping on the stress waveform

High frequency noise disturbs clear observation of superharmonics

Damping enhances subharmonics

(a) γ=0  Time t (μ s)  
(b) γ=0.7  Time t (μ s)
Effect of damping

Frequency $f$ (MHz)

Time $t$ (µs)

(a) $\gamma=0$

(b) $\gamma=0.7$

$f/2$ is enhanced by the damping
Comparison with experiments
SCC (type 304 stainless steel, high temperature pressurized water)

SCC was formed in a sensitized type 304 stainless steel pipe in high temperature pressurized water (280°C) in an autoclave. After that, we cut the pipe, and then, machined it for ultrasonic testing.
Imaging of SCC by single array SPACE

**Measurement condition**
- PZT array transducer (5 MHz, element pitch 0.5 mm, 32 elements)
- Input wave: 7 MHz, 3 cycles, 150V (Focal point: -12.6, 15.0)

**Imaging results**
- **FA**: Focal point (-12.6, 15.0)
  - 7.0 ± 1.2 MHz
- **SA**:
  - 3.5 ± 1.2 MHz

The SCC was not imaged because of strong linear scattering at various coarse grains.

The SCC was clearly imaged.

**To confirm the subharmonic generation**, we performed the frequency analysis of the sum of phase-shifted waves at response A and B.

Single Array SPACE is useful in imaging closed crack with high selectivity.

**Ohara, Horinouchi, Yamanaka et al, Session 17 (Wed), 27 (Thu), QNDE2011**
**Frequency analysis of sum of phase-shifted waves at response A**

**Sum of phase-shifted waves at response A**

**FFT**

Peak at subharmonic frequency (3.5MHz) was clearly observed.

**Wavelet transformation**

Generation of subharmonic component separated from fundamental component was confirmed.

Phase-shifted waves: Waveform distortion was observed around 8.7 μs.
In experiment, the subharmonic generation was not local.

At this point, the result in oblique incidence was closer to experimental results than that in normal incidence.

We succeeded in reproducing the subharmonic generation similar to experimental observation.
Conclusion

• We introduced our works on a nonlinear imaging method, *subharmonic phased array for crack evaluation (SPACE)* to significantly improve the depth measurement accuracy of closed cracks.

• We developed a two-dimensional model to reproduce subharmonic generation at closed cracks using damped double nodes (DDNs).

• Numerical simulation using finite-difference time-domain (FDTD) method was performed and successfully compared with experimental waveforms and time–frequency wavelet analysis.

• The DDN model together with SPACE will enhance the testing condition and probes to *significantly improve the depth measurement accuracy of dangerous cracks*.

• It will contribute to enhance safety of *atomic power plants* and other important structures.
Thank you

For your attention