

# INTERACTIVE ULTRASONIC FIELD SIMULATION FOR NON-DESTRUCTIVE TESTING



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## Context

### Non Destructive Testing (NDT)

Non-invasive techniques used for the detection of critical defects in parts or industrial structures

- Examinations are performed during manufacturing, in maintenance or in-service.
- Many industries: energy, petrochemical, aeronautics, transports, etc.
- Strong economic and public safety issues implied.
- Multiple techniques are used: ultrasounds, Eddy currents, radiography X or g, etc.

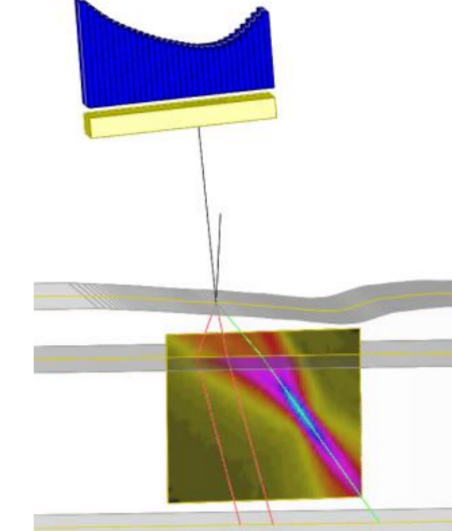


### CIVA software

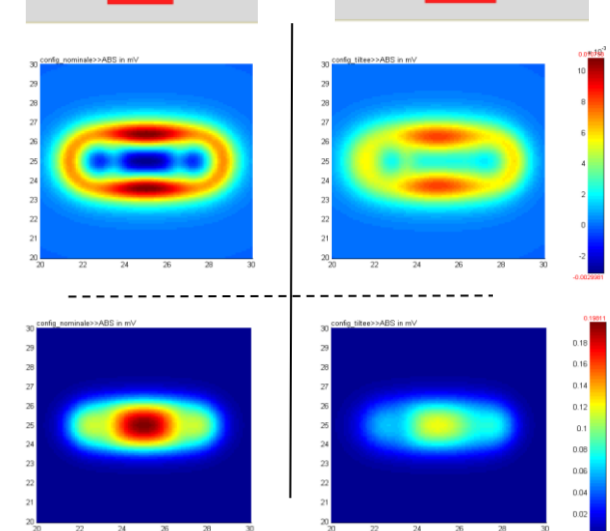
#### NDT Simulation and Analysis Platform

- Design of new methods/probes
- Qualifications of methods
- Interpretation of complex results
- Virtual Testing at designing of parts
- Training
- 200 customers, world-wide commercial distribution many contexts and use cases.

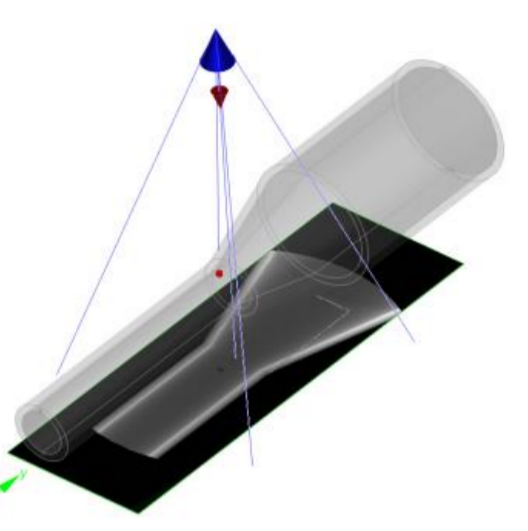
#### Ultrasounds



#### Electromagnetism



#### X-Ray



**Need for interactive simulations**

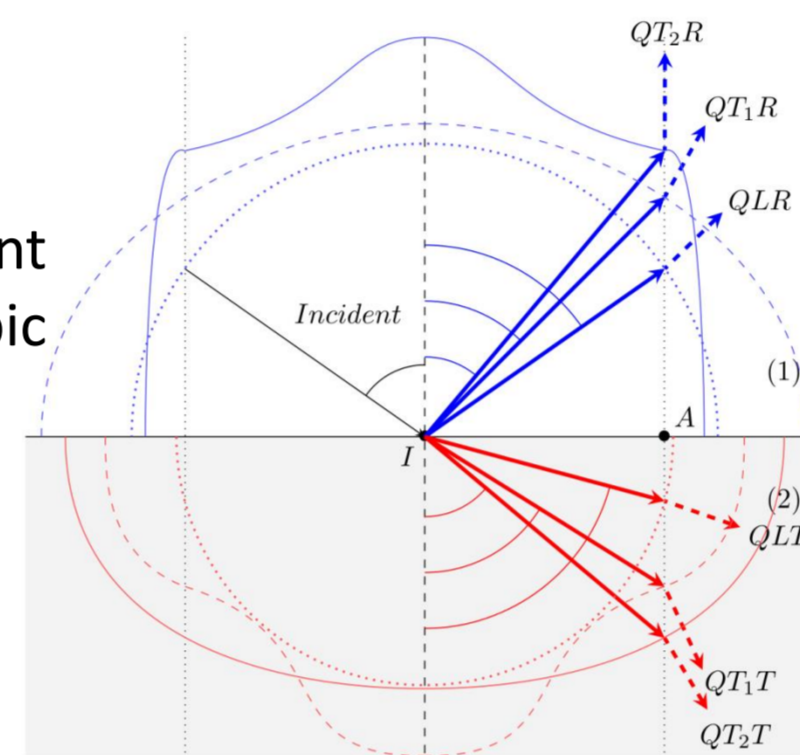
## Ultrasonic Field Simulation

### Ultrasonics Wave propagation

- Propagating in materials that can be :
  - Homogeneous or heterogeneous,
  - Solid or liquid, isotropic or anisotropic.
- Can interact with interfaces with :
  - Specular reflexions,
  - Refractions,
  - Possibly diffraction on edges.
- Two main types of volume waves in isotropic materials :
  - Longitudinal (compression waves) = L mode,
  - Transversal (shearing waves) = T mode.
- At any interface, mode conversions (from L to T or from T to L) can happen.
- Boundary representations for pieces.
- Probes : US waves emitters/receivers, mono-element or phased array.

### Anisotropy

- Anisotropic materials behave differently depending on the orientation.
- Three different mode (= wave types) :
  - QL (quasi-longitudinal),
  - QT1 and QT2 (quasi-transversal).
- Two directions to be taken into account that are generally different in anisotropic materials :
  - Phase direction (= direction of the wave front),
  - Energy direction (= direction of the ray).
- A single interaction of a wave on an interface between two anisotropic materials can generate up to 6 new waves.



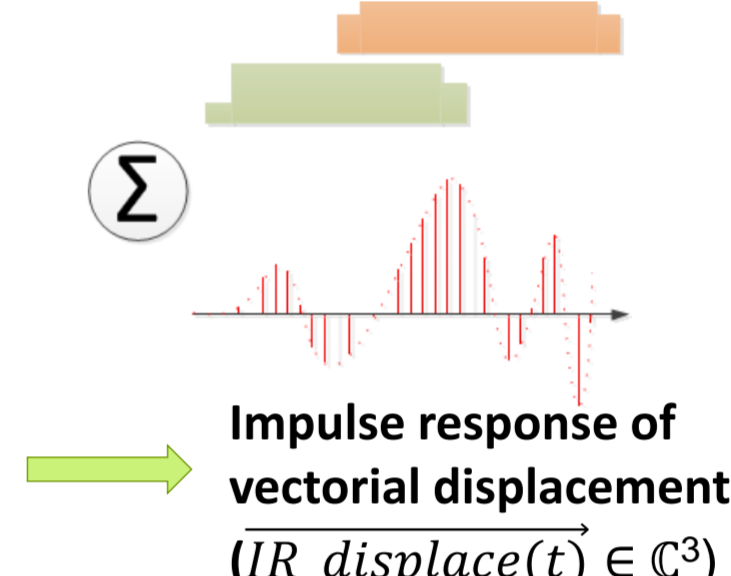
### Algorithmic Principle [1]

#### Pencils computation

- Probe surface and field area are discretized.
- Computation of paths following Snell-Descartes laws
- Computation of pencil contribution (Amplitude = divergence factor x Fresnel coefficients x dS), Time of Flight, Duration).

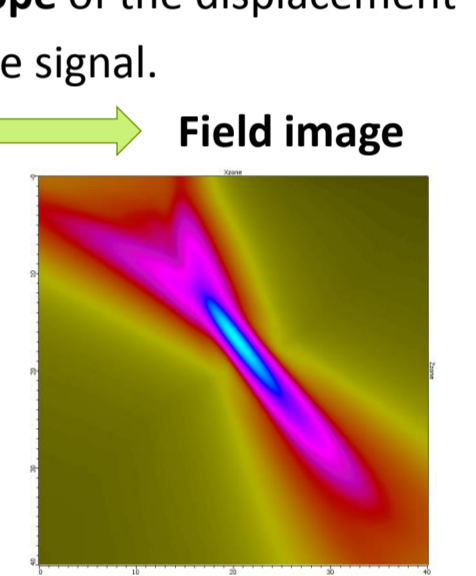
#### Delay laws application and impulse response

- Temporal Shift of pencil contributions according to delay laws.
- Accumulation of pencil contributions on Impulse response.



#### Extraction of field amplitude

- Convolution with probe signal
- Computation of displacement module signal
- Amplitude = maximum of the envelope of the displacement module signal.



## A fast implementation for simple configurations

### Pencil computation

#### Homogeneous isotropic specimen with planar surfaces

#### Path computation for immersion or contact probe

- For a single refraction at the interface between coupling material and specimen material following Snell-Descartes following equation can be written :

$$\frac{x_i - x'_i}{c_1 \sqrt{(x_i - x'_i)^2 + z_i^2}} = \frac{x'_i - X}{c_2 \sqrt{(x'_i - X)^2 + z^2}}$$

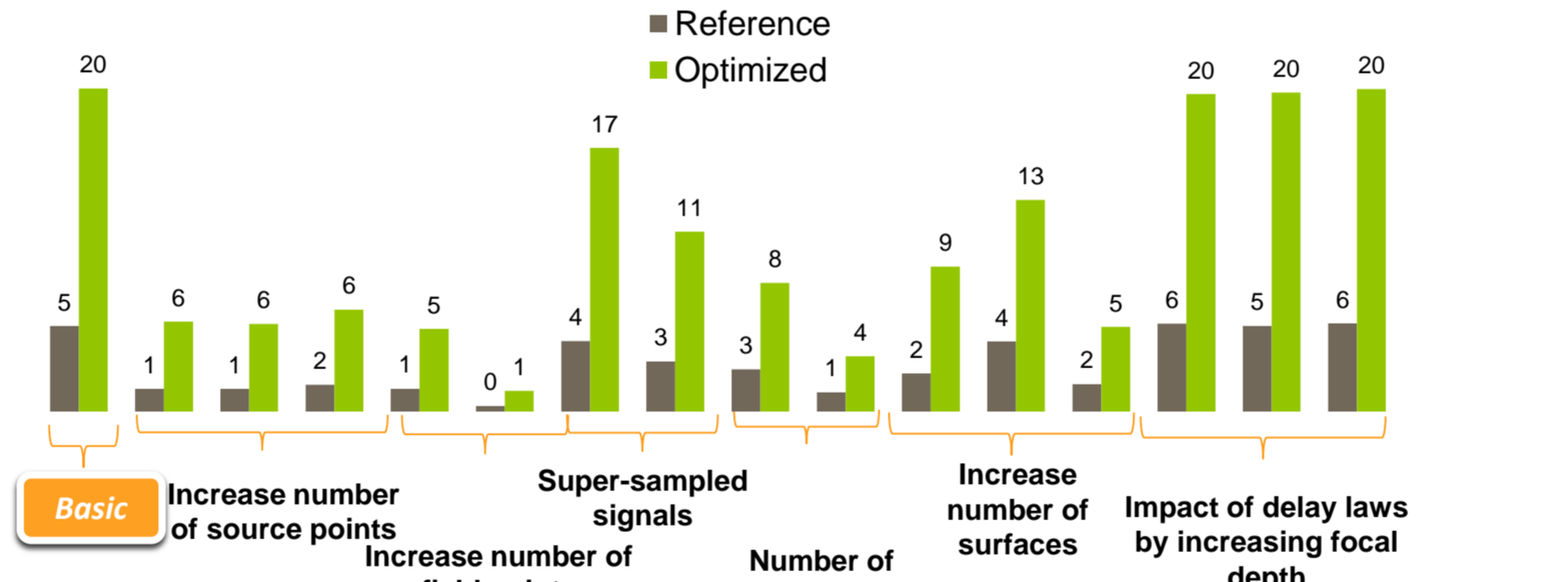
where  $X$  is unknown  
Non-linear equation solved via iterative 1D Newton method (Similar to [2])

- Direct and indirect paths computation.
- Indirect paths = refraction + single reflexion without mode conversion.
- Validity of paths computed are tested : location of points on surfaces, occlusions.

Fresnel coefficient and divergence factor = analytic formulae.

### Results

#### Field image per second



- Good acceleration by **vectorization** of pencil computation and amplitude extraction + use of Intel MKL FFT.
- Good **scaling** on recent CPUs.
- Up to **20 field image per seconds** on simple configurations

**Interactivity goal on CPU is reached !**

### What's next ?

- Build and test of an AVX version (256bits – 8 floats/register)
- Use of Intel MIC architecture (Xeon Phi) – hope a good scaling
- Cuda reference version for GPU needs optimization (can benefit from SIMD implementation analysis on CPU).
- Functional extensions :
  - Longer ray paths (more reflexions/refraction with mode conversion) implies solving a set of N non linear equations (or use [3])
  - Non-planar surfaces (quadric, quartic) raise equations complexity.
  - Need for heuristics in order to avoid testing all the possible sets of surfaces ([2])

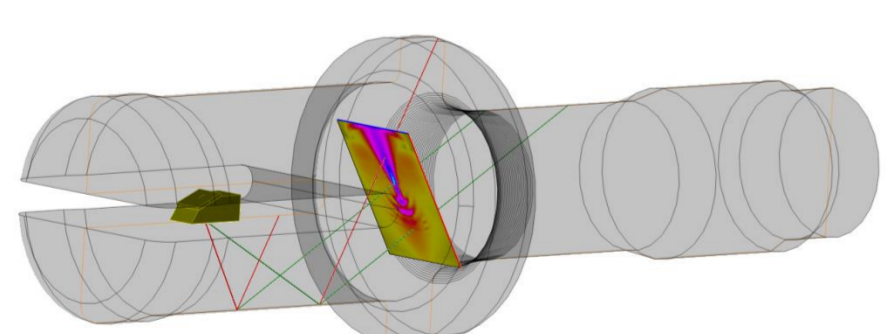
**Difficult and still limited**

## Towards more complexity

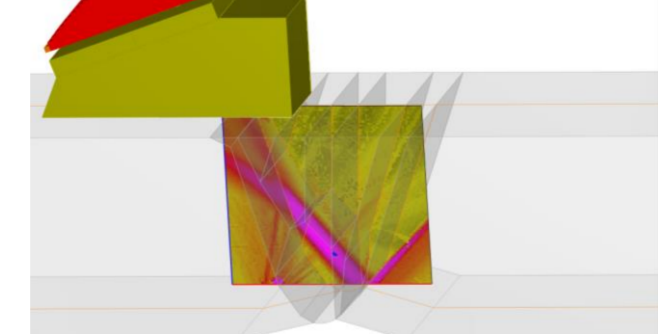
### Complex cases

- Any geometry (non planar-surfaces, triangle meshes)
- Heterogeneous specimen
- Ray paths of any length
- Isotropic / anisotropic materials

**Complex but still needs to be interactive**  
(progressive computation)



3D CAD



Heterogeneous anisotropic weld

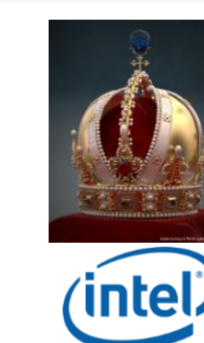
#### Pencil computation step is the most expensive step

Find paths between field point and probe surface + costly computation of divergence factor, Fresnel coefficients...

### Basic tools



**Preliminary results = fast ultrasonic ray tracer based on Intel Embree (CPU) and Nvidia Optix (GPU)**



Acceleration of phase and energy directions computation for anisotropic material = Fast computation by intersection of meshed slowness surfaces and interpolation of normals. **Acceleration vs analytic = x7 to x8**

Specimen	Material	Number of ray paths with two reflections Mrays / s	
		PC 2x12 cores	Nvidia Geforce GTX Titan
Planar specimen (12 tri)	Isotropic	17,7	45,7
	Anisotropic	5,0	7,8
CAD Specimen (32 kTri)	Isotropic	6,9	6,9
	Anisotropic	2,7	3,0

### Solutions considered

#### Progressive pencil step computation + intermediary US field images

##### Solution 1

##### Iterative geometrical method

For each field point and each mode, find pencils reaching the probe surface via a reverse beam tracer. Pencil solid angles are then gradually decreased, and occlusion or surface discontinuities are processed via an adaptive algorithm (like AD-Frustum [4]). At each iteration, for pencils reaching the surface probe, Fresnel coefficients are computed.

##### Solution 2

Perform a MC light tracing (or MCMC) with importance sampling, and possibly regularization (like in [5]) following ray paths starting from the probe until they reach the field area and contribute to the field points impulse responses. Pbm : *coherent sources* !

## Perspectives and Conclusion

- Interactive ultrasonic field simulation for simple configurations can be performed on recent CPUs
- Tests on AVX, AVX2 CPUs and Intel MIC shall be performed for this method.
- A fast Cuda-based GPU implementation shall be carried-out.
- Non-planar surfaces or longer paths with wave conversion shall have to be taken into account.
- For complex cases (heterogeneous specimen with anisotropic materials, complex geometry and long ray paths) another method based on fast ray tracing shall be developed.
- Fast ultrasonic field simulations shall be derived to perform interactive computations of echoes on defects or specimen boundaries.
- These interactive tools shall be available in next Civa software commercial releases.
- As different codes developed for different hardware (CPUs and GPUs) will be available, an auto-tuning mechanism will be settled in order to choose automatically the best one for a given ultrasonic field configuration. Another mechanism might be developed to automatically tune computation options in order to keep a satisfactory level of interactivity ([6]).

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