Vahan BARONIAN¹, Karim JEZZINE²

¹CEA, LIST, Gif-sur-Yvette, France
²CEA, LIST, Toulouse, France
- **Context:** CIVA GWT

- Hybrid SAFE-FE modelling

- Numerical validations on circular cylinders

- Application to square rods / rail inspections

- Conclusions & Perspectives
CIVA: NDT SIMULATION SOFTWARE

WHY USING SIMULATION IN NDT?

- Design of new methods and probes (e.g. phased arrays)
- Qualification of methods, performance demonstration
- Interpretation of complex results, diagnosis
- « Virtual testing » in product design phases
- Training

CIVA: SIMULATION FOR NDT

- Multi-technique platform: UT, ET, RT-CT… Guided Waves (since 2012)
- Experimental validation within international benchmarks

UT: Transmitted beam computation

ET: 2D map of a complex defect

RT: weld inspection

CT: tomographic reconstruction of complex parts
1) Knowledge of modes propagating in a waveguide (*modes computation*)

2) Knowledge of the beam emitted by an ultrasonic transducer (*beam computation*)

3) Knowledge of the response of a defect (*inspection simulation*)
PRESENTATION OF CIVA GWT (2/2)

SPECIMENS
- Plates (with weld, groove or CAD defined junction) \([2D \text{ computation: Lamb/SH wave}]\)
- Pipes/cylinders \([2D \text{ and } 3D \text{ computation}]\)
- Arbitrary CAD defined waveguide cross-section (eg. Rail) \([3D \text{ computation}]\)

MATERIALS
- Isotropic solid (anisotropic in development version)
- Inner fluid in pipes
- Attenuation law: linear with frequency

TRANSDUCERS
- Contact with or without wedge
- Encircling/encircled probes (phased arrays)
- EMATs
- Different type of solicitations
- Pulse-echo/pitch-catch configurations

FLAWS
- Cracks, FBH, spherical,...
- CAD defined
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MODELLING APPROACH: MODE COMPUTATION

Mode computation with the Semi-Analytical Finite Element method
(discretization of the guide section with finite elements)

\[
(K_1 - j\beta K_2 + \beta^2 K_3)d - \omega^2 Md = 0
\]

- Eigenvalues: wavenumbers
- Eigenvectors: modal displacement

CIVA mesh
169 elements P2
1188 dof

Phase velocity
Frequency
CIVA
Mazzotti et al. (2013)
(1496 elements P1, 2505 dof)

Modal displacements
HYBRID MODAL/FE MODELLING

Use of **modal decomposition** in regular parts of waveguides and **Finite Elements** in perturbation zones (V. Baronian PhD thesis, 2009)

\[ s(\omega) = -j\omega \sum_{n \in \mathbb{N}} \sum_{m \in \mathbb{N}} A^e_m(\omega) e^{-j\beta_m(\omega)L_1} + S_{nm}(\omega) A^r_n(\omega) e^{-j\beta_n(\omega)L_2} \]

Modal amplitudes (emission) ~Green function

Modal diffraction matrix

Use of Inverse Fast Fourier Transform to obtain signals in the time domain
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CRACKS OF DIFFERENT DEPTHS IN CIRCULAR CYLINDERS

F. Benmeddour, F. Treyssède, L. Laguerre, Numerical modeling of guided wave interaction with non-axisymmetric cracks in elastic cylinders (2011)

Materials properties:
- radius $r = 10$ mm
- Poisson coefficient $\nu = 0.25$
- density $\rho = 7800$ kg/m$^3$
- Young modulus $E = 2e11$ Pa
- dimensionless frequency is $\Omega = \omega \left(\frac{r}{cL}\right)$
CRACKS OF DIFFERENT DEPTHS IN CIRCULAR CYLINDERS

Power Reflection/Transmission for the F11 (flexural) incident mode:

Excellent agreement with *Benmeddour et al.* results

- Sharp variations at cut-off frequencies
- Very little reflection for the smallest crack
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➢ **Hybrid SAFE-FE modelling**

➢ **Numerical validations on circular cylinders**

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➢ **Conclusions & Perspectives**
SIMULATION OF RECTANGULAR RODS INSPECTIONS (1/2)

Steel rectangular rod (10 x 20 mm)

Dispersion curves (50 kHz to 200 kHz)
Multi-faceted flaw

- \( f_{\text{exc}} \approx 160\text{kHz} \)
- \( \text{bw} \approx 10\% \)
Natural candidate for GW inspection
(a large length of rails can be inspected from a single position)

Typical defects

- shelling (head)
- transverse cracks (head)
- longitudinal cracks (head or web)
- corrosion
- defective welds

Frequency range: ~20-80kHz
CRACK DETECTION IN THE RAIL HEAD (1/2)

Computation of dispersion curves

Selection of a mode whose energy is confined in the rail head

7th mode (at 70 KHz)
Reflection and transmission of mode 7 for different crack sizes

- detection of smallest crack difficult at such low frequencies
- various modes are reflected/transmitted depending on the frequency
DETECTION OF BOLT HOLE CRACK (1/3)

Used to connect the ends of two rails

May be subject to fatigue cracking

Simulation in transmit mode

\[ f_c \approx 25 \text{ kHz} \]
DETECTION OF BOLT HOLE CRACK (2/3)

- 15 existing modes at 25kHz
- wedge transducer (incidence 45°)
- fc ~25kHz, 50% bw

~11000 nodes

Computation time ~20’ on a Intel Xeon 2.4 GHz desktop
DETECTION OF BOLT HOLE CRACK (3/3)

Influence of crack skew angle

Max amplitude as a function of crack skew angle

Influence of probe center frequency

Max amplitude as a function of probe center frequency
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CONCLUSIONS AND PERSPECTIVES

- The use of simulation is now well-established in NDE applications. Efficient tools exist for the major NDE techniques (UT, ET, RT, …).

- For guided waves: FE/modal hybrid models have been developed and implemented in the GW module of CIVA platform.

- Work in progress
  - Simulation of SHM configurations (network of sensors)
  - Account of leaky modes
  - Post-processing of signals

- Contact and demonstration for CIVA: visit EXTENDE stand.