Modelling guided wave reflection from defects in pipes - an integrated approach

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Abstract: Computational modelling is increasingly utilized for the qualification and design of ultrasonic inspections applied to pipelines in the petrochemical industry. Numerical methods, and particularly the finite element method, facilitate the simulation of ultrasonic inspection with realistic geometries. However, their computational memory and processing requirements limit their usage for large structures such as long lengths of pipe. This work presents a methodology for integrating analytical dispersion curves, obtained from Disperse, with finite element modelling: it uses dispersion curves to model guided wave propagation over long lengths where the pipe geometry is unchanged, and finite element modelling where it contains a feature, for example a defect. This integrated model allows the full potential of numerical modelling to be realised without restricting computational and memory requirements. A numerical finite element study of the scattering of the torsional T(0,1) mode from defects in straight pipes is carried out using Pogo, a graphical processing unit based solver. Both axisymmetric and non-axisymmetric defects have been considered. The results show that there is excellent agreement in the displacement profiles between the integrated model and the full numerical model for the axisymmetric case whereby no mode conversion is seen. With non-axisymmetric defects, mode conversion to the F(1,2), F(2,2) and higher order flexural modes is generally seen. A mode separation technique based on a guided wave reciprocity relation is applied, and analytical techniques applied to propagate the separated waveforms in the pristine pipe length. It is shown that there is good agreement for the integrated model with full numerical results when applying this mode separation technique. The results indicate the viability of the integrated approach thereby permitting the inspection of thick section components with large propagation distances.
Integrated modelling of guided waves reflection from defects in pipes

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Outline
1. Motivation for numerical modelling and finite element method
2. Overview of the integrated approach
3. Analytical propagation
4. Results
   a) Integrated approach for axisymmetric defect
   b) Integrated approach for non-axisymmetric defect, using 2D-FFT for mode separation
   c) Integrated approach for non-axisymmetric defect, using Auld’s orthogonality for mode separation
   d) Integrated approach for non-axisymmetric defect using circumferential FFT
   e) Integrated approach for a corrosion patch
5. Plan Ahead
There is a strong motivation for numerical modelling in non-destructive testing

Examples of applicable areas are:

- Developing new approaches and methods before running costly experiments
- Carry out parametric studies of defects and setups
- Acquire training data for machine learning algorithms

Pogo – GPU based finite element solver (Link: pogo.software)
Large, complex models can be computationally expensive, requiring a long time to solve.
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Select excitation frequency and mode e.g. T(0,1), L(0,2) or \( F(m,n) \).

**Analytical propagation**
- Analytically propagate excited signal to source nodes using dispersion information from Disperse.
- Solve the truncated FE model with absorbing boundaries using Pogo and obtain solution at monitor nodes.

**Mode decomposition**
- Apply suitable mode decomposition techniques to identify scattered modes and amplitudes at monitor nodes.
- Analytically propagate decomposed signal at monitor nodes using dispersion information from Disperse.

**Comparison**
- Compare propagated signal to solution from full FE model.

**Full FE**
- Defect

**Truncated model**
- Defect

**Source nodes**
- Monitor nodes
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Analytical techniques allow signals to be propagated over a pristine section by taking into account mode phase velocity from Disperse.

3 cycle 50kHz Hann windowed toneburst wavepacket A0 mode in a 10mm thick steel plate.

Results shown here demonstrate the effect of dispersion.
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The integrated model shows good agreement with full finite element solutions when axisymmetric defect is used.
Using a refined mesh provides better agreement between results\textsuperscript{[1]}

\[\text{Plot of displacement in tangential direction vs time, maximum element size = 5mm}\]

\[\text{Plot of displacement in tangential direction vs time, maximum element size = 1mm}\]

\textsuperscript{[1]}: M. Drozdz, Imperial College London, PhD Thesis
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Mode separation using 2D FFT is not suitable for the integrated model approach

The reasons are:

1. Mode separation by 2D FFT leads to wave smearing – adding errors to the reconstructed results
2. Mode separation by 2D FFT requires displacement data across multiple axial locations to provide sufficient spatial resolution – making it computationally expensive (more results available for discussion)
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5. Thesis Structure
6. Plan Ahead
Mode separation can also be achieved by using Auld’s orthogonality relationship

\[ <O> = \int_{a}^{b} \int_{0}^{2\pi} \left( v_m(r, \theta) \cdot \sigma_n^*(r, \theta) + v_n^*(r, \theta) \cdot \sigma_m(r, \theta) \right) \cdot \hat{z} \, d\theta \, dr = 0 \]

for \( m \neq n \) and \( m \neq -n \)

where \( m \) is obtained from **Pogo (finite element)** and \( n \) from **Disperse**

\[ <Q> = \int_{a}^{b} (v_m(r, \theta) \cdot \sigma_n^*(r, \theta)) \cdot \hat{z} \, r \, dr. \]
Using displacement data from a single axial location around the circumference of the pipe, we are able to separate the T(0,1) and F(1,1) guided wave modes from each other.
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Tangential displacement at axial location $z = 0.5\text{m}$

Tangential displacement at axial location $z = 1.5\text{m}$
Using displacement data from a single axial location around the circumference of the pipe, we are able to separate the $T(0,1)$ and $F(1,1)$ guided wave modes from each other.

Tangential displacement at axial location $z = 0.5m$

Tangential displacement at axial location $z = 1.5m$
The time history displacement data shows good agreement between the integrated and full FE results.

Comparison of circumferential time history at pipe 3 o’clock

Comparison of circumferential time history at pipe 6 o’clock
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The circumferential FFT method allows us to separate flexural modes generally

1. Avoids having to define the exact mode shape for the flexural modes (hence more applicable to corrosion patches and non-ideal non-axisymmetric defects)

2. This approach is used to separate circumferential order first i.e. $T(0,1)$ from $F(1,n)$ and $F(2,n)$, and use a radial integration to separate mode number $F(1,1)$ from $F(1,2)$

Does it work? Yes .. (further results available for analytical case, FE scattering case in appendix)
Results for the integrated model using the circumferential FFT method show good agreement.

Normalized propagated result $dz = dr$, circumferential displacement vs time.

Normalized propagated result $dz = dr/10$, circumferential displacement vs time.
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A corrosion patch is chosen so that we can attain a general solution for all forms of wave scattering.
A corrosion profile is generated using a convolution of a random number grid with a Gaussian distribution.

1. Select a corrosion roughness $\sigma$ and correlation length $\lambda$.
2. Generate grid of random numbers normally distributed with s.d $\sigma$.
3. Generate Gaussian filter based on correlation length $\lambda$ and convolve with random grid.

Overview of method to generate corrosion patch for use in FE model.
We are able to reconstruct the finite element signal to a high degree of accuracy after mode decomposition.
We are able to reconstruct the finite element signal to a high degree of accuracy after mode decomposition.
The integrated results agree well and errors reduce with greater mesh discretization.
The integrated results agree well and errors reduce with greater mesh discretization.

**Comparison of axial displacement**

**Convergence plot over varying levels of mesh discretization**
Plan Ahead

Short/medium term
1. Multiple features in a single pipe setup

Long term
1. Develop an interface that would integrate this into a single platform (Pogo + Disperse with a backend) rather than having to go back and forth
Conclusion

– We have shown that the integrated approach has a generalized versatility for pipe features
– Achieved a high level of accuracy compared to full FE (< 3% residual) at a fraction of the computational cost (10% of the full FE)

Proposed application:

– Usage for ML/AI/MAPOD applications to generate a larger pool of data
– Provide solution to service providers where clients can test their setups in a “plug and play” system
Thank you

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Literature

- Where does it fit in the wider literature?
  - Giurgiutiu and group (USC):
    - WDIC method: Wave damage interaction coefficient to determine mode scattering
    - Method requires two FE models to be run – one with damage and one without
    - Have not described “hybrid” method
  - Phillip Loveday and group (South Africa)
    - SAFE method for rail tracks etc to determine modes
    - SAFE-3D method shows moderate agreement (we achieve better agreement) (cc: Long et al. 2018: Numerical verification of an efficient coupled SAFE-3D FE analysis for guided wave ultrasound excitation)
  - Hybrid method (Imperial College)
    - Mainly tested for bulk waves (Rajagopal)
    - Requires defect and non-defect models to be run
Planned Publications

• What papers are planned and where?
  - “An integrated technique for modelling guided wave reflections from defects in pipes”
  - Journals considered: JASA, Ultrasonics, NDT & E, Proc. Of Royal Society A

  - “Selective mode excitation and mode decomposition techniques in pipes: analytical and FE cases”
  - Journals considered: similar to above, Sensors
• Project Aim: Integrate finite element models with analytical approaches which calculate wave modes and dispersion curves for guided wave propagation in uniform structures.
• Project Motivation: Reduce computational burden particularly in long pipelines
• Results
  – Excellent agreement for axisymmetric notch defect
  – 2D FFT requires the acquisition of displacement data from multiple axial locations
  – More work needs to be done with Auld’s orthogonality based approach – particularly with different defects
  – Aim to develop an interface that links automatically
For non-axisymmetric defects, mode scattering from torsional to flexural occurs. Analysis of wavepackets by considering group velocity.

First wavepacket 5122 m/s is $F(1,3)$
Second wavepacket 2935.9 m/s $F(1,2)$
Mode separation using 2D-FFT requires data from multiple axial locations to provide sufficient spatial resolution, making it computationally expensive.
Mode separation using 2D-FFT leads to wave smearing, adding another source of error in results.
After analytically propagating the reconstructed signals, discrepancies with the full FE still persist despite refining the computational mesh.
The F(1,3) portion does not get resolved by increasing mesh resolution.
The F(1,2) portion shows less discrepancy with the full FE by increasing mesh resolution.
Propagated results (26 points around, dz = dr)
Propagated results (100 points around, $dz = dr$)
Update

Full integrated model

Propagated results (26 around, dz = dr/10) error
Normalized propagated result $dz = dr$

Normalized propagated result $dz = dr/10$
Full integrated model

Error residue

Error residue
The circumferential FFT method allows us to separate flexural modes generally.

Does it work analytically?

Source and reconstructed signal – 3 o’clock

Residual
The circumferential FFT method allows us to separate flexural modes generally.
The circumferential FFT method allows us to separate flexural modes generally.

Does it work for the FE scattering case?

Source and reconstructed signal – 6o'clock

Residual
The circumferential FFT method allows us to separate flexural modes generally.
The circumferential FFT method allows us to separate flexural modes generally.
Stress calculations for L02

Szz (26 points circumferential)

Srз (26 points circumferential)
Stress calculations for L02

Sqz (26 points circumferential)