Realistic modeling of austenitic welds ultrasonic inspection

P. Guy (INSA Lyon)

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フィリップ・グイ

フランス語ピレネー

PhD in Physical Acoustics
Paris 7 -Denis-Diderot University

1992 - now : Associate Professor @ Institut National des **Sciences** Appliquées de Lyon INSA-Lyon (National Institute of Applied Science)

Teaching activities :

- General Physics at sophomore level (Electrognetism, waves, optics)
- **NDE** for 4th year engineering students in Material Science and master degree students.
- **NDI** for professionals (preparation to COFREND* certifications Level 2 and Level 3)

  ***COFREND** is the equivalent of **JSDNI** in France.

International responsabilities :

- Deputy of the EURINSA - European First Cycle Program (1999 - 2003)
- Head of the European First Cycle Program (2003 – 2005)
- In charge of the recruitment of spanish students for Eurinsa (2000-2010)

Administrative responsabilities :

- Member of the administration council of INSA since 2006

Research Laboratories :

1992-2012 : MATEIS INSA Lyon (Materials Engineering and Science)

2012-present : LVA INSA Lyon (Laboratoire Vibrations Acoustique)

Research topics (mainly ultrasound) :

- Materials ultrasonic characterization
- Non Destructive Evaluation
- Structural Health Monitoring

Industrial cooperations :

EDF (Electrical production), CEA (French Atomic Agency), RTE (electricity distribution), ...

My relationship with Japan

- 2000 - 3rd Japan France Seminar on Intelligent Materials and Structures – 3rd JFSIMS
  Tokai University – 08/28-30
- 2002 – Chairman of the 4th JFSIMS
  INSA Lyon FRANCE – 07/8-9
- 2004 – 1st INABIO
  Sendai 02/24-25 (1st time in Sendai)
- 2004 – Chairman of the 5th JFSIMS
  Presqu'île de Giens FRANCE october
- 2005 - International Joint Conference of 'the JFSIMS' and 'the International Symposium on Smart Materials for Engineering and Biomedical Applications'
  Tokyo & Hakone 10/29-31
- 2016 - Visiting professor, **EMAT NDT** , Institute of Fluid Science, Sendai 08/30-10/08
- 2018 – 1st **PYRAMID** joint meeting 01/22-24
- 2018 - Visiting professor, PYRAMID project , Institute of Fluid Science, Sendai 08/24-10/05

Laboratoire Vibrations Acoustique

http://lva.insa-lyon.fr

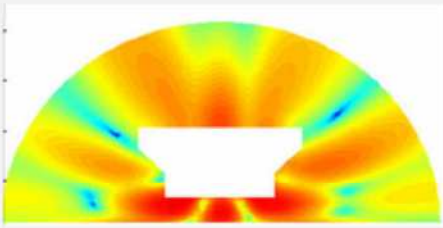
- Staff : (a medium size lab)
  - 16 professors and associate professors
  - 2 research engineers
  - 1 technical assistant
  - 3 post-doctoral researchers
  - 23 Ph.D. students

- A+ ranking from the national research agency (ANR)
- Member of LabEx CeLyA (Lyon Acoustics Center)
- Member of Carnot Institute Ingenierie at Lyon

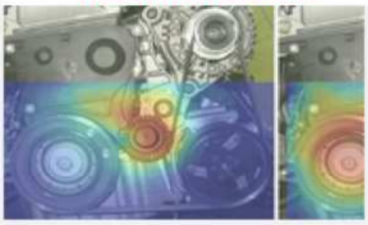
  The Carnot institutes network combines scientific excellence with professionalism and is committed to develop research for companies innovation.

Research fields

Vibro-acoustics



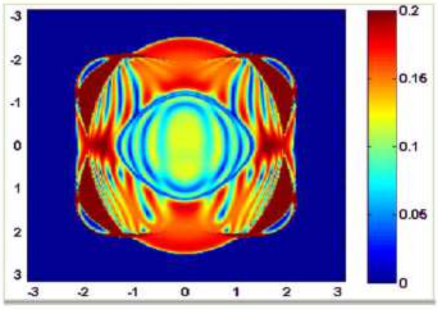
Sources identification



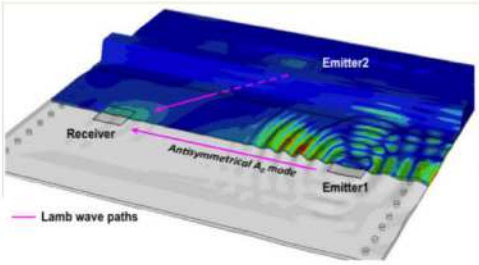
Sound and vibration perception

Monitoring – Diagnosis - NDT

Monitoring – Diagnosis - NDT



- Materials and structures characterization
- Condition monitoring from vibration or rotational speed measurements
- Flaws detection, sizing and identification,in structures (ultrasound, SHM, X-rays)



Equipments for X-Rays

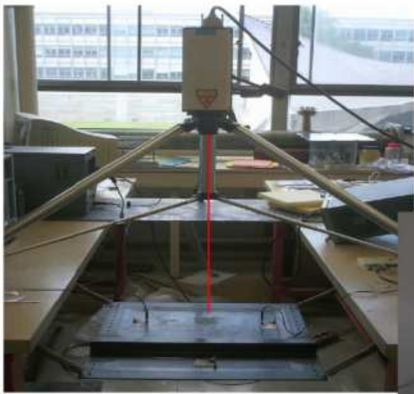
Xrays Tomography

Multimodal Xrays bench (diffraction, scattering, fluorescence)

Experimental equipments : for ultrasonics

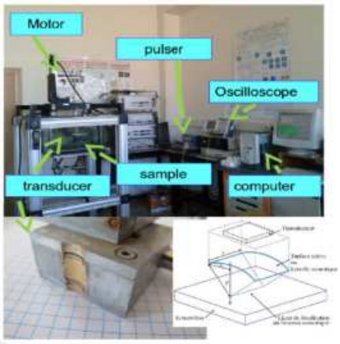
Anisotropic materials
ultrasonic characterization bench

Laser probe 2.5 MHz bandwidth



PowerBoxH for EMAT

Prisma phased array/UT device



Imaging and
Acoustic microscopy

Major on-going projects for Monitoring – Diagnosis – NDT topic

- 2016-2019 : **MUSCAD** web site
  Méthodes **U**ltra**S**onores pour la **C**aractérisation de matériaux de composants nucléaires pour l'**A**mélioration du **D**iagnostic
  Ultrasound methods for the characterization of nuclear component materials for diagnostic improvement

- 2017-2020 : **PYRAMID** web site
  配管減肉のモニタリングと予測に基づく配管システムのリスク管理
  Piping s**Y**stem, **R**isk management based on w**A**ll thinning **Mo**n**I**toring and pre**D**iction
  ANR/JST project

- 2017- 2021 : **SCCoDRa** web site
  Suivi et **C**ontrôle de la **Co**rrosion des composants métalliques pour le stockage des **D**échets **Ra**dioactifs
  Monitoring and Corrosion Control of Metal Components for Radioactive Waste Storage

- 2016-2019 : **CARAPACE** web site
  Coldspr**A**y pour **R**evêtements polymères h**A**utes **P**erform**A**n**CE**s
  Coldspray for High Performances Polymer Coatings

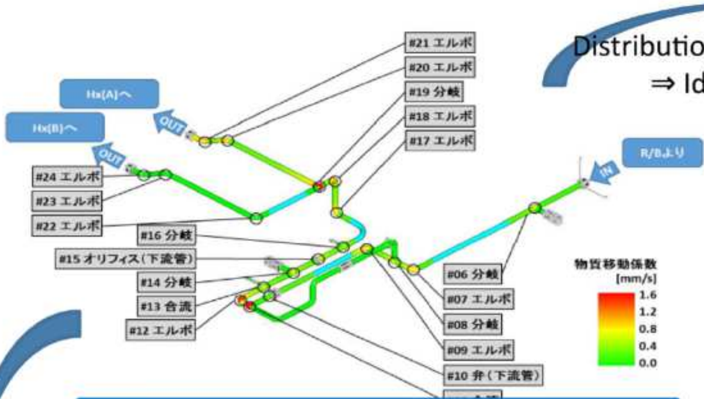
PYRAMID

PYRAMID
Japan & France collaboration research

“Piping sYstem, Risk management based on wAll thinning MonItoring and prediction”

Coordinators of PYRAMID Project Toshiyuki TAKAGI
Philippe GUY

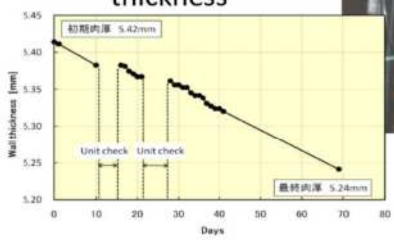
Risk management system for pipe wall thinning due to slurry flow



Distribution of mass-transfer coefficient
⇒ Identify locations of monitoring

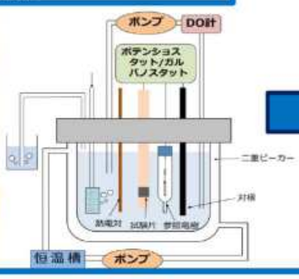
Remote monitoring of wall thickness. <TU, INSA>

Accurate remote monitoring of wall thickness



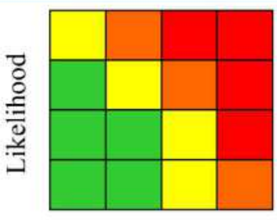
Evaluation of mass-transfer coefficient by numerical & experimental methods. <CRIEPI, Tohoku>

Predicted mass-transfer coefficient



Electrochemical evaluation of corrosion under slurry flow.
Mechanistic understanding of wall wastage phenomena.
<TU, INSA>

Risk management system. <GU, CEA>



Realistic modeling of austenitic welds ultrasonic inspection

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The presented research has been realized by all these people

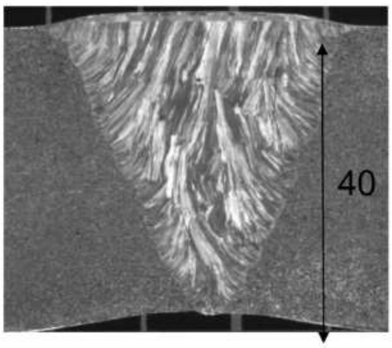
MUSCAD		MOSAICS	
Leymarie Nicolas	CEA LIST	Chassignole Bertrand	EDF R&D
Darmon Michel		Rupin Fabienne	
Chatillon Sylvain		Espinasse Gilles	
Mascaro Benoît	INSA Lyon - LVA	Fouquet Thierry	
Blachier Patrick		Rose Christian	
Chatard Julien		Lathuilliere Bruno	
Gueudré Cécile	LMA	Carpreau Jean-Michel	
Corneloup Gilles		Recolin Patrick	DCNS
Mailhé Jean		Mahaut Steve	CEA LIST
Ploix Marie-Aude		Leymarie Nicolas	
Schumm Andreas	EDF R&D	Baronian Vahan	
Lhuillier Pierre-Emile		Corneloup Gilles	LMA
Ferré Antoine		Moysan Joseph	
		Gueudré Cécile	
		Monnier Thomas	INSA Lyon LVA
		Alaoui-Ismaili Naima	
		Foucher Fabrice	EXTENDE

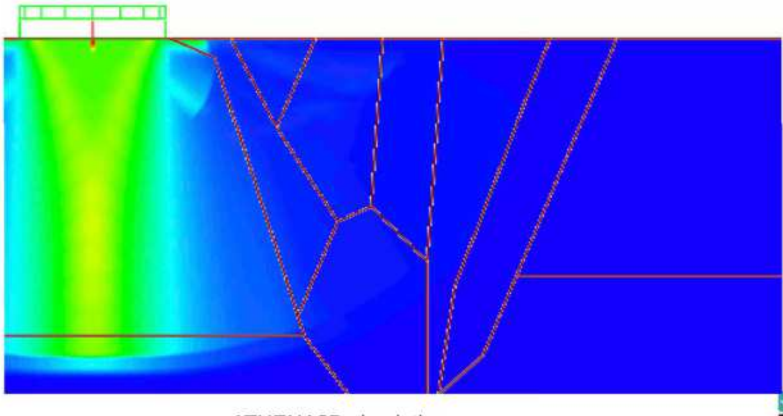
With the support of

Context

- **Pipings of primary circuit of EDF PWR plants and Naval Group structures are subject to thermal and mechanical stresses:**
  - In-service flaws
- **Regulatory requirements:**
  - **In-depth** inspection of components ⇒ UT techniques: flaw detection and sizing
  - Qualification of UT process
- **But UT inspection of austenitic welds is limited by:**
  - Anisotropic, heterogeneous and coarse grain structures highly disturbing UT propagation:

Beam deviation, division and attenuation





ATHENA2D simulation

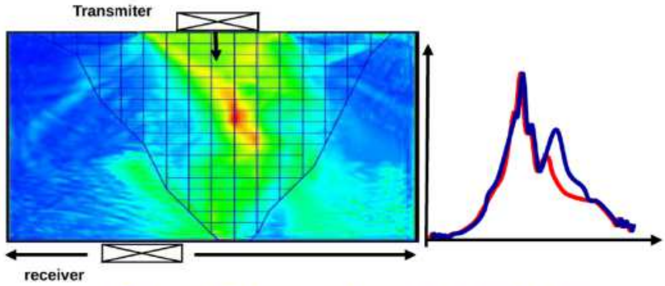
Ultrasonic NDT

The interaction of ultrasonic waves with this welds is very complicated

A simulation code is needed to get a physical understanding of ultrasound propagation in austenitic steel

diagnosis help

Tool for the inspection process design



Simulation of propagation: ATHENA code (EDF)

Input data :

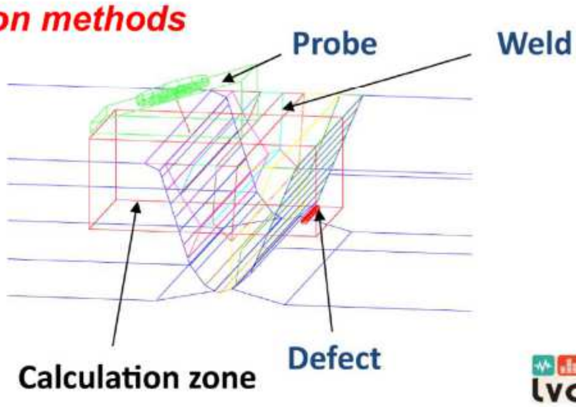
- **Sitffness tensor**
- **Global attenuation of the beam**
- **Complex stiffness tensor**

MOSAICS followed by MUSCAD projects

(supported by French National Research Agency)

- **UT simulation: process development and qualification:**
  - Parametrical studies for performance demonstration
- **BUT current code had limitations:**
  - Semi-analytical models (CIVA) : not adapted to highly heterogeneous structures (current ray theory not valid)
  - Finite element code (ATHENA) : only in 2D version

- ***Development and validation of numerical tools used for ultrasonic testing of austenitic welds in 3D configurations***
- ***Improvement of the ultrasonic characterization methods***
- ***Cross validation : simulation/experiments***



*MOSAICS only

process development

Technical specifications
(Industrial applications and mock-ups)

CHARACTERIZATION and MATERIAL MODELLING

FE ATHENA (EDF)
CIVA semi-analytical models (CEA)
Hybrid code CIVA/ATHENA (CEA/EDF)

EXPERIMENTAL TESTS

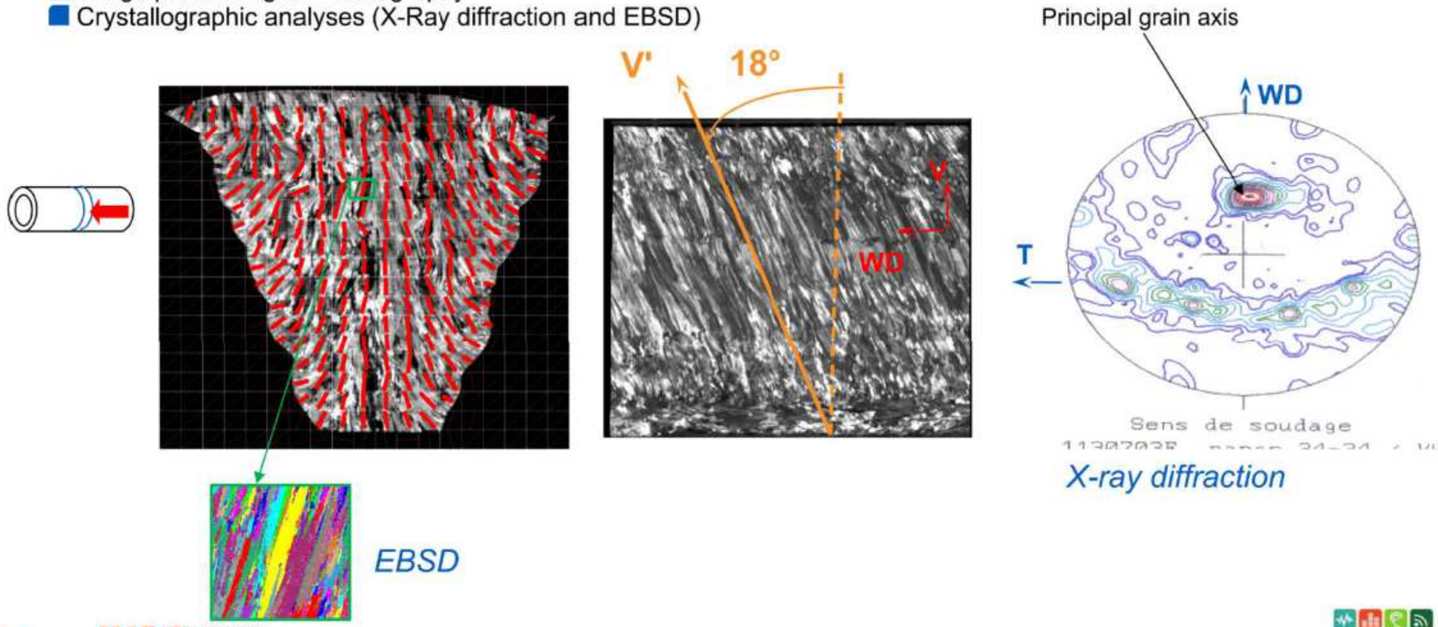
Validation

UT NDE Simulation and code exploitation

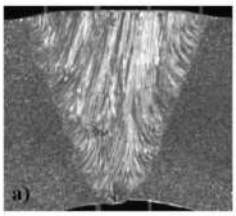
Dissemination (Integration in CIVA)

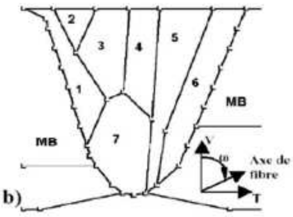
Metallurgical weld characterization

- Up-vertical position: 3D modelling
- Weld description (grain orientation mapping) compatible with modelling codes:
  - Image processing on macrography
  - Crystallographic analyses (X-Ray diffraction and EBSD)



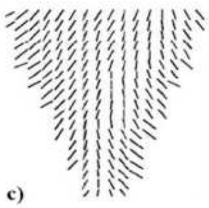
Grains orientations determination

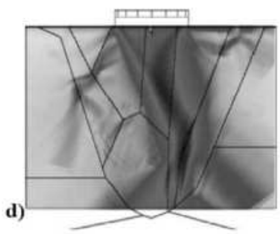




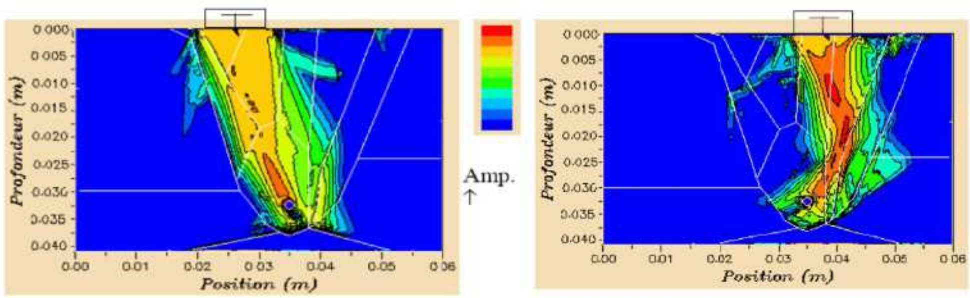
Domaines orthotropes	ω (°)
1	35
2	11
3	18
4	8
5	0
6	-31
7	14
Domaines isotropes	
MB	/

Sub-domains with variable orientation

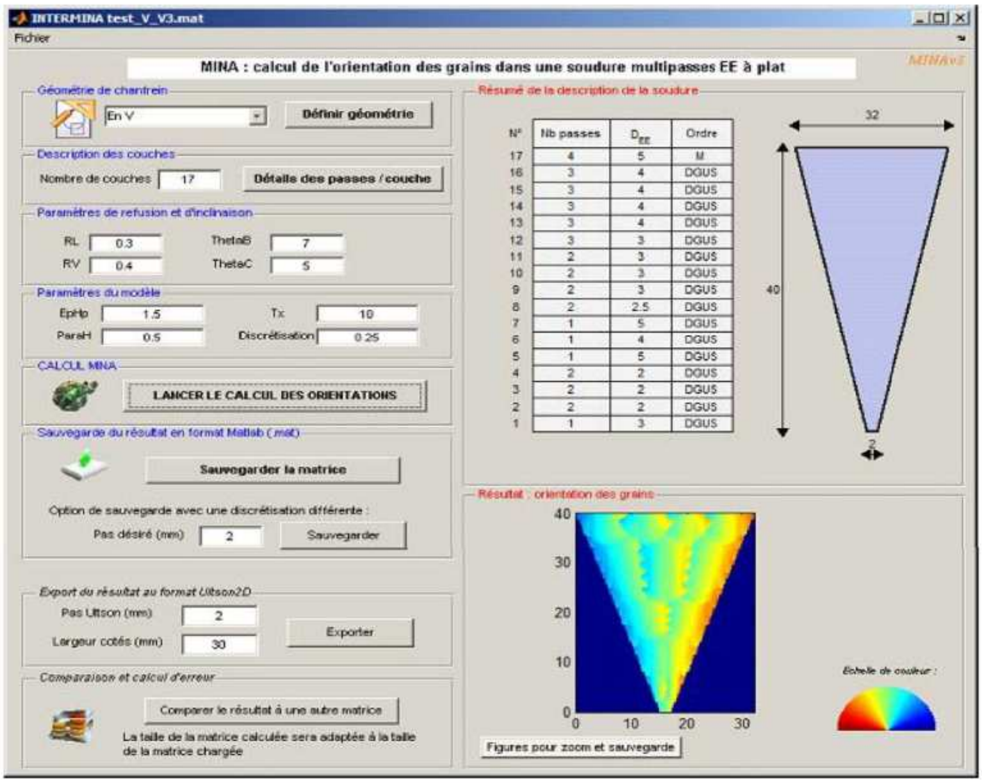




Simulation code : *ATHENA developed* by EDF and INRIA

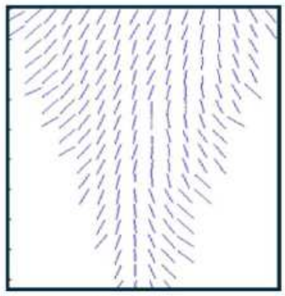


MINA Model (inputs from the welding report)



2D configurations SMAW

Adaptation to GTAW in progress



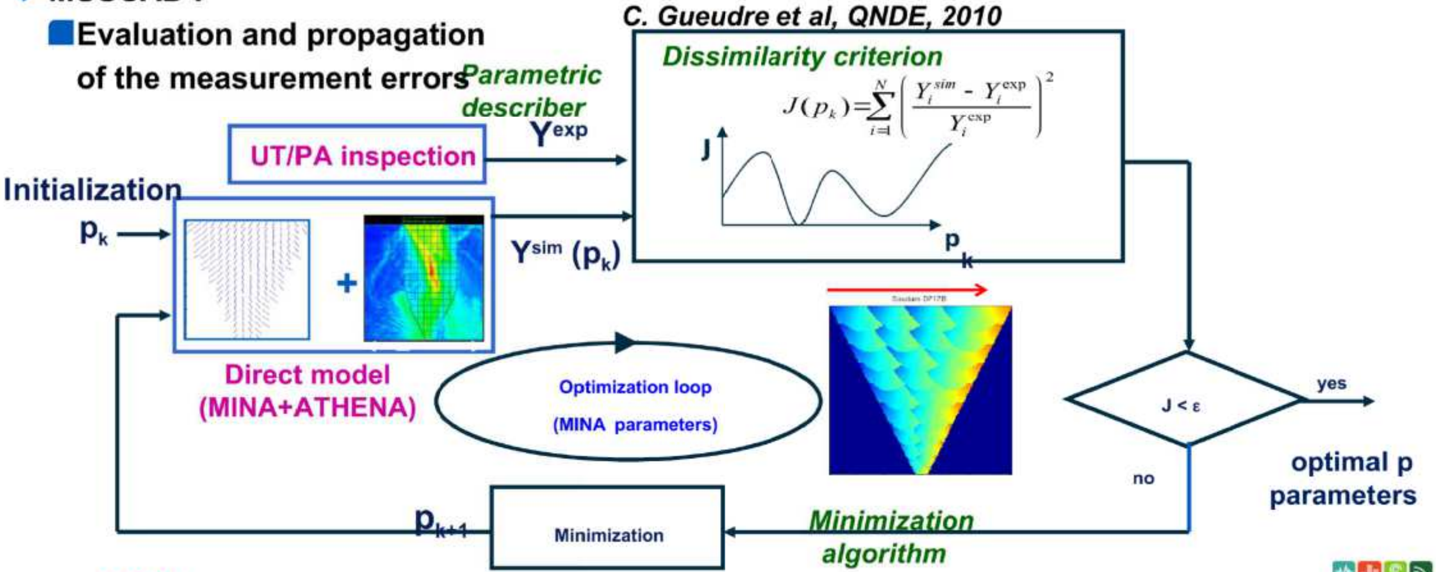
Meshing 2x2 mm^2

J. Moysan et al, IJVPV, 2003
A. Apfel et al, Ultrasonics, 2005

Inversion process for weld characterization

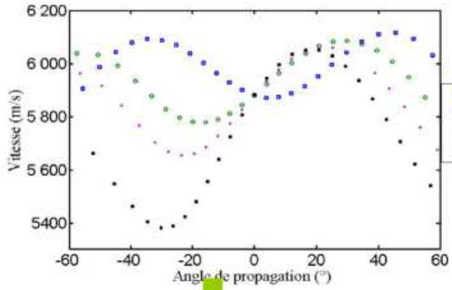
- **Objective: weld characterization of unknown structure (number and order of passes, velocity...)**
- **Previous work: process validation on numerical results in transmission mode**
- **MOSAICS :**
  - Experimental data in tandem mode
  - Inversion on passes order
- **MUSCAD :**
  - **Evaluation and propagation of the measurement errors**

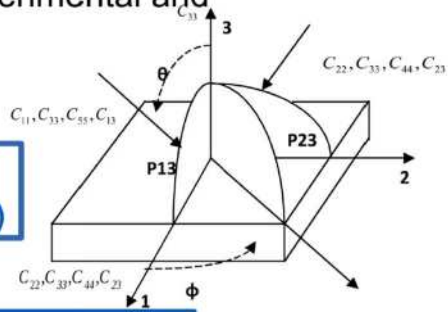
C. Gueudre et al, QNDE, 2010

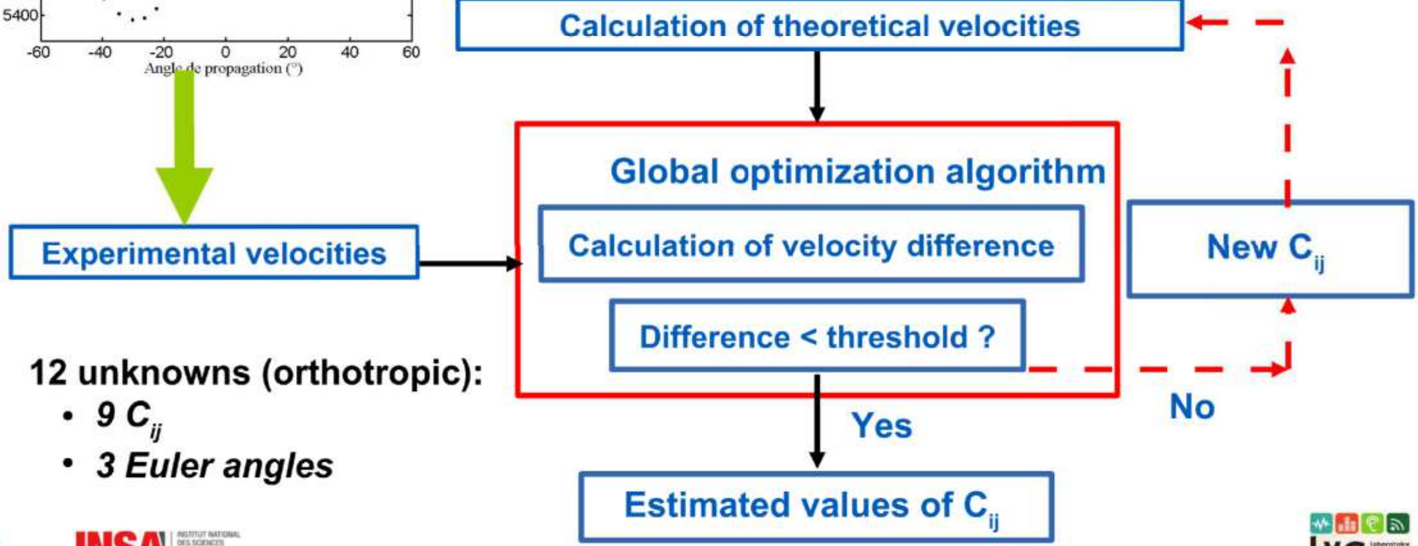


Elastic properties measurement: strategy

- Inverse problem resolution based on comparison between experimental and theoretical velocities for a large set of transmitted waveforms







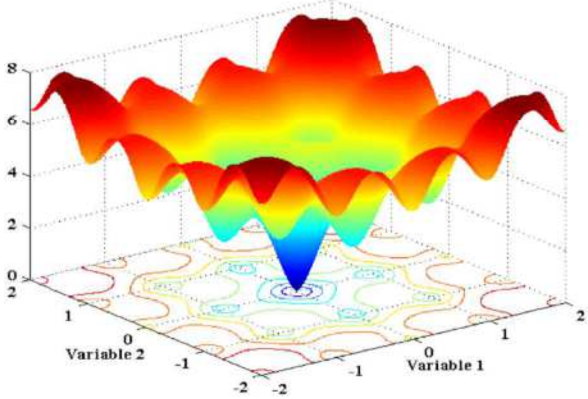
12 unknowns (orthotropic):

- ***9 C_{ij}***
- ***3 Euler angles***

Optimization Algorithms : choice

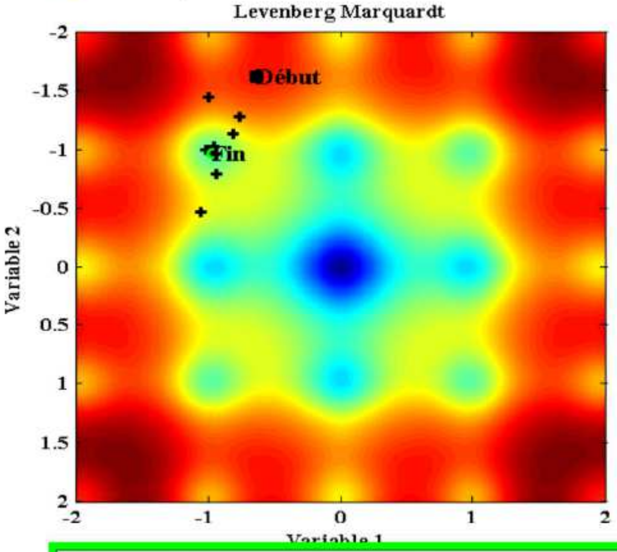
- Two kinds of methods.
  - ✓ **local**, steepest descent type,(conjugated gradients, Newton...), **Levenberg Marquardt (LM)**;
  - ✓ **global**, Simulated annealing **(SA)**, neural networks, genetic algorithms .

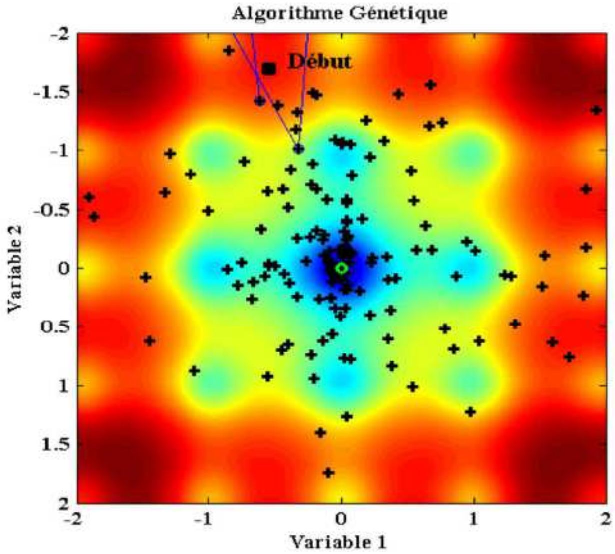
- Fonction de Ackley (test function)



Comparison of performances

- Ackley function





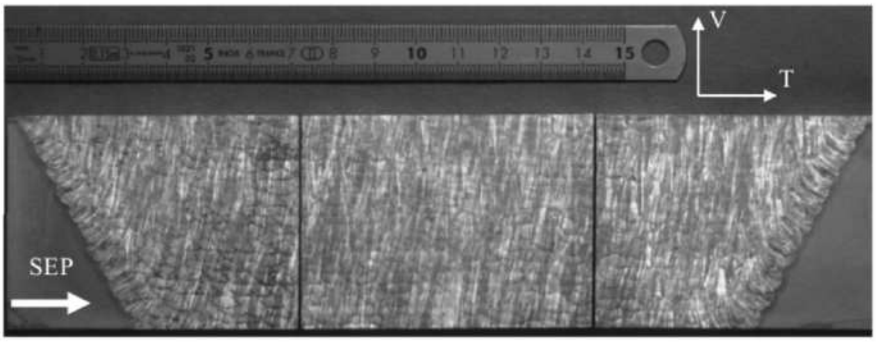
Calculation time almost independent of variables number

Calculation time grows with the variables number

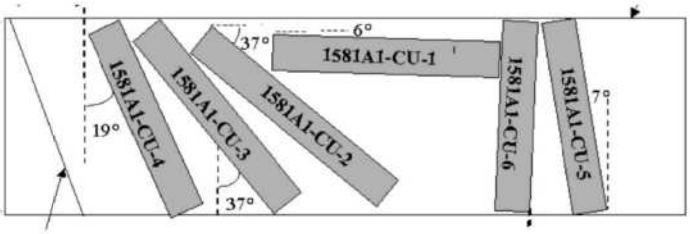
We finally opted for a hybrid algorithm : Simulated annealing + gradient based method

Ultrasonic characterization of weld properties: samples

Inconel 182



Vertical texture



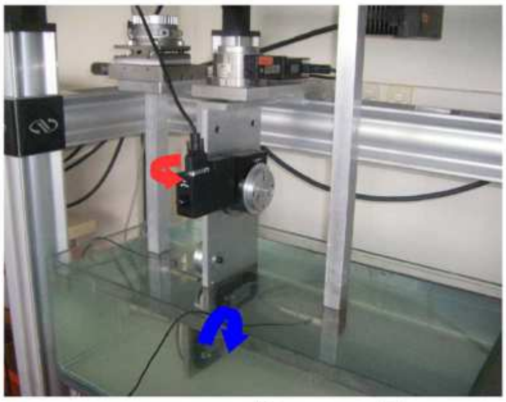
9 Cij + 3 angles d'Euler

Parameters in the 'crystal' coordinate system

Crystal orientation in the sample coordinate system

Ultrasonic characterization of weld properties

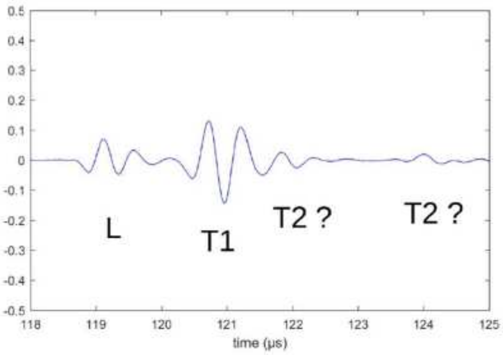
- **Original 6 automated DOF ultrasonic device in transmission mode:**
  - Phase velocity measurements in various planes and directions of propagation
    ⇒ elastic properties and Euler angles
  - Measurement of attenuation of shear and compression waves

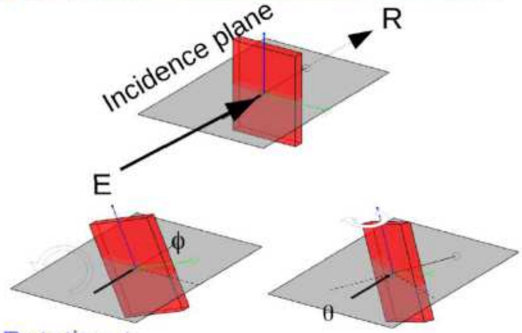


Velocity measurement from the received waveforms (L or T_1 or T_2)

$$\theta_1 = \arctan\left(\frac{e\sin\theta_0}{c_0\left(dt + e\left[\frac{1}{c_{1Lp}} + \frac{\cos\theta_0 - 1}{c_0}\right]\right)}\right)$$

$$c_1 = \frac{e\cos\theta_1}{dt + e\left[\frac{1}{c_{1Lp}} + \frac{\cos\theta_0 - 1}{c_0}\right]}$$

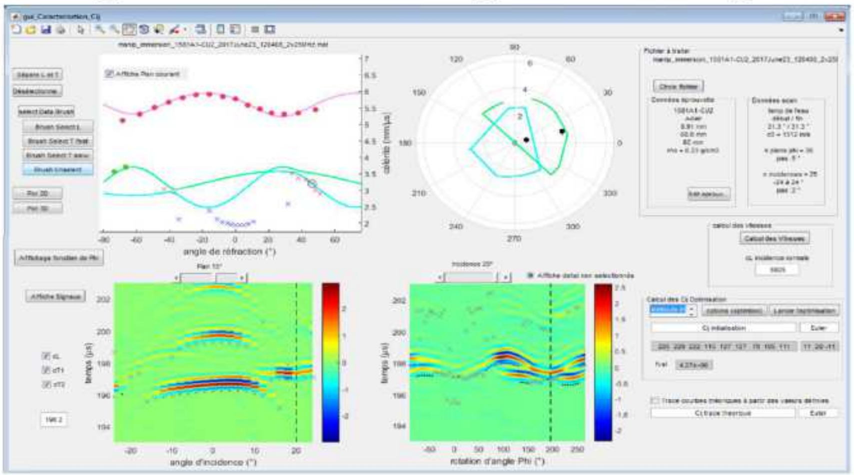




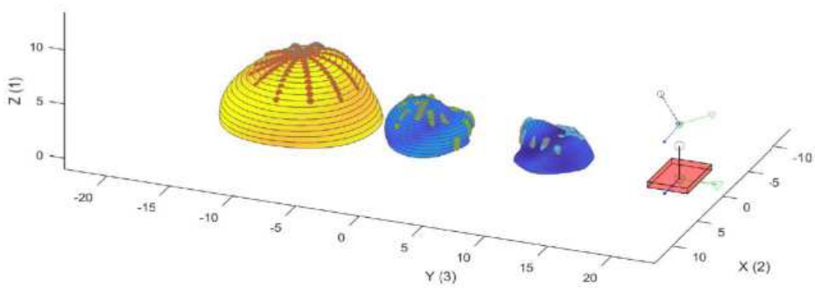
Rotation ϕ varies incidence plane

Rotation θ varies incidence angle

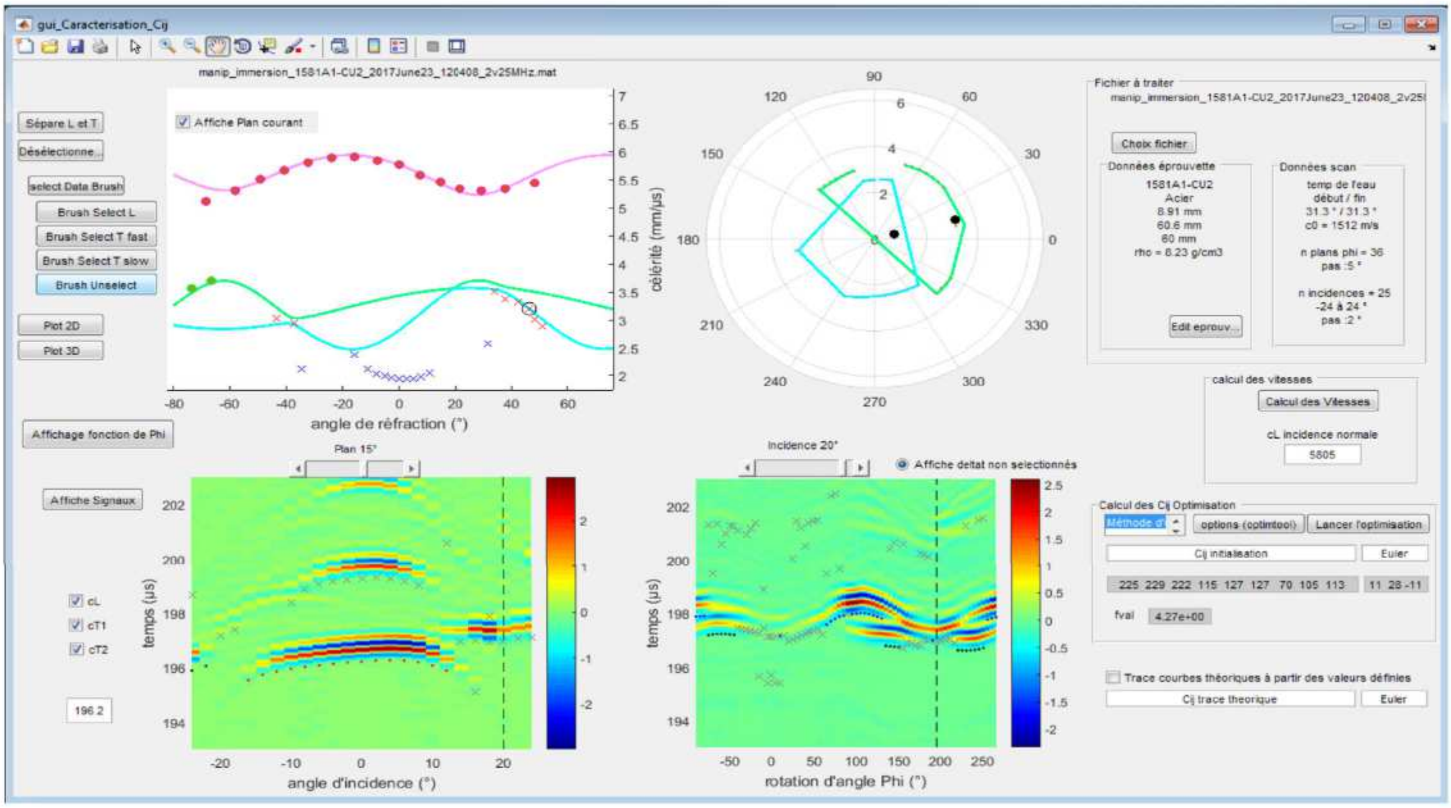
Signal conditioning and data processing



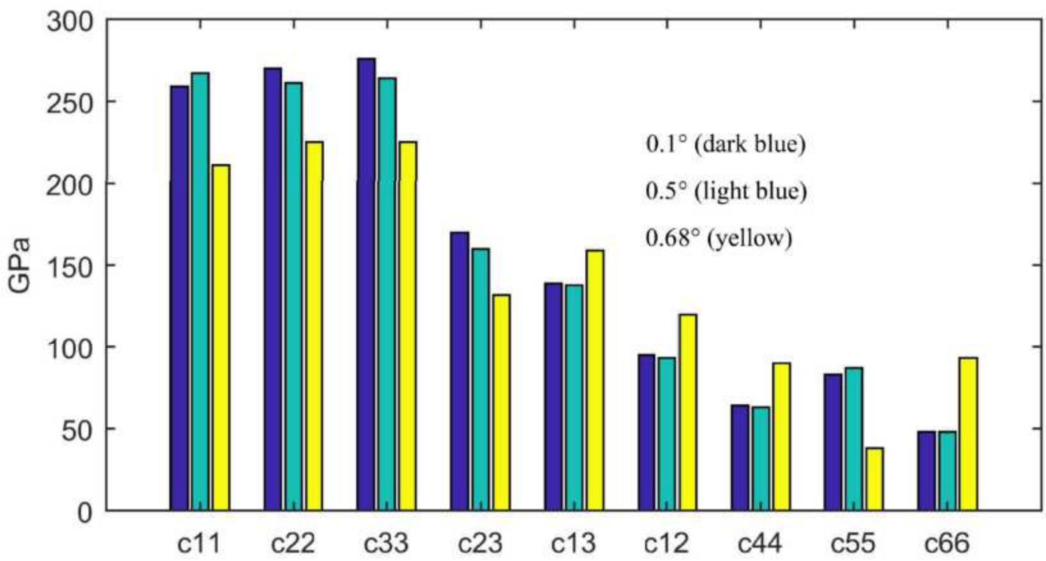
- 5 different display of data
- Mode labelisazion directly on the graphs L T_1 T_2
- Data display plane by plane or all
- Enhancement of the selected data
- 3D Plots 3D of the selected data
- Run the optimization with the selected data.
- Comparison of the of the experimental values and optimized ones



Signal conditioning and data processing



Influence of the incidence angle misalignement

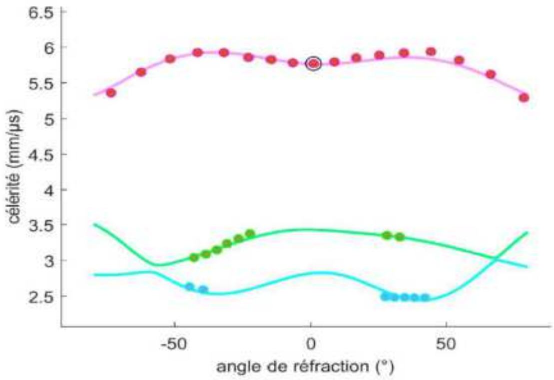


The optimization results are very sensitive to the exact value of the incidence angles

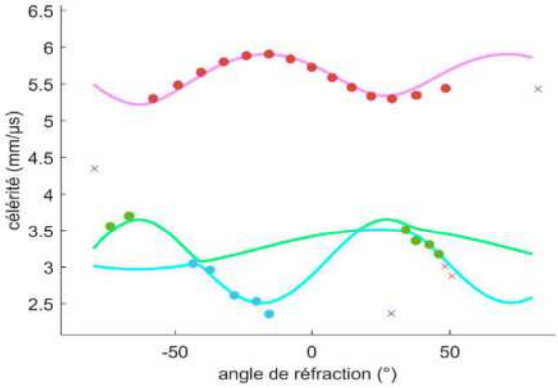
=> definition of a new experimental process
=> automatic alignement of the normal with the ultrasonic axes.
=> automatic correction of the screwness of the sample during rotation

Influence of signals selection

Selection of shear waves



A) Rapid and slow shear waves are separated

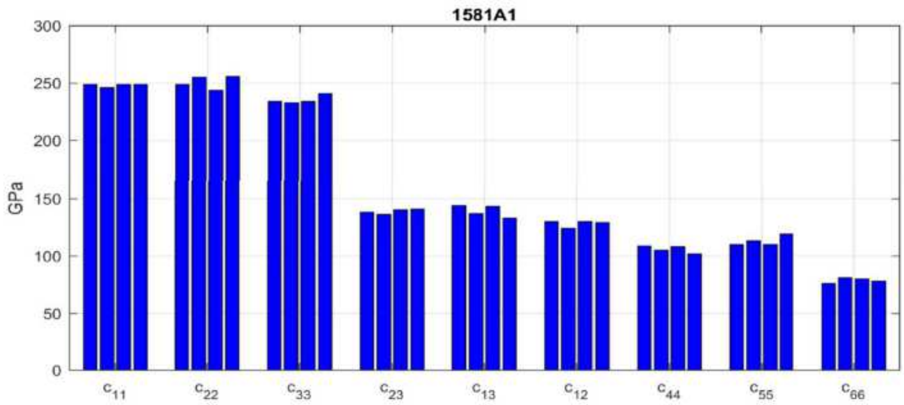


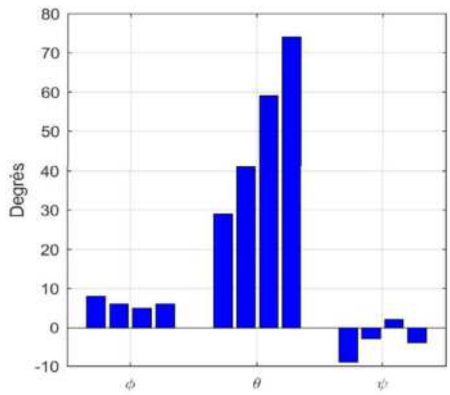
B) Rapid and slow shear waves on a continuous branch

The optimization results are very sensitive to the shear waves identification

=> remove all the experimental data can't be clearly identified

Optimized stiffness tensor and crystal orientation : Inconel 182

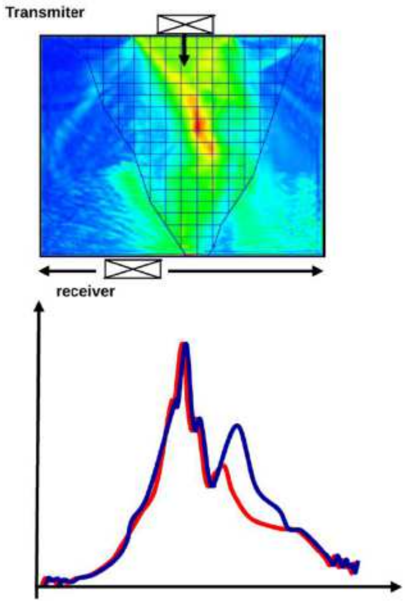




	c_{11}	c_{22}	c_{33}	c_{23}	c_{13}	c_{12}	c_{44}	c_{55}	c_{66}	
C_{ij} average	248	251	236	139	139	128	106	113	79	(GPa)
Std. dev.	1,5	5,6	3,7	2,2	5,2	2,9	3,2	4,2	2,2	(GPa)

	θ optimized	θ cut
sample 1	29°	37°
sample 2	41°	53°
sample 3	59°	71°
sample 4	74°	83°

Simulation results (ATHENA2D by EDF R&D)



echo dynamic
normalized amplitude

The position of the peaks are OK

BUT

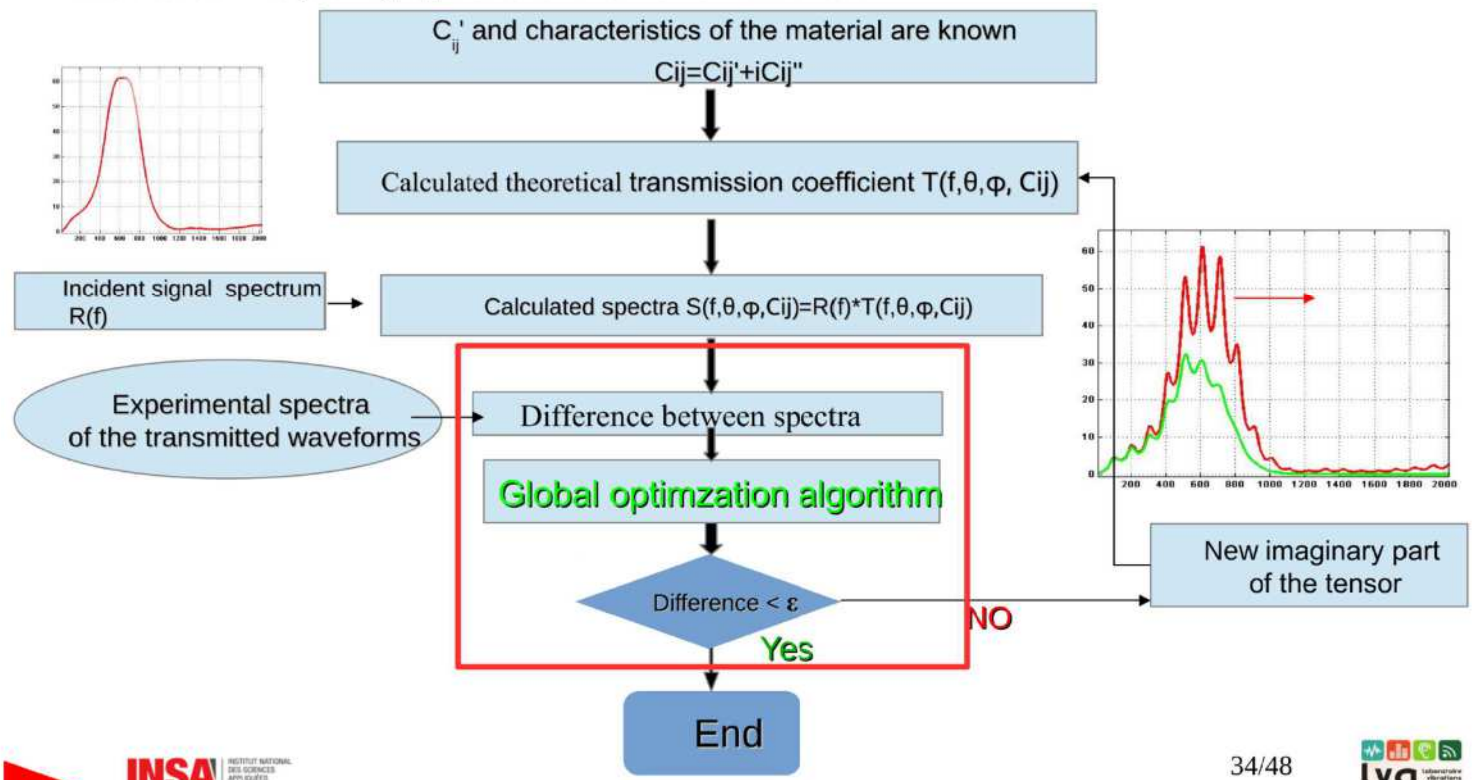
Their amplitudes are NOT

Regarding the inputs :

- **Elastic modulii and orientations are not enough**
- **Ultrasonic Attenuation is also needed**

Attenuation measurement strategy

- Inverse problem resolution based on comparison between experimental and theoretical frequency spectra of the transmitted beam



Validation of the optimization algorithm on simulated data

Carbon epoxy composite **orthotropic** plate

	C_{11}	C_{22}	C_{33}	C_{12}	C_{13}	C_{23}	C_{44}	C_{55}	C_{66}
C'(GPa)	12,1	12,3	132	5,5	5,9	6,9	6,15	98	77
η (GPa μs)	0,043	0,037	0,400	0,021	0,016	0,001	0,02	0,015	0,009

Experimental condition :

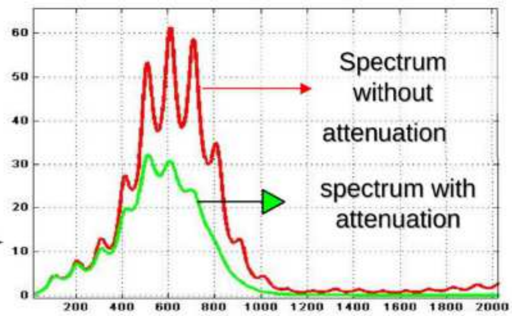
Density =1500 (Kg/m³)

Thickness = 3,434 mm

- Frequency = 2,242 MHz
- $C_{ij}=C_{ij}'+* \eta*2*pi*f$

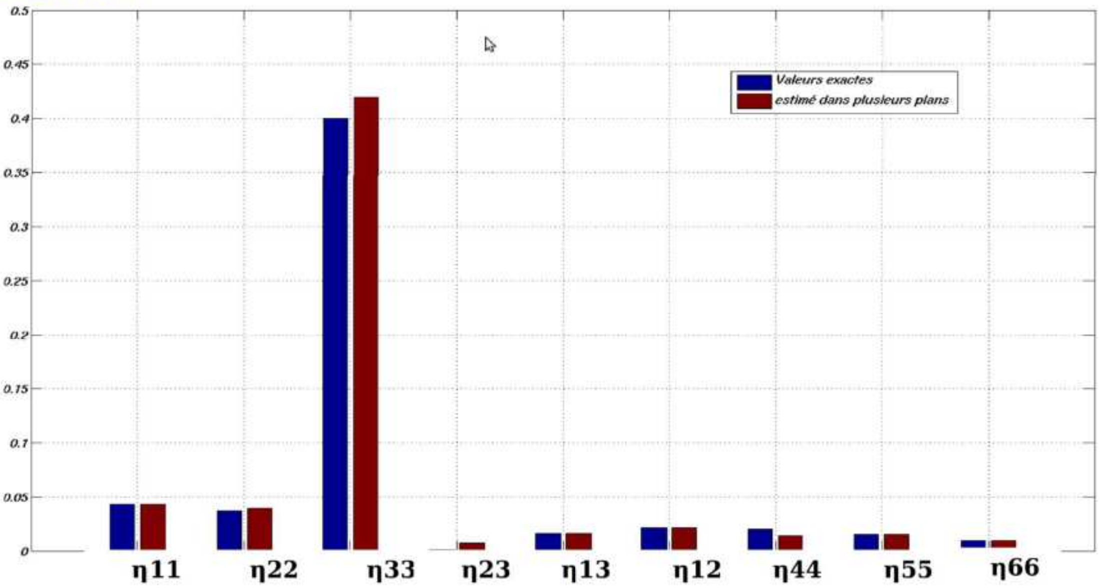
We simulate transmitted spectra in many incidence plane and angles

Plane : 30°, incidence 5°



Data from : Marc Deschamps and Bernard Hosten « The effects of viscoelasticity on the reflexion and transmission of ultrasonic waves by an orthotropic plate», Journal of the Acoustical Society of America, 91(4, April 1992)

Simulation results using data from many planes and angles of incidence



The parameters are obtained with a maximum error of 1% of the exact values

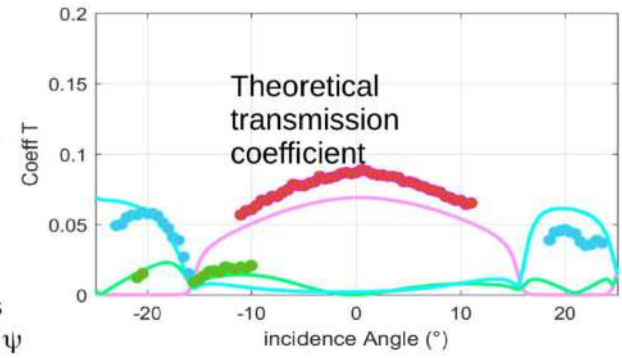
Complex C_{ij} estimation: Results @ 2.25 MHz

Imaginary parts

$$C_{ij} = C' + i\,C''$$

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} + i \begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix}$$

+ Rotations φ, θ, ψ



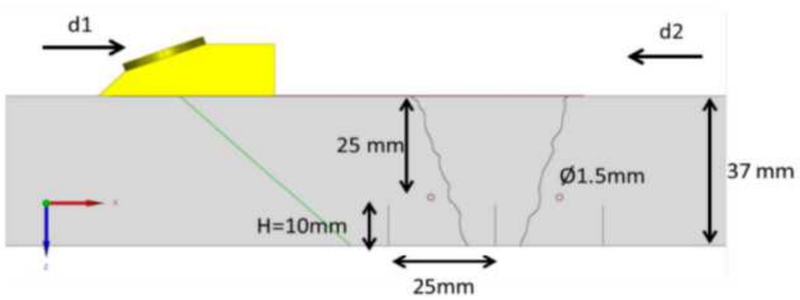
Average values for the 4 samples

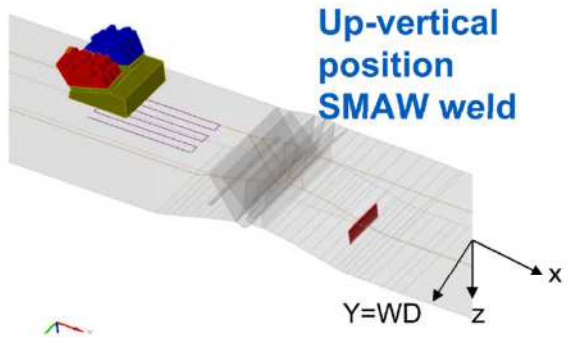
	C_{11}	C_{22}	C_{33}	C_{23}	C_{13}	C_{12}	C_{44}	C_{55}	C_{66}	
C'	254	240	232	137	144	123	107	106	78	(GPa)
C"	7,3	11,4	14,8	4,2	7,7	1,4	1,8	0,7	0,1	(GPa)

Results to be validated

UT experiment

- Calibrated flaws (Side drilled holes, notches) machined in welded mock-ups

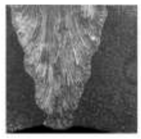


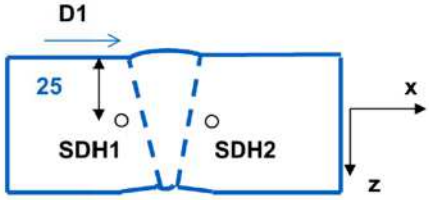


- Inspections in automatic mode:
  - Standard single-element probes and TRL phased arrays
  - Longitudinal waves
  - Two directions of inspection
  - Influential parameters:
    - ***Beam angle***
    - ***Beam focusing***
    - ***Frequency***

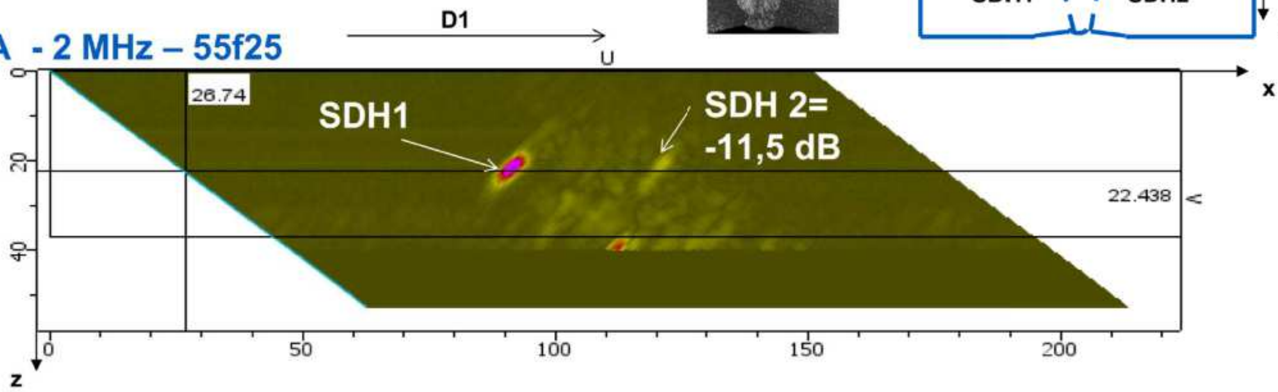
Results: SDH

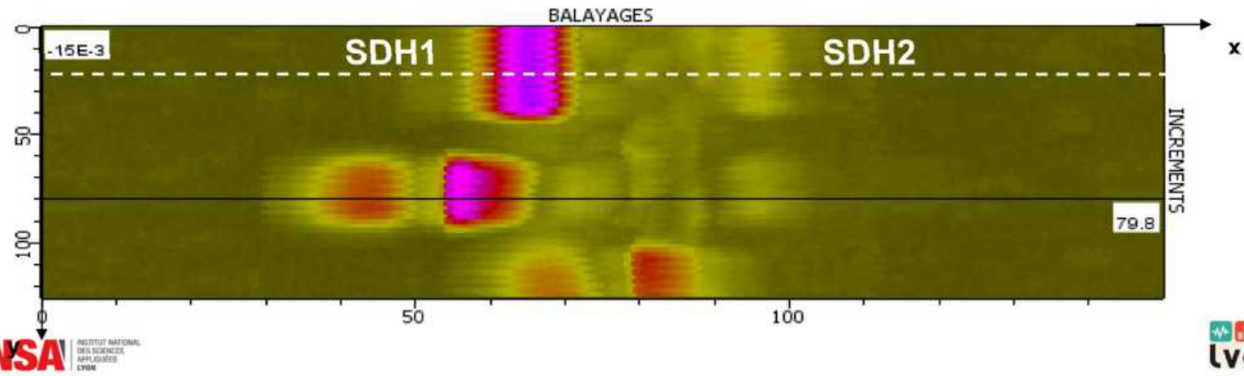
High attenuation due to the weld structure





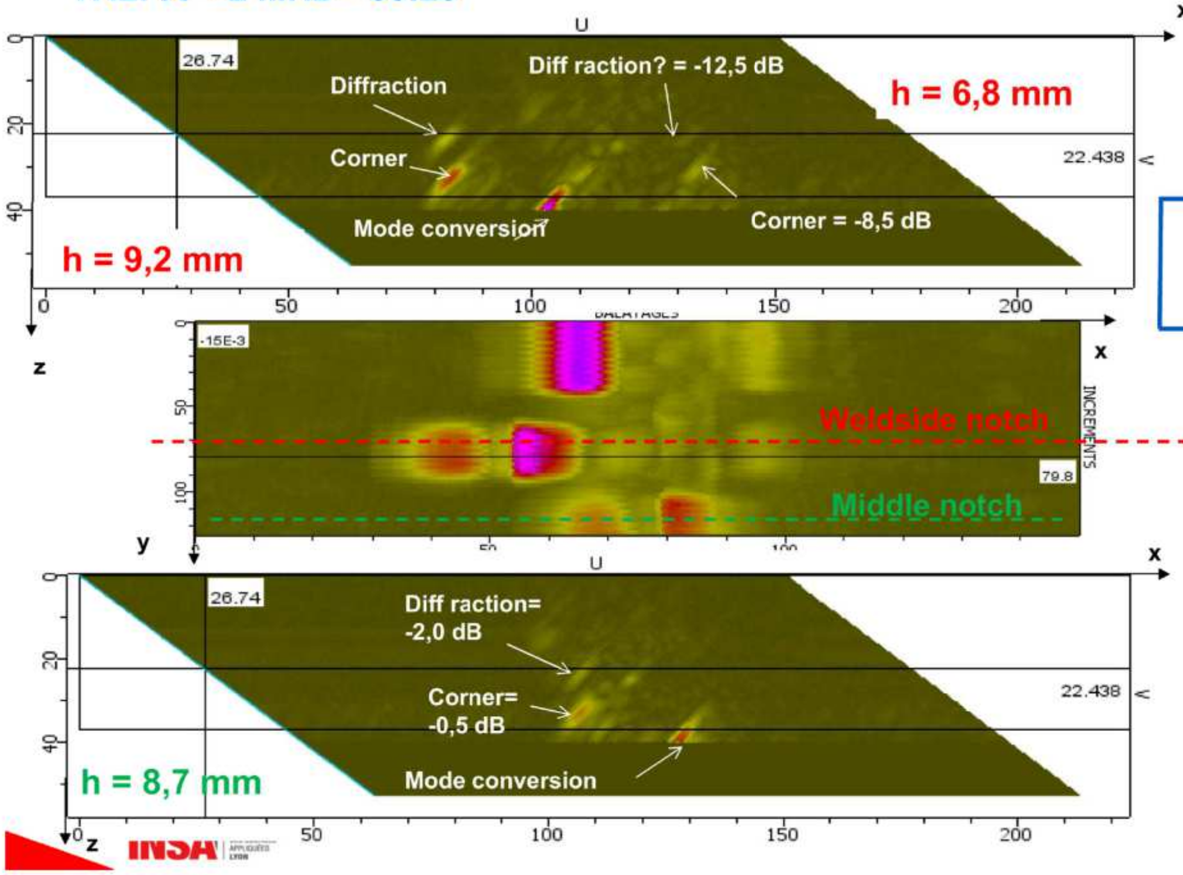
TRLPA - 2 MHz – 55f25

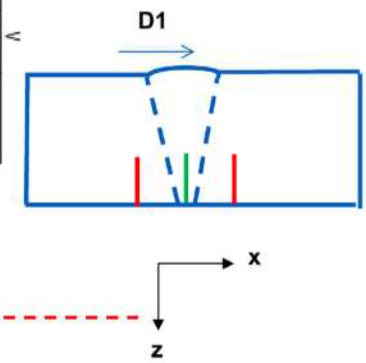




Results: notches

TRLPA - 2 MHz – 55f25

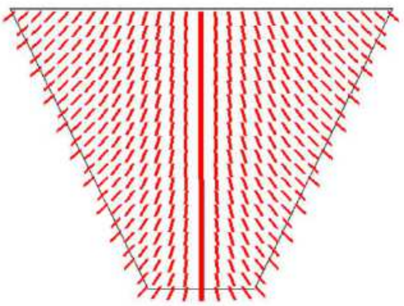




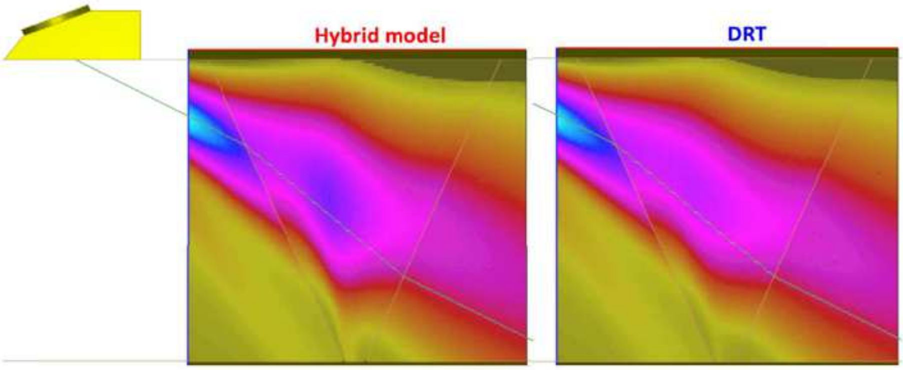
Weldside notch:
- high attenuation
- sizing error
- spurious echo

UT modelling: CIVA

- **Current model : limitation when $\lambda \approx$ anisotropic domain size**
- **Solution: smoothly inhomogeneous weld description**
  - From macrography, analytical model or MINA model
- **Dynamic (paraxial) Ray Tracing model (DRT) :**
  - Implementation of paraxial quantities in semi-analytical models (pencil method)



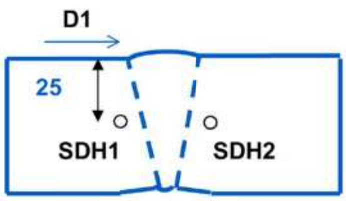
Smoothly inhomogeneous weld description



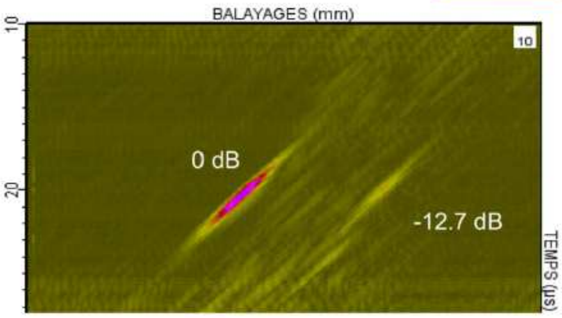
N. Leymarie et al, BINDT, 2013

Austenitic welds: modelling results

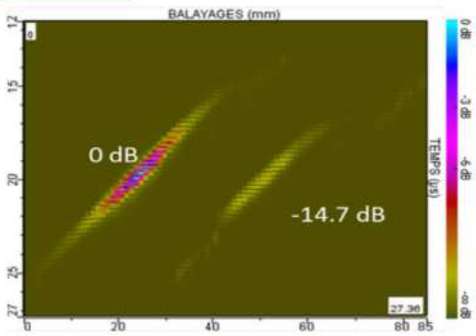
- **CIVA DRT Results**
  - **2D attenuation model**



Up-vertical weld



Experiment

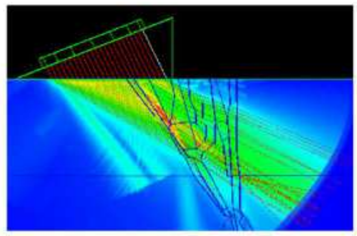


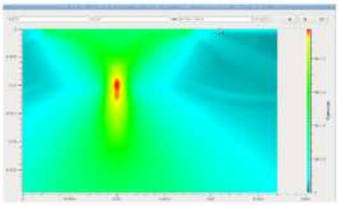
CIVA DRT (2D attenuation model)

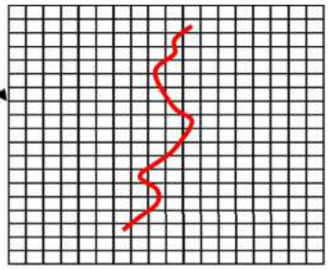
- Good estimation of weld attenuation for each direction and each flaw (SDH, notch): discrepancy <3 dB
- Empirical adjustement of parameters for weld structure smoothing: influence to be analyzed

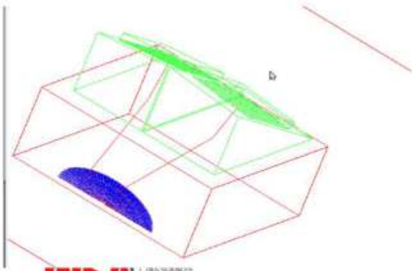
UT Modelling: FE code ATHENA

- Quasi-explicit scheme and regular mesh **: good numerical performances**
- Beam propagation in anisotropic and heterogeneous media
- Beam to flaw interaction (fictitious domain method)
- 2D version
  - Various probe types (TOFD, phased arrays,…)
  - Coupled with CIVAv11 (2012)
  - Attenuation model
  - GUI
- 3D needs :
  - **3D probe (TRL PA)**
  - **3D flaw (elliptical)**
  - **3D anisotropy**

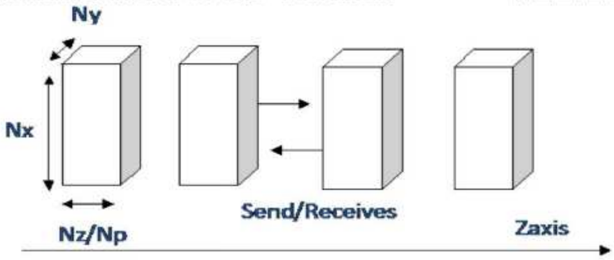






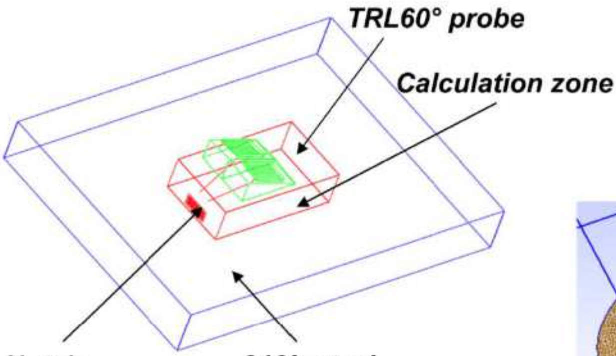


Parallelization of 3D version

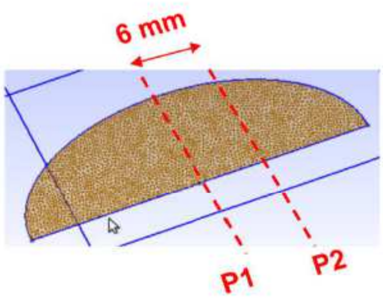


ATHENA 3D: results in isotropic and homogeneous medium

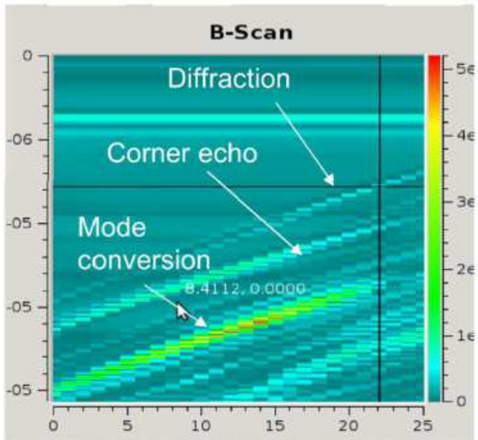
C. Rose et al, 10th AFPAC



10*20 mm
depth = 30 mm



Flaw meshing (GMSH)

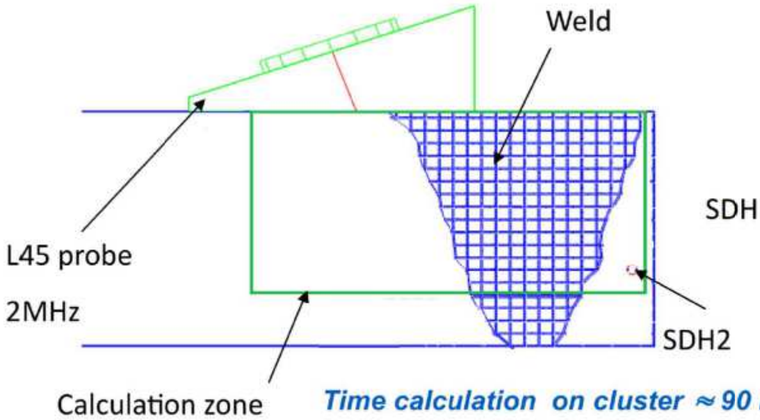


Reference = SDH 1 mm-radius

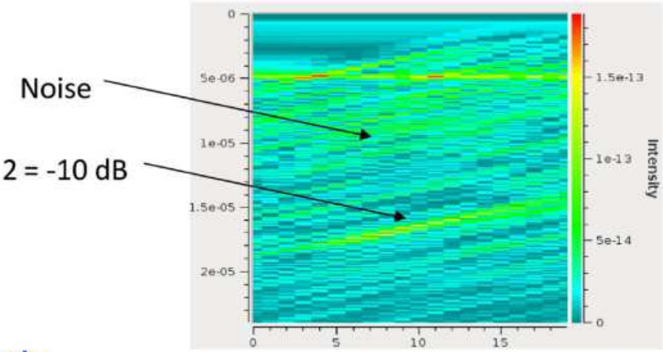
	Diffraction (dB)		
	Rectangular	**½ elliptical – P1**	**½ elliptical – P2**
ATHENA 3D	-9.0	-12.0	-17.5
Experiment	-8.0	-12.0	-16.5

ATHENA3D: austenitic welds

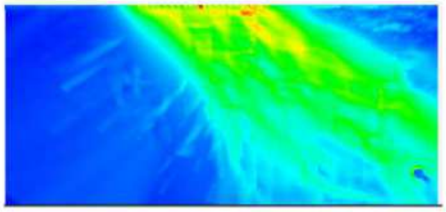
- **Example : vertical-up SMAW**



Time calculation on cluster ≈ 90 min.

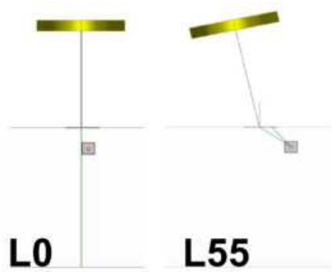


- Prediction of beam division and distortion
- Prediction of scattering at each domain interface but underestimation of attenuation and overestimation of noise:
  - New calculations with 3D attenuation model using INSA characterization work to be performed
  - Influence of weld description and uncertainties on input data to be analyzed: ***sensitivity analysis***



Hybrid CIVA/ATHENA : 3D version

- Previous work (MOHYCAN project) : 2D version (CIVA11)
- MOSAICS :
  - **3D version with optimized model (reduction of FE box)**
  - **Calculation on HPC clusters**
  - **Validation on isotropic medium (ongoing)**

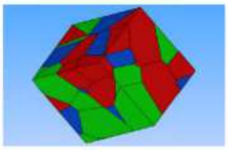


$Ø_{SDH}$ = 1.5mm
Depth = 10 and 20mm
Focused immersion probe (2MHz)
EF box: 5.6×12×5.6mm³

	ΔA - L0	ΔA - L55
ATHENA 3D	+15.0 dB	-4.0 dB
CIVA 3D	+15.5 dB	-2.5 dB
HYBRID 3D	+14.5 dB	-3.0 dB

Conclusion and prospects

- Metallurgical characterization realized on various welded mock-ups
- Inversion process for unknown structure to be developed and validated
- Experimental database for code validation
- Simulation:
  - **Specific developments on CIVA and ATHENA codes to take into account complex 3D configurations (material, probe, geometry, flaw)**
  - **First validation for « 2.5 » extruded weld : to be continued**
  - **Code adaptation for real 3D anisotropic and heterogeneous structures**



  - **Implementation of a 3D attenuation model based on ultrasonic characterization**

$$\frac{\partial \sigma}{\partial t} + D\sigma = C\varepsilon(v) \longrightarrow \overline{C} = i\omega(i\omega + D)^{-1}C$$

  - **3D Hybrid model : validation on isotropic media and adaptation to weld configuration**

ご静聴ありがとうございました

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