RECENT MODELLING ADVANCES FOR ULTRASONIC TOFD INSPECTIONS

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CONTEXT

- TOFD inspection principle
- Simulation tools developed for TOFD inspection

LATERAL WAVES

- 3D simulation on planar components
- 2D simulation on irregular surfaces
- Shadowing by a near surface crack

CRACK DIFFRACTION

- 3D models

CALIBRATION ECHOES

- Exact SOV model on SDH

CONCLUSION AND PERSPECTIVES
CONTEXT
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- Widespread ultrasonic inspection technique using two probes mechanically connected
  - ✓ used for locating and sizing cracks by their diffraction echoes
  - ✓ used in more and more complex and realistic 3D geometries
Two probes of opposite axis are used in a pitch-catch arrangement.

**Case of an embedded crack**

Emitter

Receiver

1: lateral wave
2: top diffraction
2': bottom diffraction
3: backwall echo

**Case of a backwall breaking flaw:** shadowing effects from the flaw

Emitter

Receiver

1: lateral wave
2: top diffraction
3: backwall echo
TOFD INSPECTION PRINCIPLE

CONTEXT

• Widespread ultrasonic inspection technique using two probes mechanically connected
  ✔ used for locating and sizing cracks by their diffraction echoes
  ✔ used in more and more complex and realistic 3D geometries

IMPROVEMENTS OF TOFD SIMULATION TOOLS FOR COMPLEX CONFIGURATIONS

• Simulation of lateral surface waves in complex geometries
• Account for shadowing effects from flaws
• Prediction of the ultrasonic response in realistic 3D configurations
  (misoriented rectangular or complex flaws)
• Precise modelling of calibration echoes
LATERAL WAVES
3D SIMULATION OF LATERAL WAVES ON PLANAR ENTRY SURFACES

1) Discretization of transmitting and receiving surfaces

2) Between two points $P_i$ and $P_j$:
   - Calculating the 3D path of the lateral head wave (HW)
   - Application of asymptotic ray theory (Cerveny’s model) for HW amplitude

3) Summation over the transmitter and receiver surfaces and frequency loop

Numerical validations by comparison with FEM modeling (Athena)
LATERAL WAVES

2D SIMULATION ON IRREGULAR SURFACES

- Experimental highlight on scoured specimens:

Compared to the planar case, differences are observed on the time of flight and on the amplitude of the head wave signal.
SIMULATION OF LATERAL WAVES FRONTS USING RAY TRACING

- Development of a Generic Ray Tracing Tool (GRTT) based on the Generalized Fermat’s Principle
  - Able to simulate ray paths between two points for all waves (including head waves)

  
  “Modeling of ray paths of head waves on irregular interfaces in TOFD inspection for NDE”
  A. Ferrand, M. Darmon, S. Chatillon and M. Deschamps, Ultrasonics (in press)

Comparison of the wavefront obtained by GRTT and FEM simulations near the receiver surface

- Good agreement between GRTT and FEM (Athena) results using

  the head wave propagation includes bulk propagation and diffraction on surface irregularities.
LATERAL WAVES ON IRREGULAR SURFACES

**2D AMPLITUDE MODEL FOR LATERAL WAVES USING RAY TRACING**

- Ray path between the source and observation points determined by GRTT time of flight
- Application of an amplitude ray model for each interaction
  - Creeping ray along a cylindrical part
  - Grazing ray along a planar part

Source Point $P_0$

Observation point $P_n$

$\left(V_L^{(1)}, V_T^{(1)}, \rho^{(1)}\right)$

$\left(V_L^{(2)}, V_T^{(2)}, \rho^{(2)}\right)$

$\left(V_L^{(3)}, V_T^{(3)}, \rho^{(3)}\right)$

$\left(V_L^{(4)}, V_T^{(4)}, \rho^{(4)}\right)$
LATERAL WAVES ON IRREGULAR SURFACES

2D AMPLITUDE MODEL FOR LATERAL WAVES USING RAY TRACING

- Numerical validations (comparison with FEM) on cylindrical irregularities for large radii of curvature
- First experimental validation on a realistic scouring

![Diagram of lateral waves on irregular surfaces with annotations for entry surface, head wave, backwall reflection, and calibration using a 2mm SDH.]

-$\Delta$ 2dB
LATERAL WAVES

SIMULATION OF SHADOWING BY A NEAR SURFACE CRACK

- Complex interferences between the head wave and the top edge diffracted wave.
- Development of an empirical model using finite elements calculations
  - Adjusting an amplitude law for the HW amplitude according to the ligament
    \[ A_{HW} = A_{HW0} \left( \frac{l_{ligament}}{l_c} \right)^2 \]
    where \( A_{HW0} \) is the HW amplitude without flaw
    \[ l_c = 3\sqrt{\lambda} \]

Interruption of the lateral wave

Effect of the ligament on the lateral wave
LATERAL WAVES

SHADOWING BY A NEAR SURFACE CRACK

• Analytical Civa Simulations on a plane specimen

P60° 2MHz PCS 70mm

Ligament 6mm  Ligament 2mm  Ligament 1mm  Ligament 0mm

Lateral wave (+top edge)  Bottom edge diffraction

Total HW transmission (no flaw influence)  Decrease of HW amplitude  HW extinction

The simulation provides a progressive extinction of the lateral wave with a decreasing ligament.
CRACK DIFFRACTION
Edge diffraction echoes can be modelled identically by GTD or new PTD models.

MAIN IMPROVEMENTS

- Previous 2D GTD model in CIVA has been removed:
  directions projected onto the plane perpendicular to the edge.
- Replacement by 3D GTD and 3D PTD models developed in collaboration with L. Fradkin

 Advantages:

- Better prediction for strong 3D crack misorientation.
- Use of a new TV-TH decomposition: continuous limit when turning the 3D problem into 2D one.


- Correction of some numerical bugs due to the previous 2D codes
- Rewriting the 3D codes from Fortran to C++ for numerical optimization
SKEWING EFFECTS

Crossing point of fields near the top edge
Rotation of the specimen (skew from 0° to 70°)

-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
0 10 20 30 40 50 60 70

-3D GTD
-3D PTD
-Experiment
-2D GTD CIVA 10

• Very good agreement between 3D PTD/GTD and measure.

• Improvement obtained with 3D GTD/PTD for important skew.

P45° 2.25MHz
Defect 10*20mm
DIFFRACTION ECHO AMPLITUDE VERSUS $\beta$ ANGLE

300 mm diameter Cylinder, 5MHz probe
Large planar flaw (real fatigue crack)

Bottom and top edge diffraction, probe fc=5MHz

Bottom edge diffraction
Top edge diffraction

Relative amplitude (dB)

$\beta$ Probe position (°)

Bottom and top edge diffraction, probe fc=5MHz

Good agreement 3D PTD/measure
Civa11 improvement for small incident angles on bottom edges

F. Ravenscroft, C. Scruby, Ultrasonics 1991
SIMULATION OF THE CALIBRATION ON SDH
ACCURATE SIMULATION OF THE RESPONSE OF CALIBRATION DEFECT IS A CRUCIAL ISSUE

EXACT ANALYTICAL MODEL (SOV) FOR SDH

PCS Effect on SDHs response

Specular reflection

Creeping wave

For more important PCS:

• more field amplitude on the SDH bottom
• Smaller path and attenuation for creeping waves (CW)

Increasing CW amplitude

Improvement due to creeping waves modelling (not accounted in Kirchhoff model)
CONCLUSION AND PERSPECTIVES
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CONCLUSION

• Lateral waves
  • 3D simulation on planar components
  • 2D simulation on irregular surfaces (cylindrical or scoured irregularities)
  First validation: Good agreement. To be completed by other studies
  • Shadowing by a near surface crack

• Edge diffraction
  • Integration of 3D models and of the generic PTD

• Calibration reflectors
  • New SOV exact analytical model: account of creeping wave for better prediction

PERSPECTIVES

• Lateral waves on irregular surfaces
  • 3D configuration / wedge irregularities
  • Impedance interfaces / anisotropic media
  • Interaction with defects located in the specimen shadow

• Edge diffraction
  • Simulation improvement near critical angles
Thank you for your attention

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