Pedagogical presentation on ultrasonic guided waves

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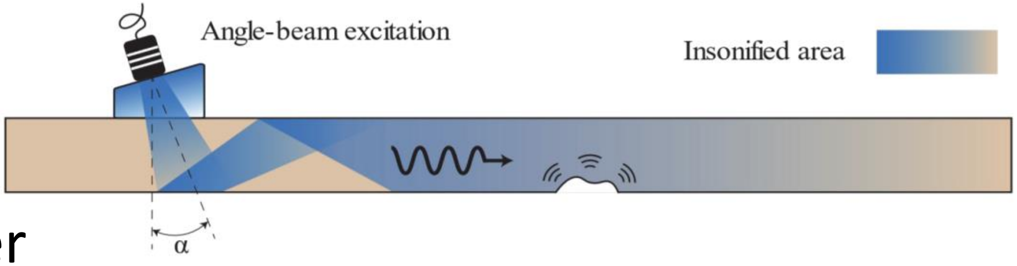
Outline of presentation

- Background of guided waves (bulk vs GW); GW terminology.
- Vibration modes, dispersion, phase and group velocity.
- Slowness, leakage losses and “best” mode for inspection.
- High order modes.
- Guided wave excitation and reception; active and passive GW.
- Guided wave imaging.
- Defect detection in pipelines in axial direction.

Background of guided waves

- Guided waves propagate:
  - In structures with well defined boundaries (like plate or shell);
  - When the wavelength of the wave is greater than or on the order of the thickness of the plate.

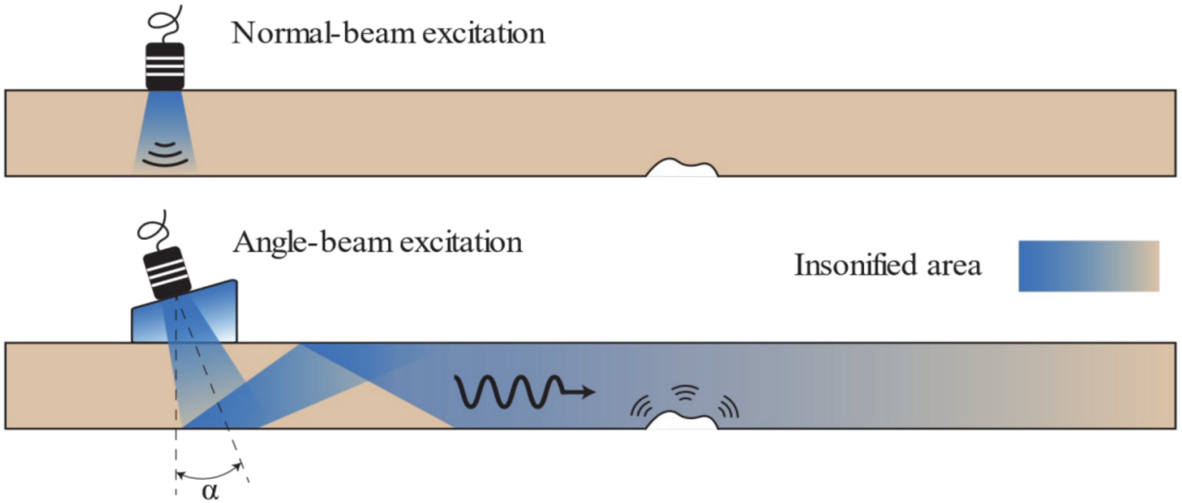


- Key advantages:
  - Rapid inpection over long distances;
  - Limited access required;
  - Suitable for hidden, underwater, encapsulated and coated structures.

*Phan, Haidang, Physics of ultrasonic guided waves in composite materials

GW vs conventional UT

	Frequency	Screening range	Defect resolution	Detection purpose	Available modes
Conventional Bulk wave NDT	MHz, relatively high	The area under probe	Relatively high	Accurately quantify defects	Longitudinal and shear
Guided wave NDT	kHz, relatively low	Large area, ideally up to 100 m	Relatively low	Extensive defect screening	Infinite



*Phan, Haidang, Physics of ultrasonic guided waves in composite materials

GW terminology

Generic terminology

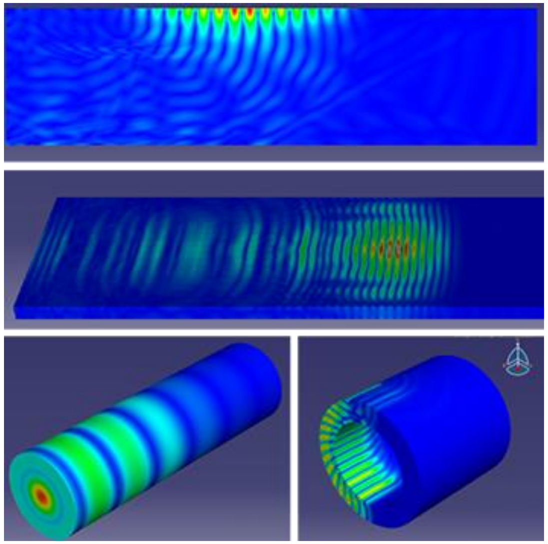
- Guided waves
- Long range/medium range ultrasound

Boundary specific

- Surface waves → Love, Rayleigh
- Interface waves → Scholte/ Stoneley

Structure specific

- Plate waves → Lamb
- Rod waves
- Cylindrical waves
- Rail waves



https://www.innerspec.com/guided-waves

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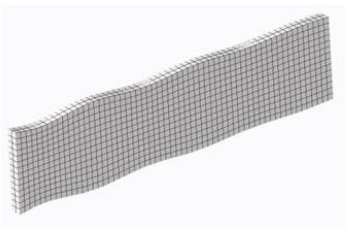
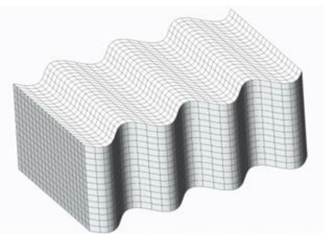
Vibration modes

GW vibrate out-of-plane (perpendicular to the surfaces of the plate) and in-plane parallel to their propagation direction. The vibration modes can be generally classified:

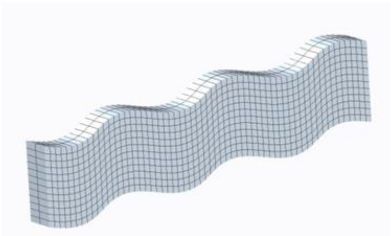
Plates



Symmetric (i.e. S_0)

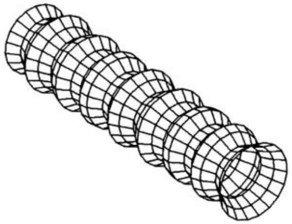


Shear horizontal (i.e. SH_0)

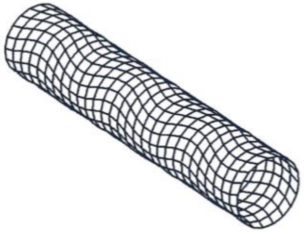


Asymmetric (i.e. A_0)

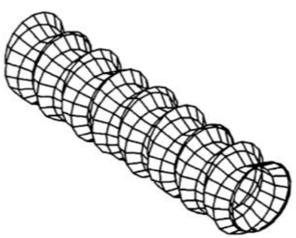
Pipes



Longitudinal (i.e L(0,1))



Torsional (i.e. T(0,1))



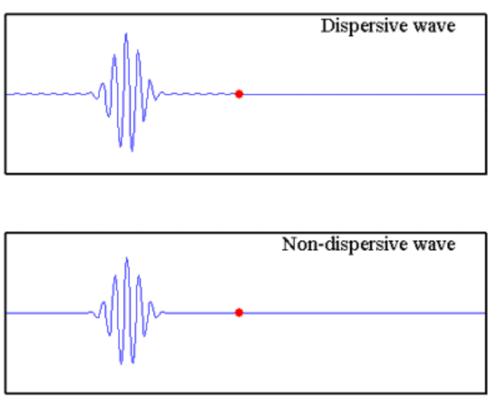
Flexural (i.e. F(1,1))

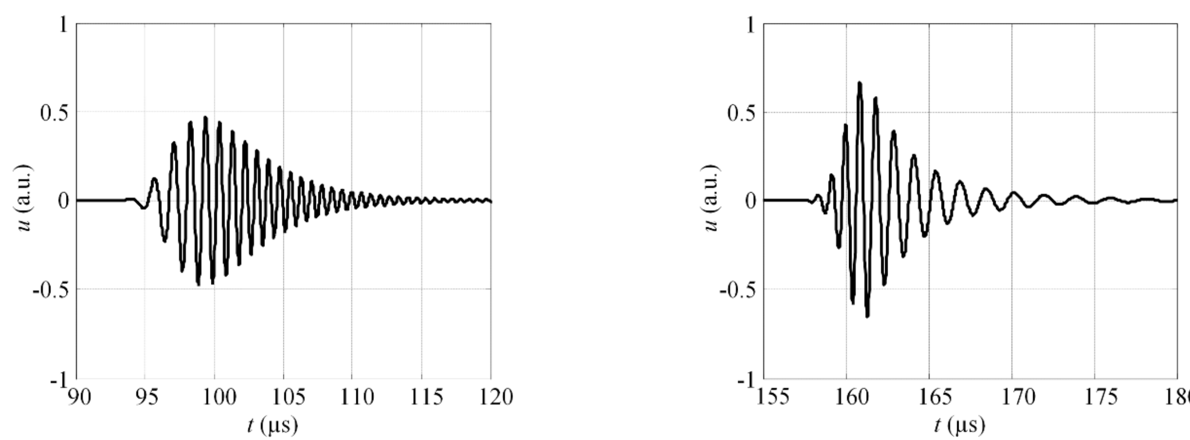
The first index (*n*) is associated with the circumferential order (0 for longitudinal modes and 1 for flexural modes) and the second index (*m*) refers to the order of vibration along the wall of the cylinder.

Dispersion

Guided wave velocities change with the mode and frequency used, and these velocity relationships depend not only on the material of the structure but also on its geometry.

Characteristic	Bulk wave	Guided wave
Phase velocity	Constant	Function of frequency
Group velocity	Equal to phase velocity	Not equal to phase velocity
Pulse shape	Non-dispersive	Generally dispersive





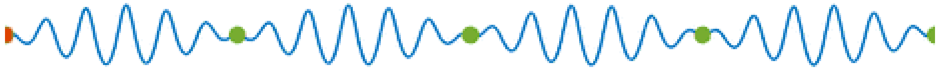
The 1MHz waveforms of 3 cycles after traveling 0.5m in 1mm thickness aluminium plate: the S_0 mode and the A_0 mode

Phase and group velocity

Phase velocity is the speed at which a single frequency component (or phase) of the wave travels through the medium.

For a given frequency ω and wavenumber k,
phase velocity is calculated as:

$$c_p = \frac{\omega}{k}$$

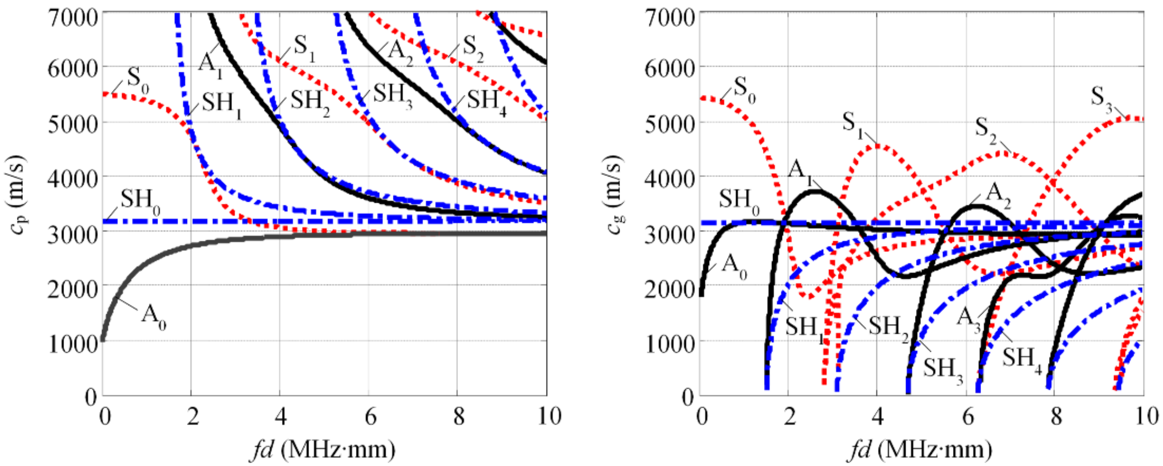


Group velocity is the speed at which the overall energy or „envelope“ of a wave packet travels.

For a dispersive wave, group velocity is given by the derivative of the angular frequency with respect to wavenumber:

$$c_g = \frac{d\omega}{dk}$$

Dispersion curves

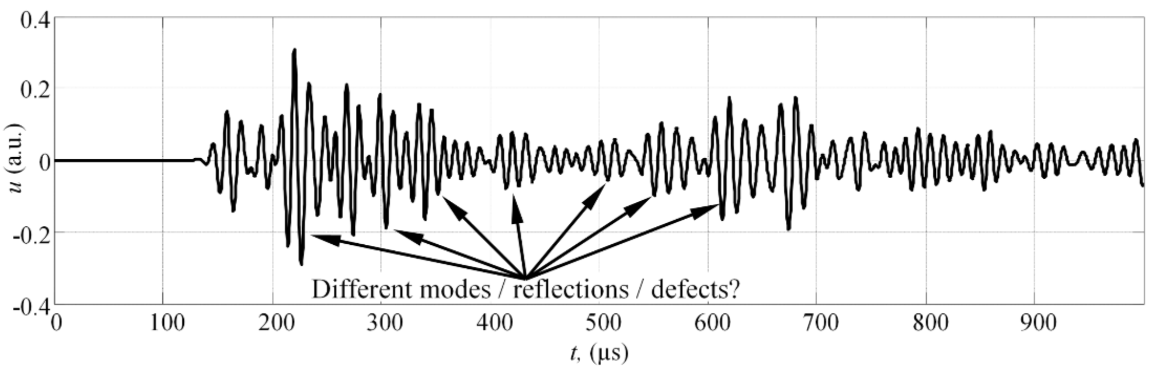


The phase (left) and group (right) velocity dispersion curves for a traction-free aluminium plate with thickness of 1mm

Dispersion curves gives the possible combinations of group/phase velocity and frequency within the structure.

A – asymmetric;
S – symmetric;
Indices – harmonic order.

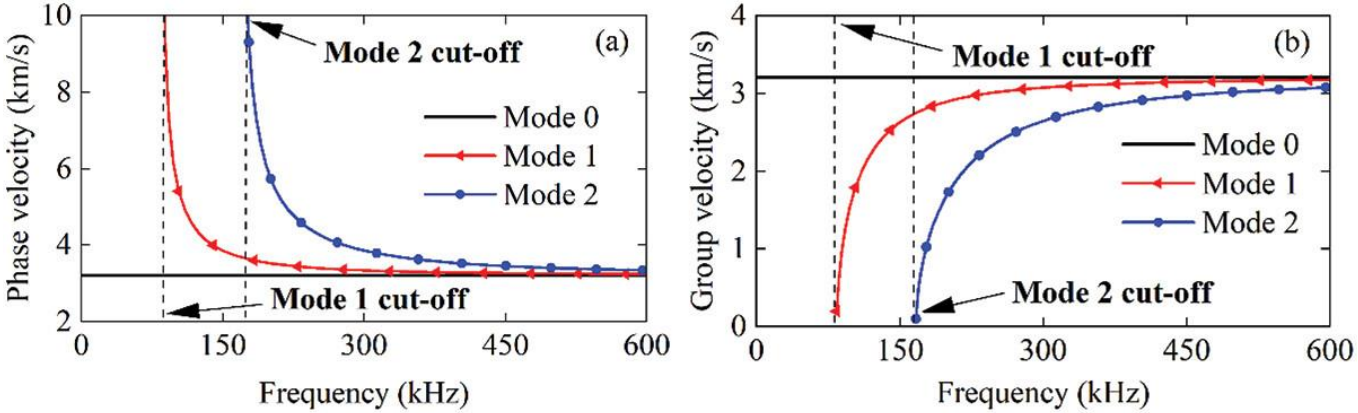
DC discussed so far employs a harmonic plane wave excitation in the wave guide.



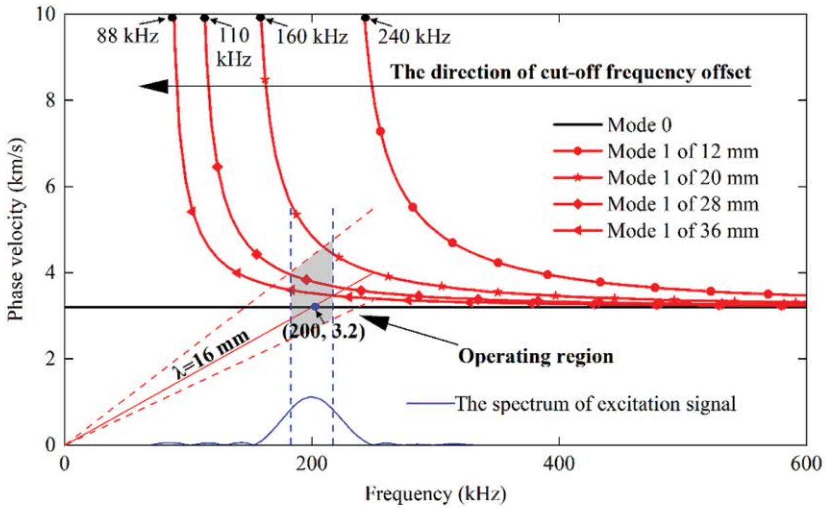
An example of the multimodal, dispersive and interfered waveform captured on 4mm thickness glass fibre reinforced plastic

High dispersion can limit the spatial resolution, sensitivity to the damage as well as the distance of propagation.

Cut-off frequencies



Dispersion curves of the rectangular plate with a width of 36 mm: (left) phase velocity and (right) group velocity.

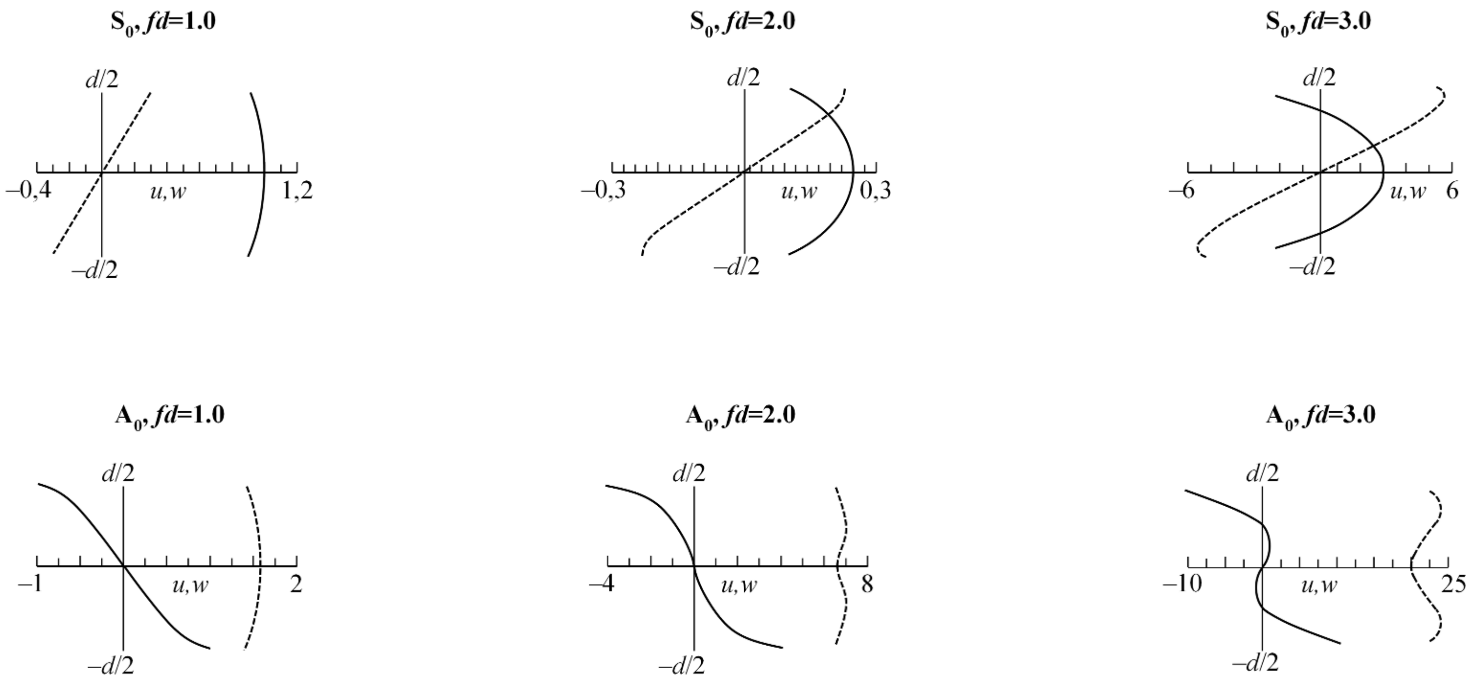


The mode 1 of rectangular plate with different width

https://doi.org/10.1080/10589759.2023.2299794

Mode shapes

In the fundamental asymmetric mode (A_0), the motion is primarily out-of-plane; in the fundamental symmetric mode (S_0), particles have a dominant in-plane motion.



The in-plane (*u*, solid line) and out-of-plane (*w*, dashed line) displacement profiles across the thickness of the aluminium plate (c_T=3.1mm/μs; c_L=6.3mm/μs) for the S_0 and A_0 modes at various frequency-thickness (*fd*) values

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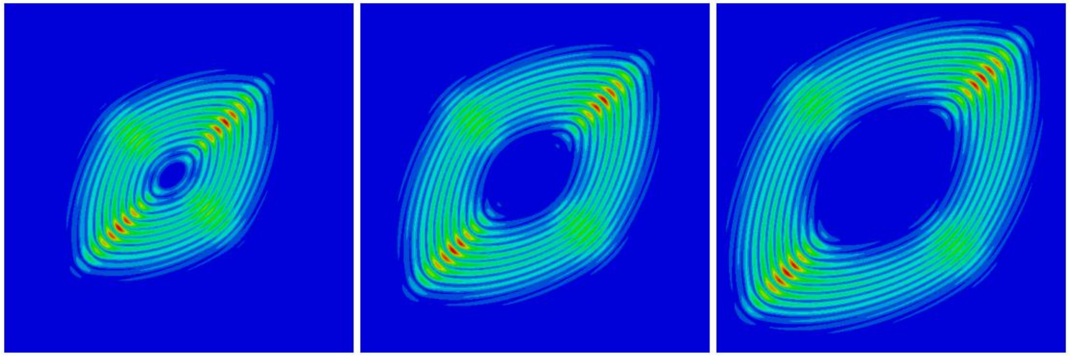
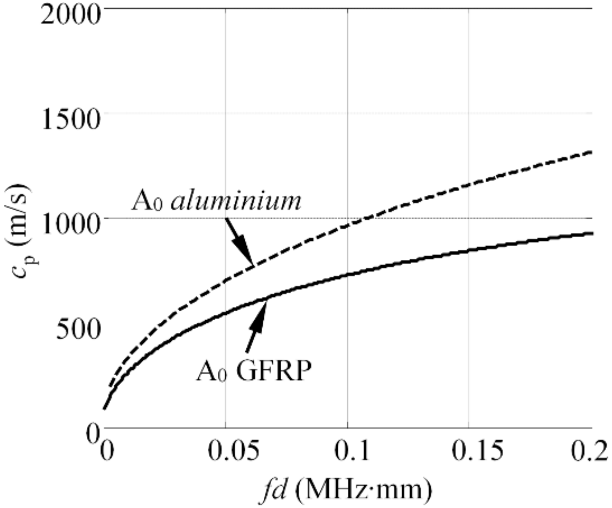
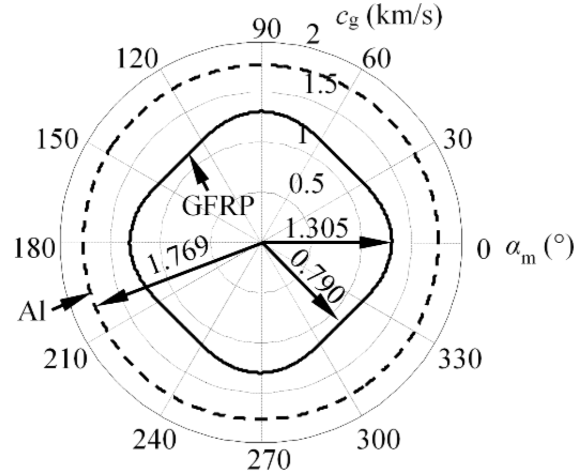
Slowness



A_0 mode guided wave propagation in 45 degree unidirectional composite (3.6 mm thickness, 100 kHz frequency) at three time instances



The phase velocity dispersion curves for A_0 mode in a traction-free Al and GFRP plates with a thickness of 1 mm at an angle α_m=0°

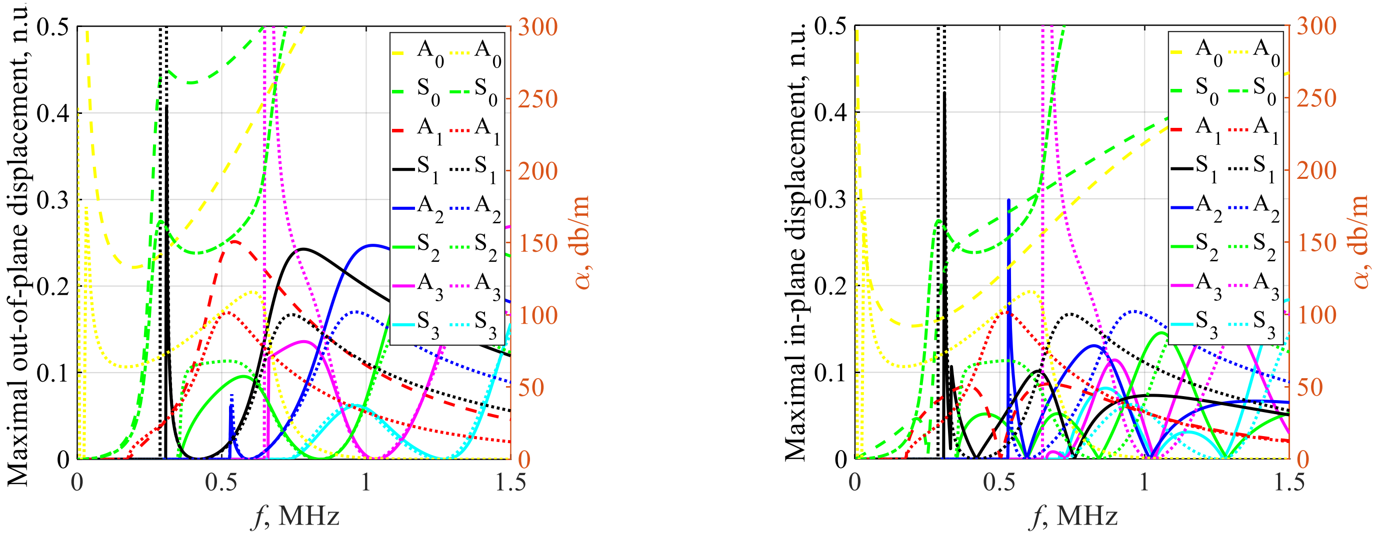


The slowness profile of the group velocity for A_0 mode propagating on aluminium (dashed line) and GFRP (solid line)

https://doi.org/10.1007/978-3-319-30050-4_24-1

Leakage losses

Leakage losses refer to the portion of the wave's energy that leaks out of the intended guiding structure to surrounding media as it propagates.



Out-of-plane and in-plane component displacement and leakage losses versus frequency

- Attenuation (losses) does not always increase as frequency is increased.
- Leakage depends on the coupling between the modes in the structure and the bulk waves that can exist in the embedded media.
- Bulk waves in the embedded media can only be excited if the phase velocity of the guided waves in the structure is above the bulk wave velocity in the surroundings.

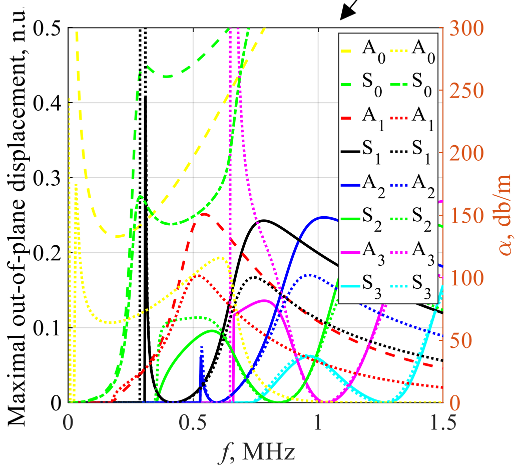
The “best” mode for inspection

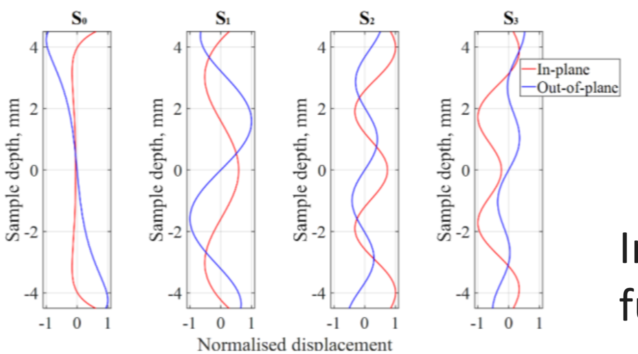
Of thousands of points on a dispersion curve, only certain ones lead to a successful inspection i.e. those with best:

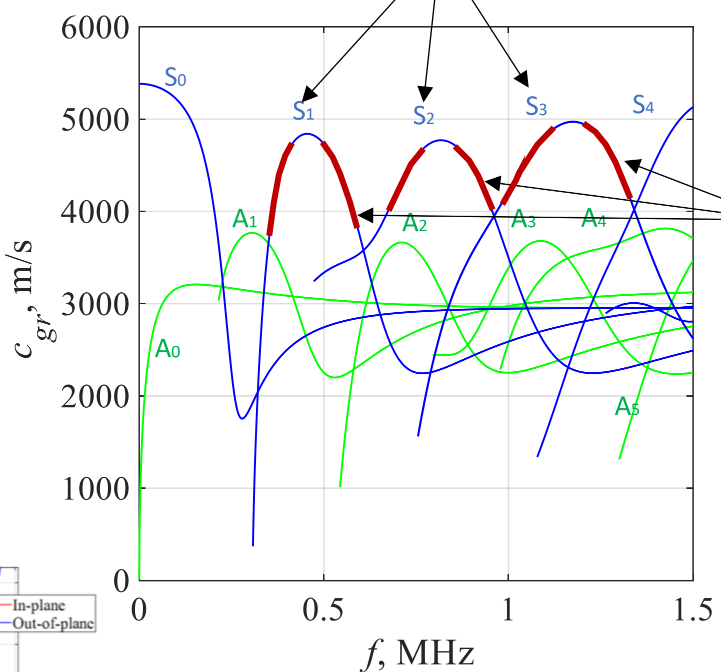
- Excitability and detectability (out of plane displacements ant surface);
- Propagation distance (attenuation, leakage);
- Penetration power (minimum power at an interface between a pipe and a coating, etc);
- Sensitivity to defects (maximum displacement on the outer, center, or inner surface);
- Ease of analysis (without dispersion, with high group velocity).

The “best” mode for inspection

Modes that simplifies the analysis, yet difficult to excite with conventional long. wave probe due to poor out-of-plane displacements







Zones that ensure good sensitivity to thickness change

In order to simplify signal processing, most applications use the fundamental modes (either S_0 or A_0).

https://doi.org/10.3390/s23146505

GW advantages

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- Inspection of long distances from single probe position.
- By using mode and frequency tuning, the defect detection can be enhanced;
- Sensitivity to defects of different origin;
- Often greater sensitivity than that obtained in normal beam ultrasonic inspection using same frequency;
- Ability to inspect structures under water, coatings, insulations, multilayered structures;
- Potential in localisation, sizing and classification of damage;
- Cost effective due to inspection simplicity and speed.

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High order modes

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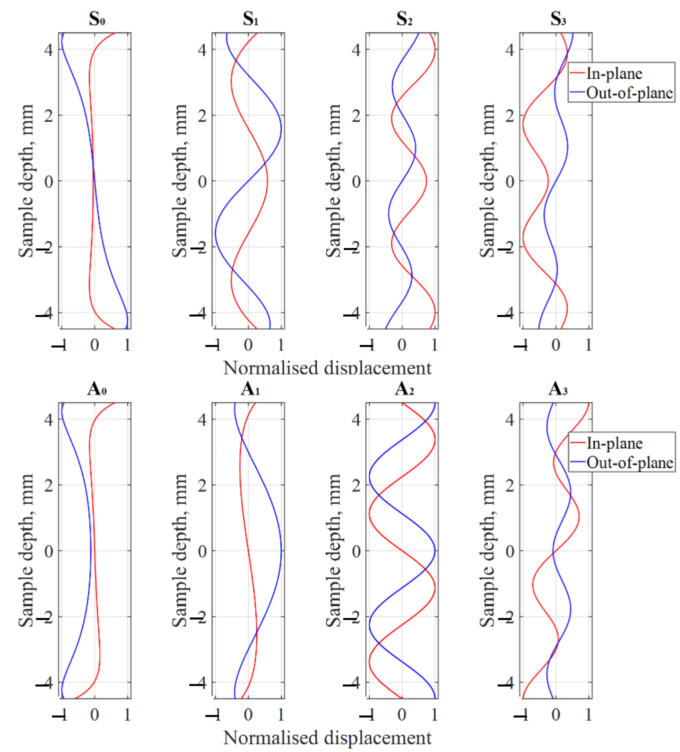
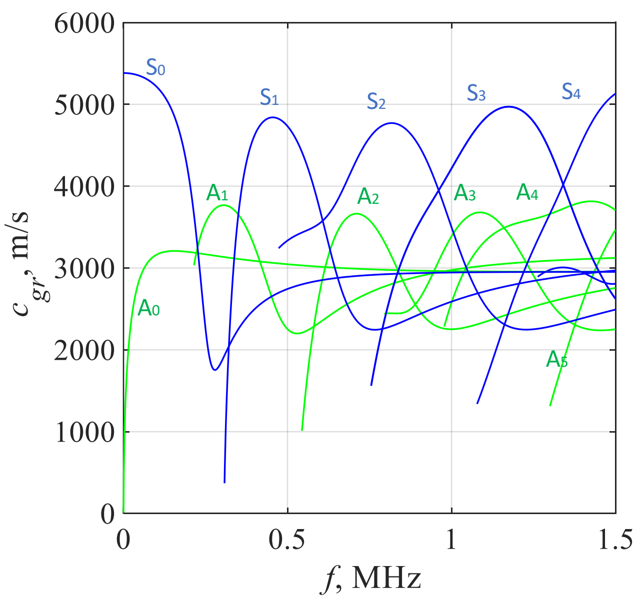
As the inspection frequency increases, the number of propagating modes also increases, as does the complexity of the received signals.

These modes can be more sensitive to certain types of defects.





Higher-order modes have more complex through-thickness displacement profiles, often showing multiple zero-displacement nodes across the thickness where particle displacement is minimal or zero.

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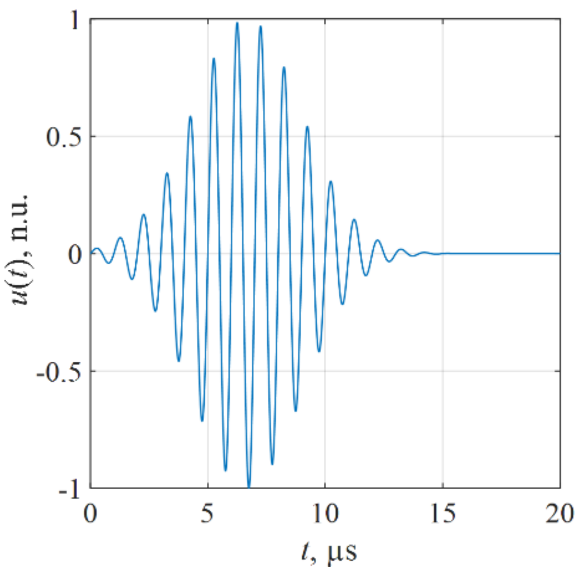
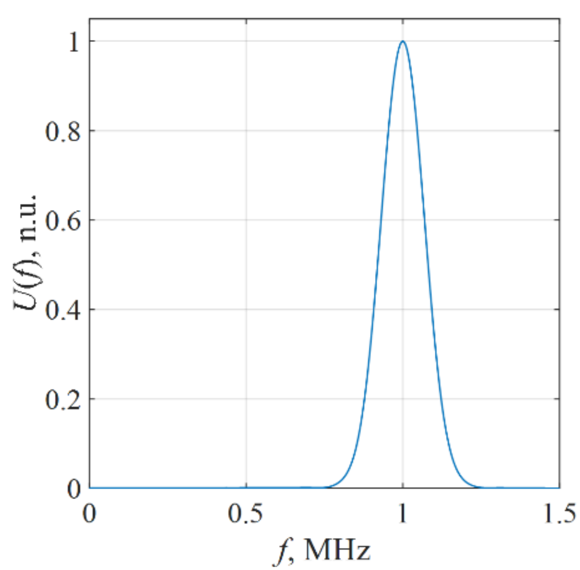
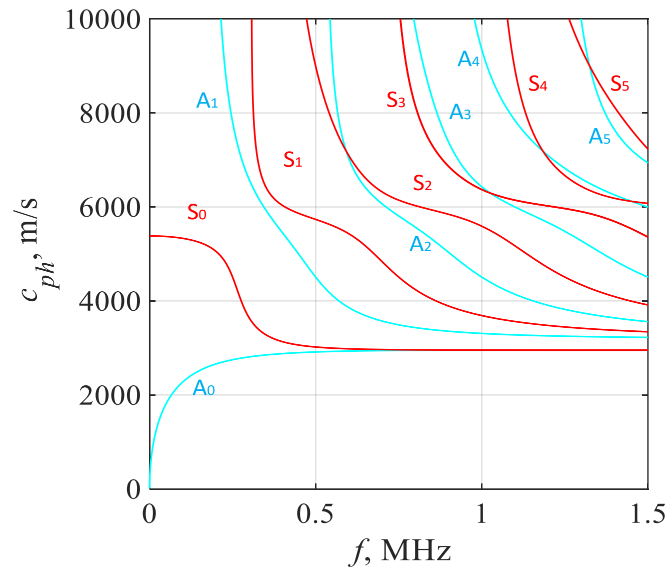
Guided wave excitation and detection

Guided wave energy can be induced into a wave guide by a variety of different techniques.

In addition to the ordinary frequency spectrum there is a phase velocity spectrum, and because of these two spectral bandwidths of frequency and phase velocity, it makes it difficult to excite a specific point on a dispersion curve







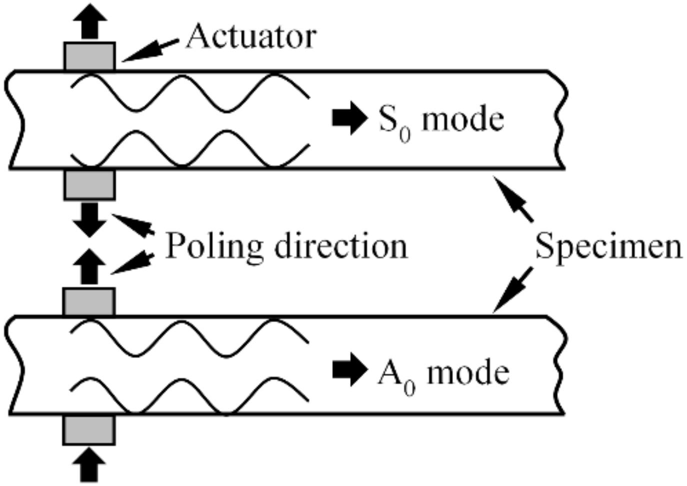
Guided wave excitation and detection

- <u>Normal beam excitation:</u>

  The simplest solution is to apply the excitation force to the surface of the specimen, with the same direction as the dominant displacements of the preferred mode:

  - Tangential force is used to excite the symmetrical modes.

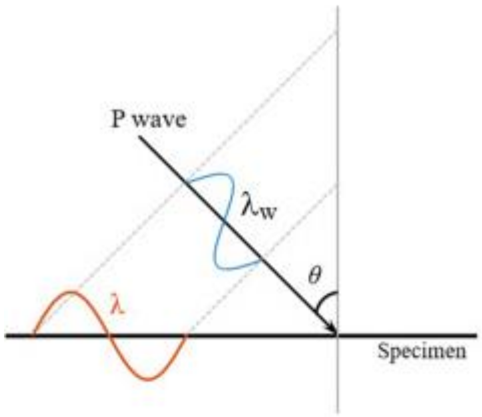
  - Normal force is used for the asymmetrical modes.



Guided wave excitation and detection

- <u>Angle beam excitation:</u>

Angle beam wedges take advantage of Snell's law to control the mode and direction of guided wave excitation. The selection of the guided-wave mode desired for excitation is done by modifying the impingement angle ϑ.



$$\theta_m(f) = \sin^{-1}\left(\frac{c_w}{c_m(f)}\right),$$

$$m=1, \ldots, M_{max}, \; c_m(f)>c_w$$

$c_w, c_m(f)$ are velocities in wedge and medium; $\theta_m(f)$ is the angle to achieve desired wavespeed.

The guided-wave wavespeed $c_m(f)$ must be greater than the P-wave wavespeed c_w in the wedge, hence some modes may not be able to be excited.

Guided wave excitation and detection

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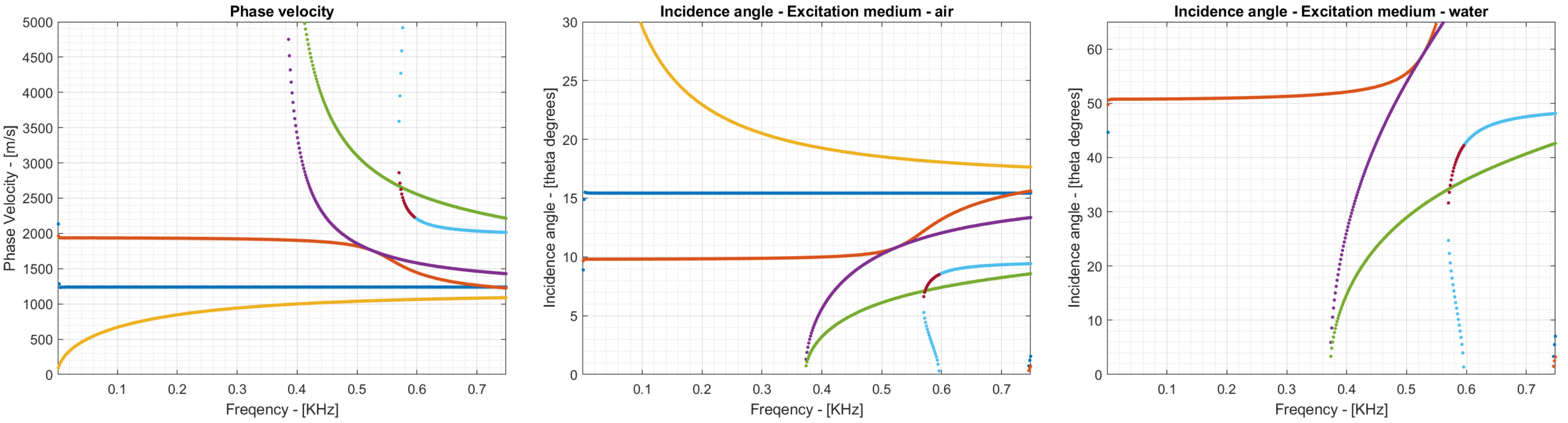
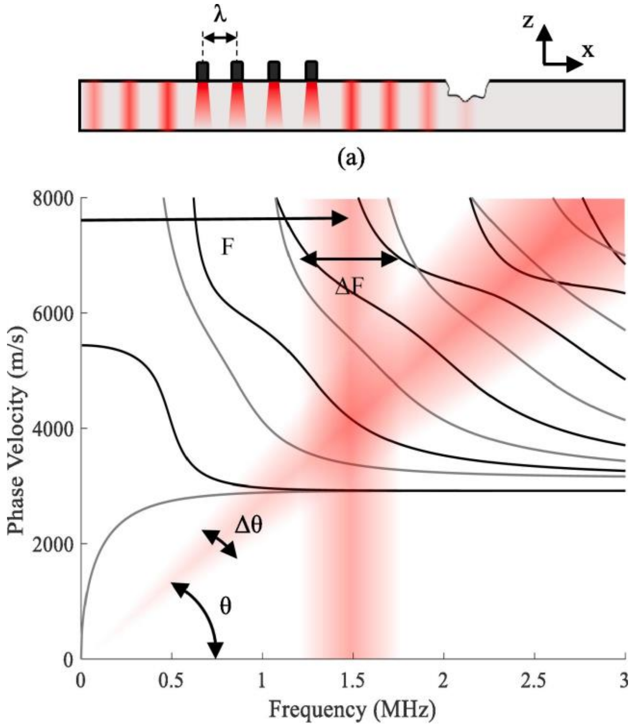


Guided wave excitation and detection

- <u>Comb excitation:</u>

  Is a constant wavelength method that allow mode selection based on the pitch between each element, which is a multiple or is equal to the wavelength of the mode(s) of interest.



F – corresponds to the center frequency of the toneburst;
ΔF – corresponds to the number of cycles of the toneburst;
θ – corresponds to the element interspace;
Δθ – corresponds to the length of the probe.

https://doi.org/10.1016/j.ultras.2019.106039

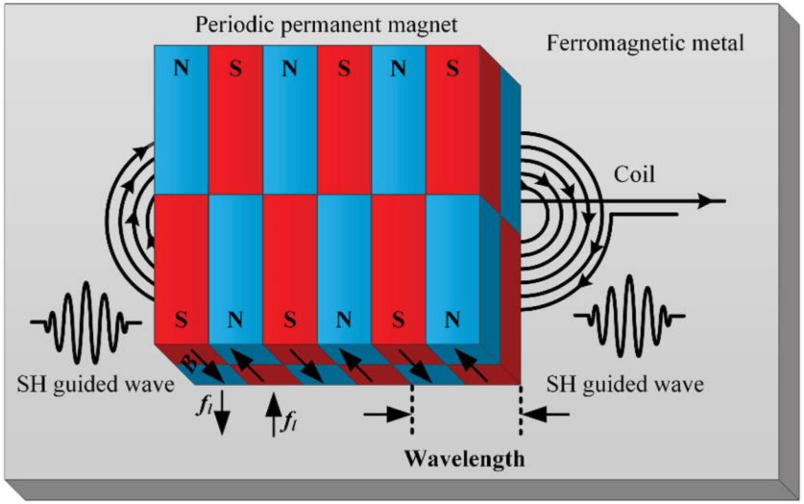
Guided wave excitation and detection

- <u>EMAT/magnetostrictive:</u>

EMATs have a series of permanent magnets providing a static magnetic field, arranged that the north and south (N/S) poles alternate periodically. A coil of wire runs parallel to the direction of the periodicity of the magnets, which will create eddy currents in the sample, that lead to a Lorentz force parallel to the surface and perpendicular to the direction of the wire.

The mechanism of <u>EMAT</u> can be classified into Lorentz force and magnetostriction for non-ferromagnetic and ferromagnetic metallic specimen.

Conductive materials only; relatively low SNR; high voltage high cost instrumentation needed.

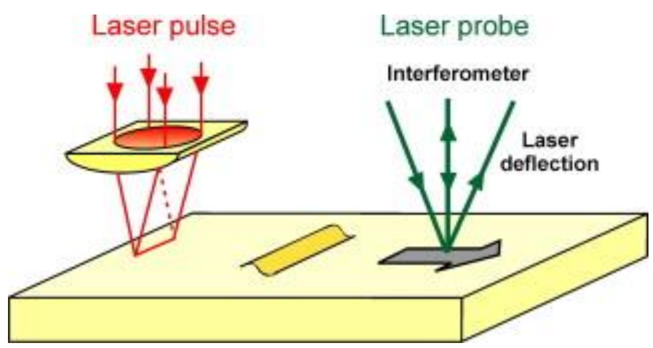


https://doi.org/10.1080/10589759.2023.2299794

Guided wave excitation and detection

- Laser:

  A pulsed laser beam is used to locally heat the material with the resulting thermal stresses exciting guided waves. Care must be taken to avoid too high laser intensity leading to material ablation.



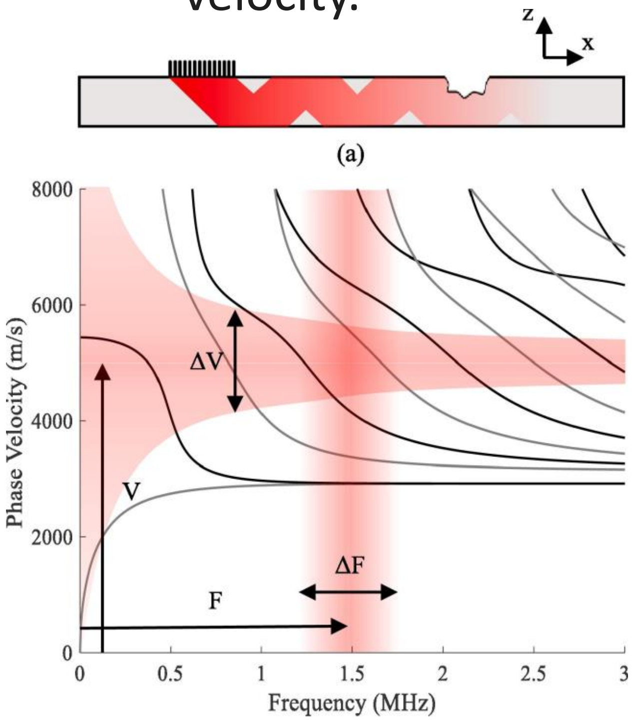
- Non-contact;
- Adaptable to surface;
- High resolution;
- Broadband/narrowband excitation.
- Limited efficiency;
- Poor SNR.

https://doi.org/10.1016/j.ultras.2013.05.013

Guided wave excitation and detection

- <u>Phased array</u>:

  Is a constant phase velocity method. For a transducer array with a fixed elementary pitch *p*, a delay t_0 in emission can be added between each element creating angled plane wavefront allowing to excite specific phase velocity.



F – corresponds to the center frequency of the toneburst;
ΔF – corresponds to the number of cycles of the toneburst;
V – corresponds to the delay between the elements;
ΔV – associated with the length of the probe.

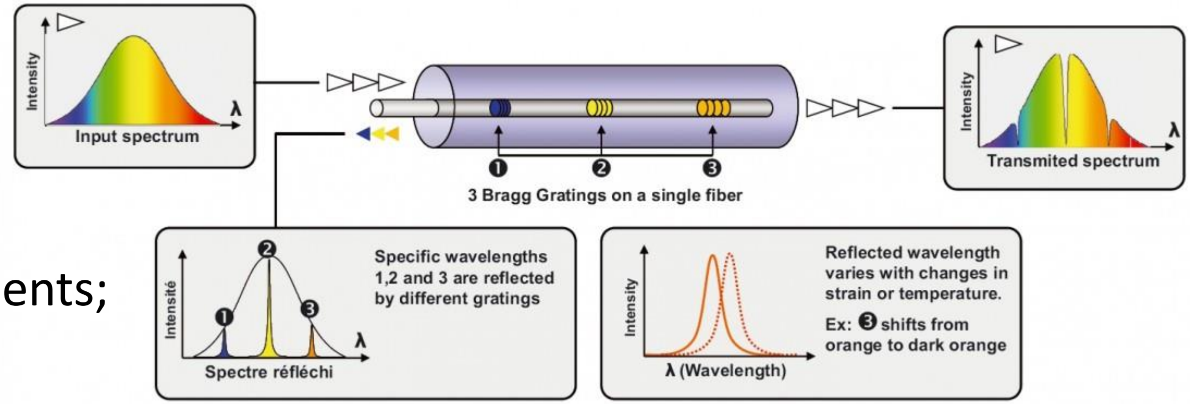
https://doi.org/10.1016/j.ultras.2019.106039

Guided wave excitation and detection

- Fiber Bragg grating sensors:

  An FBG sensor is a typical optical sensor that has the grating with periodic changes, resulting in only light with a specific wavelength being reflected. When an FBG is stretched or compressed, or when it expands or shrinks, its Bragg wavelength shifts correspondingly. The received optical signals are converted into digital signals by the balanced photodetector.

- Lightweight;
- Electromagnetic immunity;
- Resistant to harsh environments;
- Low transmission loss;
- Can be embedded.



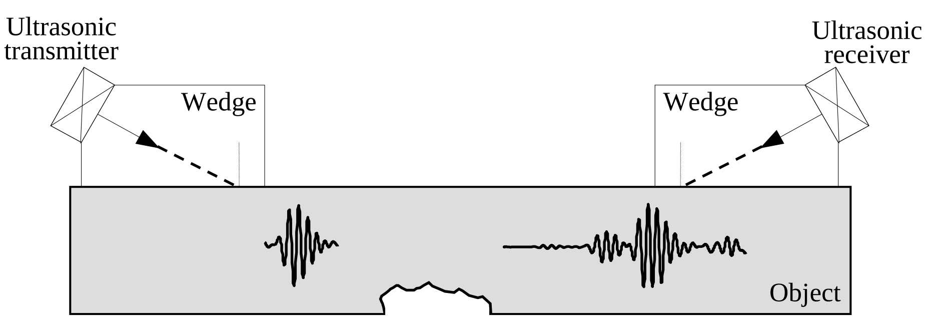
https://scaime.com/fibre-bragg-grating-technology

Active and passive GW

Active GW utilizes both actuators and sensors to measure a response of the structure to a known input.

Parameters of wave can be tuned to enhance the response from the defect

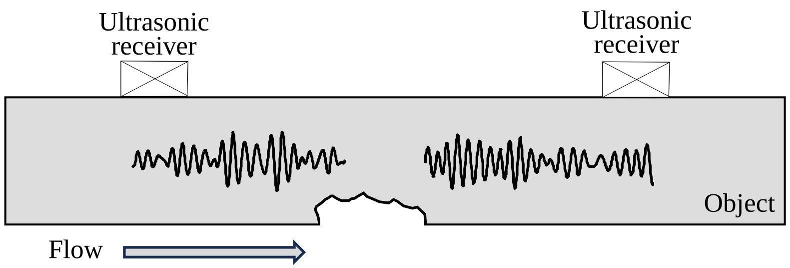
PZT sensors are mainly used



Passive GW techniques exploit the presence of ambient noise in the structure, e.g. the flow of fluids inside pipes.

Can be based on simultaneous measurements of elastic ambient noise at two points and calculation of cross-correlation to obtain Green's function.

Fiber bragg grating sensors can be used for sensing (as one of the options).



What defects can be detected?

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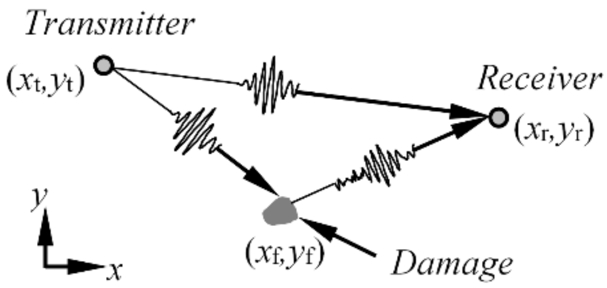
- Considered signal features:
  - Time of flight (ToF);
  - Reflection/transmission coefficient;
  - Spectral changes;
  - Mode conversion.



- Defects:
  - Fatigue;
  - Fracture;
  - Corrosion;
  - Cracks;
  - Delaminations;
  - Disbonds;
  - Inclusions;
  - Matrix cracking;
  - Fibre breakage;
  - Porosity;
  - Impacts.

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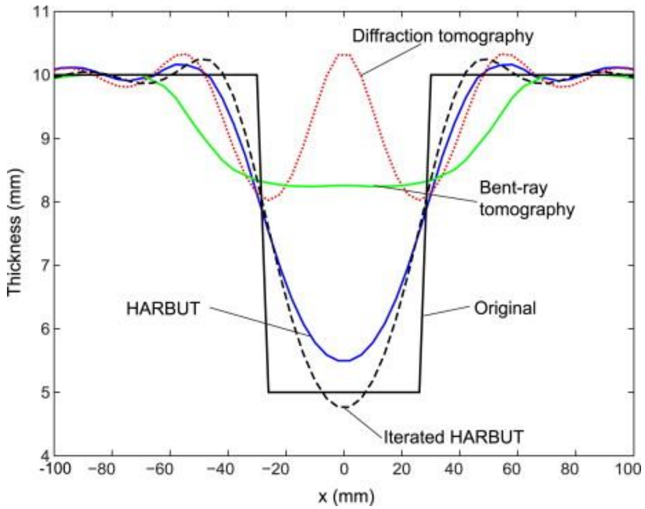
GW imaging

Tomography:

Considers single mode and aims to reconstruct the spatial distribution of the material properties, which can be based on the projection of wave velocity, attenuation, frequency etc.

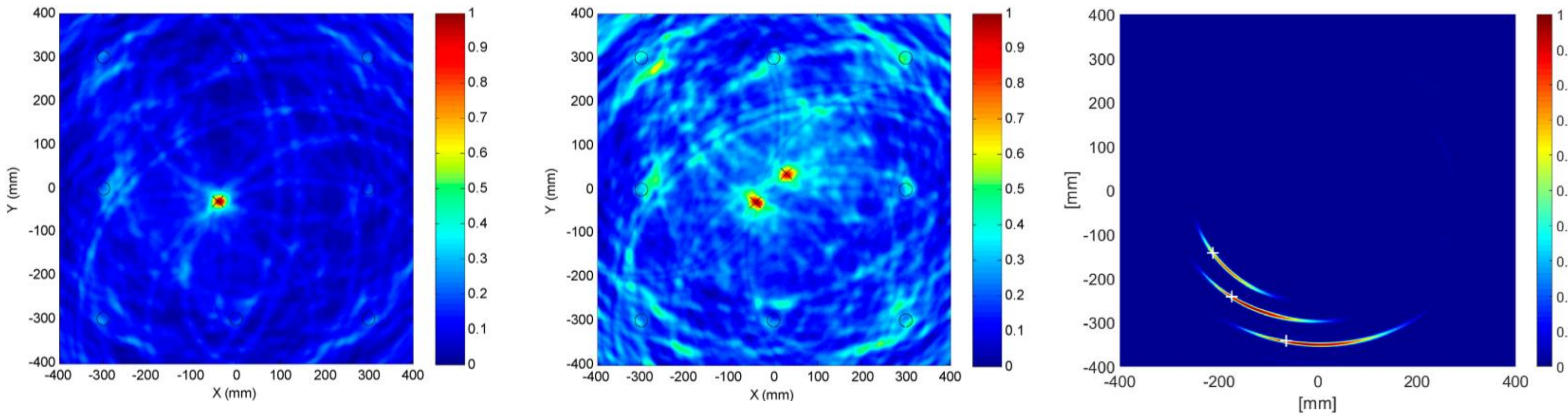
- Straight-ray
  - Ignores refraction and diffraction, so is limited to low contrast defects and can detect large smoothly varying defects.
- Bent-ray;
  - Increases resolution of straight ray tomography by considering the refraction.
- Diffraction tomography (DT);
  - Limited by use of Borns approximation, which considers that scattered field is a superposition of the scattered fields by many independent scatterers. When phase is distorted the scatterers no longer behave independently. Method is valid for defects with limited phase distortion.
- HARBUT.
  - Uses low resolution bent-ray tomography as background for DT. Accounts for phase distortion.



https://doi.org/10.1016/j.wavemoti.2013.04.004

GW imaging

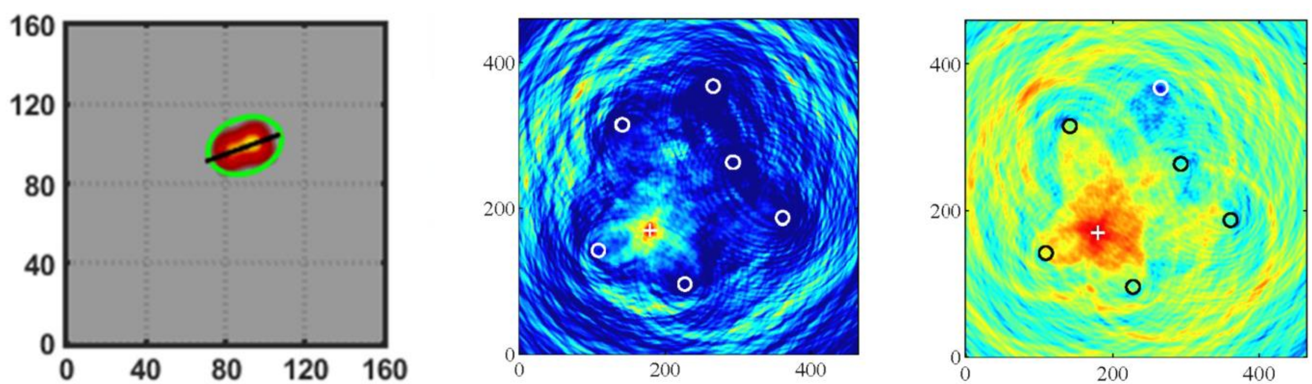
- <u>Delay and sum (DAS):</u>
  - With multiple damages present and inadequate baseline subtraction—particularly when environmental variations are significant—the method's performance declines. Dispersion effects are also neglected, and its effectiveness diminishes as the number of sensors decreases. Utilizing a non-linear DMAS or DAS-SR approach can provide an improved alternative in these cases.
- <u>Minimum variance:</u>
  - Advanced version of DAS, which considers the diffraction of GW scattered by defects, however neglects the dispersion.



https://doi.org/10.3390/ma10010004
https://doi.org/10.1115/1.4049571
https://doi.org/10.1016/j.ndteint.2021.102574

GW imaging

- <u>Probabilistic Inspection of Damage (RAPID):</u>
  - The method performs effectively even with a reduced sensor count. However, its baseline-dependent nature poses challenges with optimal baseline selection, as environmental variations can lead to false indications. In conditions with temperature fluctuations, baseline-free approaches, such as non-linear RAPID, are recommended.
- <u>Excitelet:</u>
  - Correlation based imaging which considers the dispersion and the damage is modelled as omnidirectional reflector. For each pixel method calculates the normalized correlation coefficient between residual signal and the analytically propagated signal. Computationally intensive.



https://doi.org/10.1115/1.4049571
https://doi.org/10.1121/10.0001300

Environmental factors

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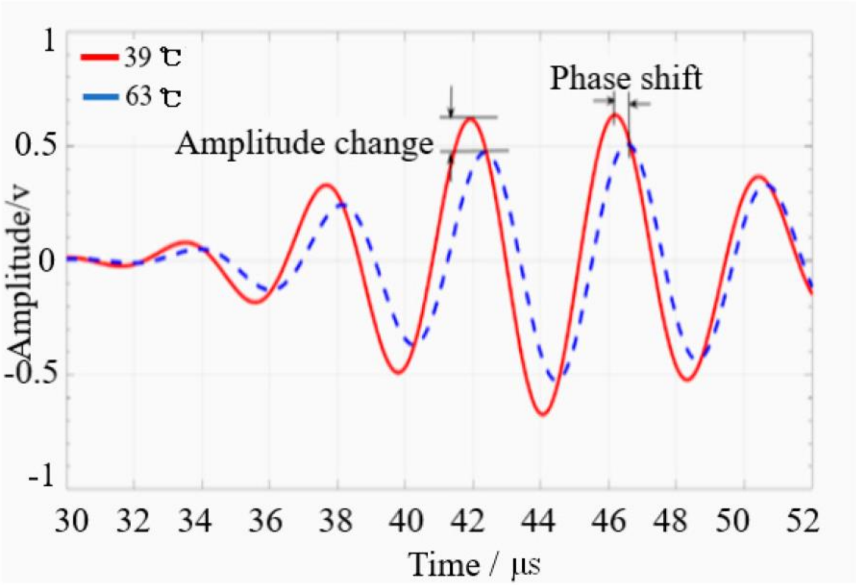
Most of wave propagation-based damage detection methodologies rely on the use of baseline data collected from the structure in the undamaged state.



Temperature, load, humidity, radiation, will cause changes in the sensor signals.

Avoiding false alerts

Compensation of temperature, load

Baseline free techniques

https://doi.org/10.3390/s19235174

Outline of presentation

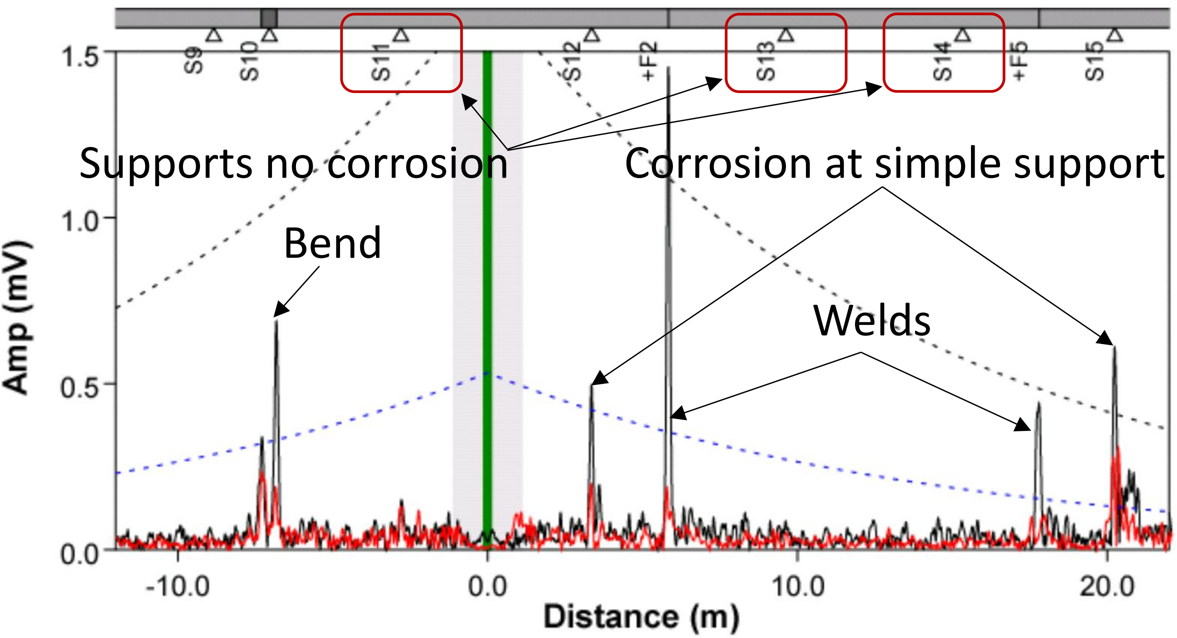
- Background of guided waves (bulk vs GW); GW terminology;
- Vibration modes, dispersion, phase, and group velocity.
- Slowness, leakage losses and “best” mode for inspection.
- High order modes.
- Guided wave excitation and reception; active passive GW.
- Guided wave imaging.
- Defect detection in pipelines in axial direction.

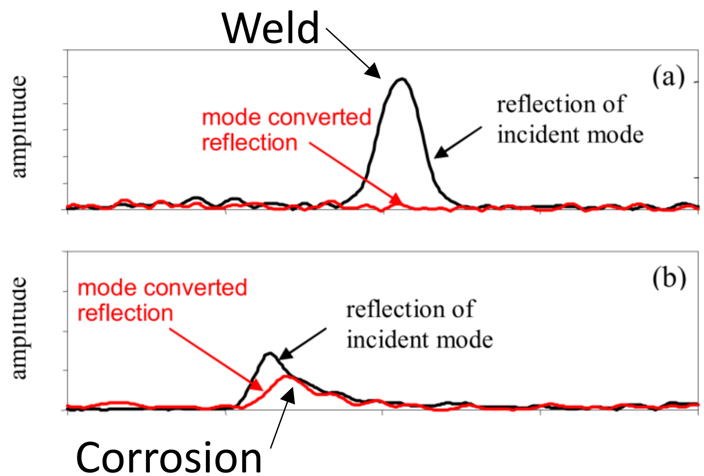
Pipe inspection/corrosion detection

Inflatable rings

Solid rings

Symmetric L(0,2) or torsional modes T(0,1) are frequently used. Symmetric modes are used for symmetric features such as welds. Asymmetric features such as corrosion will produce non axially symmetric waves.





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Pipe inspection/corrosion detection

The test range is a function of the defect size that is to be detected. The requirement has been to detect wall loss greater than about 10% of the pipe cross section. If it is necessary to find smaller defects the signal to noise ratio must be better so the range is reduced.

Application	Typical range in each direction (m)
Ideal conditions	80+
30 year old pipe with little corrosion	40
30 year old pipe with some general corrosion	20
Typical pipe wrapped in factory applied foam	15
Heavily generally corroded pipe	5
Bitumen coated pipe	<5

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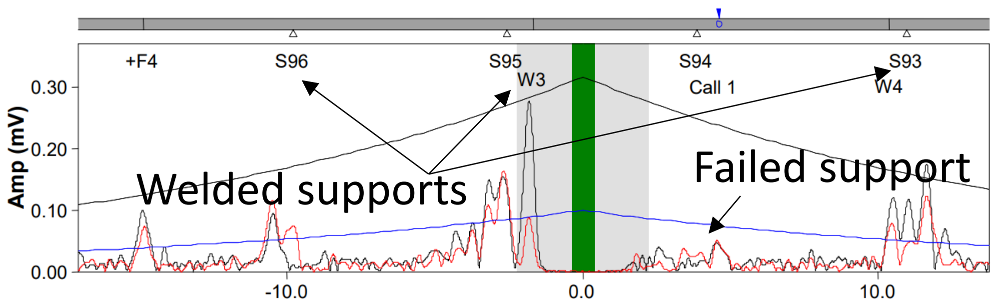
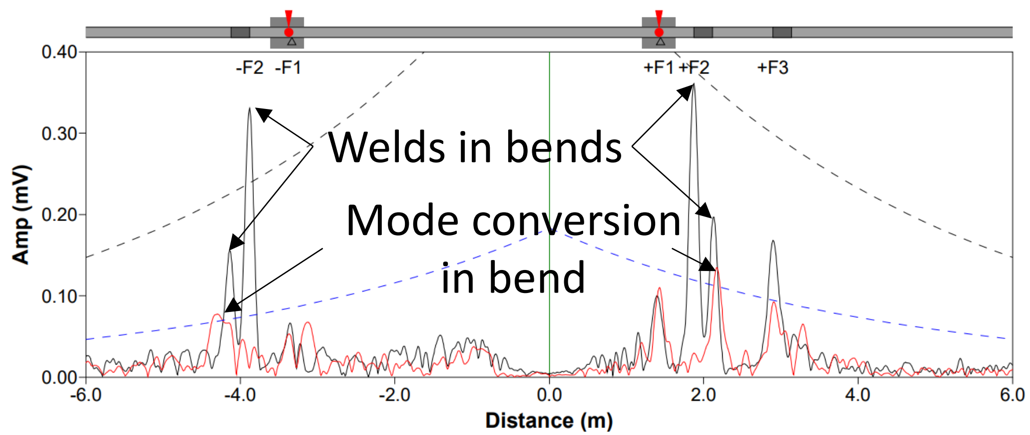
Problematic cases



Welded supports are asymmetric therefore it is difficult to determine whether there is a defect at the support.

Sharp bends (curvature to pipe diameter ratio <3). In addition to the reflections from the two welds, there is mode conversion produced by the bend.



Bitumen coatings is a particular problem as the pipe effectively becomes a bi-layer system and any energy carried in the bitumen layer is rapidly attenuated.

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Limitations

- The absolute remaining wall thickness cannot be measured directly.
- The ratio between the symmetric and asymmetric features determine the severity of feature and are used for grading. However high level experts are needed for correct interpretation of the results.
- The follow-up with the conventional NDT techniques is usually required to investigate the indications.
- Concentrated (pitting) and severe defects that lead to leakage may be missed.

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