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Recent modelling advances in NDT to improve safety and sustainability for the next generation of nuclear reactor

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Joseph Moysan, Gilles Corneloup, Jean-François Chaix,
Cécile Gueudré, Dimitri Komatitsch, Ivan Lillamand, Jean Mailhé,
Serge Mensah, Marie-Aude Ploix, Cédric Payan, Sandrine Rakotonarivo

**François Baqué, Jessie Bonnin, Matthieu Cavarro, Gilles Gobillot, Jean-Philippe
Jeannot, Christian Lhuillier, Kevin Paumel**

Emma Lubeigt, Nicolas Massacret,
Lilian D'Hondt, Pierre Kauffmann, Masaru Nagaso, Quentin Marsac

AFPAC 2019 - Anglo-French Physical Acoustic Conference
 Villa Clythia -Fréjus, France - 16-18 January, 2019

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Overview of the Laboratory

LMA = Research Unit of CNRS (UMR 7031)
bound by convention, with **Aix-Marseille University** (AMU)
and the **Ecole Centrale de Marseille** (ECM).

↳ About **140 people**:

- **90 permanent staff** (researchers, lecturers, engineers, assistant engineers and technicians),
- About **40 doctoral students**.

↳ Divided in **3 teams**:

- Materials and Structures
- Sounds
- **Waves and Imaging** ➔

Former **LCND**
(1987, Aix-en-Provence,
integrated **LMA** in 2012

Medical US

Underwater acoustics

Seismic

NDT&E of adhesion

NDT&E in civil engineering

NDT&E of metals and welds

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Overview of the Instrumentation Laboratory

SENSORS, MEASUREMENT DEVICES AND METHODS
Instrumentation, Systems and Methods Laboratory
 CEA CARARACHE DEN/DTN/STCP/LISM, Saint Paul Lez Durance, France




**Technological realisations of facilities and test benches
for methods and sensors qualification**


22 people:

- 15 permanent staff (engineers and technicians)
- 4 doctoral students
- 6 other staff (assistant and internship engineers)

Main objectives:

- Development and qualification for inspection and monitoring : instrumentation for nuclear reactors (PWRs, SFRs...) and else
- Optimization and Innovation for ultrasonic telemetry, acoustic detection, leak detection, level gauges, velocity measurement...



Recent modelling advances in NDT to improve safety and sustainability ...

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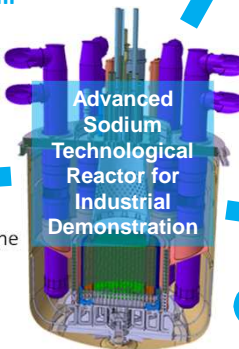
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LCND-CEA Cadarache: a long collaboration around Gen IV ASTRID project

**In Service Inspection and Repair
to insure the safety of SFR
(sodium cooled fast reactor)**

Non Destructive Testing

- 1 US inspection **from the outside** of the vessel using **Lamb waves**
- 3 **Topological imaging** for damage localization
- 4 **Description of welds** for US propagation modelling
- 5 **NDT-based recommendations** for future designs (with CEA, AREVA and EDF)



Advanced Sodium Technological Reactor for Industrial Demonstration


Non Destructive Evaluation

- 1 **Telemetry** of objects hidden behind structures (plates)
- 6 US **thermometry** at the outlet of the core
 - Modelling and experiments to previous ultrasonic setups in French SFR **VISUS** and **SONAR** (CIVA)

Characterization of liquid Na

- 2 Acoustical (Linear and Non linear) characterization of **bubbles**
- 6 US propagation at the **outlet of the core** (temperatures and flows)

Advances in NDT simulations to improve validity of performance evaluation



Recent modelling advances in NDT to improve safety and sustainability ...

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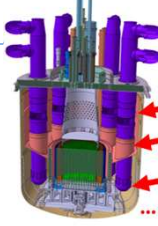
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1 Ultrasonic telemetry of objects behind screen(s)


Objectives: detect the **presence/absence** of objects, and evaluate their **position**

Various case studies: sodium return weir, tube, pump chamber...


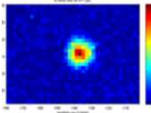
Hypothesis: walls (primary vessel, internal structures) = plane parallel plates



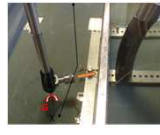
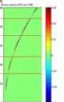
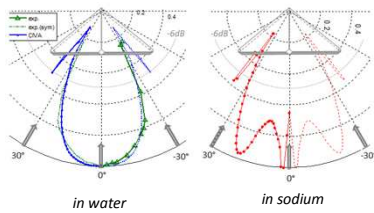
3rd plate



Cube-corner target





Curved tube behind 1 screen

- ✓ 2nd and 3rd plates: **detectable and measurable**
- ✓ 3rd and 4th plates provided with target: **detectable and measurable**
- ✓ Straight and curved cylinder behind vessel: **detectable and measurable**

in water *in sodium*

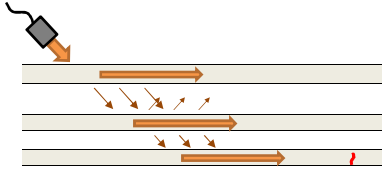
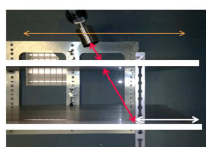
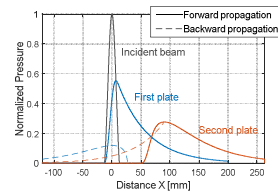
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1 Ultrasonic propagation from the outside of the primary vessel

- **Lamb waves for NDT of internal structures behind « screens »**


Principle: generation of leaky Lamb waves in the 1st plate, then re-emission generates Lamb waves in the 2nd plate, ... and reflexion if a defect exists

Hypothesis: walls (primary vessel, internal structures) = plane parallel plates

PhD : Pierre Kauffmann 2015-2018

- specific signal analysis in the frequency domain to make velocity and attenuation measurement as measurement configuration is non-trivial.
- extensive study of the emitted field of the first plate
- study of the behavior of Lamb waves in the second plate (experiments and simulations)

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2 Evaluating the gas proportion with acoustics (1/2)

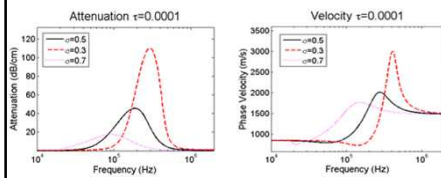
- **Use acoustical methods to get bubbles size distribution and void ratio in fluid**

Inversion of attenuation and velocity measurements:

Principle: A bubbly liquids is highly dispersive: attenuation and velocity are function of frequency.

By inverting attenuation and velocity measurement, it is possible to obtain the size distribution and the void ratio.

Limitation: High attenuation => bad signals.
Prior knowledge of the bubbles size is necessary



Attenuation and velocity curves for different log-nor size distribution

Nonlinear acoustic methods:

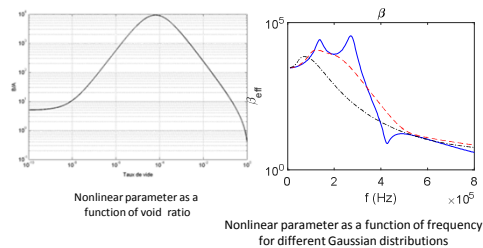
Principle: Use the high nonlinear properties of bubbly liquids, and the influence of both void ratio and size distribution to estimate them.

Rayleigh-Plesset (RPNP) equation for the radius evolution

$$\rho R \ddot{R} + \frac{3}{2} \rho \dot{R}^2 = \left(p_0 + \frac{2\sigma}{R_0} - p_v \right) \left(\frac{R_0}{R} \right)^{3\kappa} - \frac{2\sigma}{R_0} - \frac{4\mu}{R} \dot{R} + p_v - p_\infty(t)$$

Linearized equation with non linear parameter

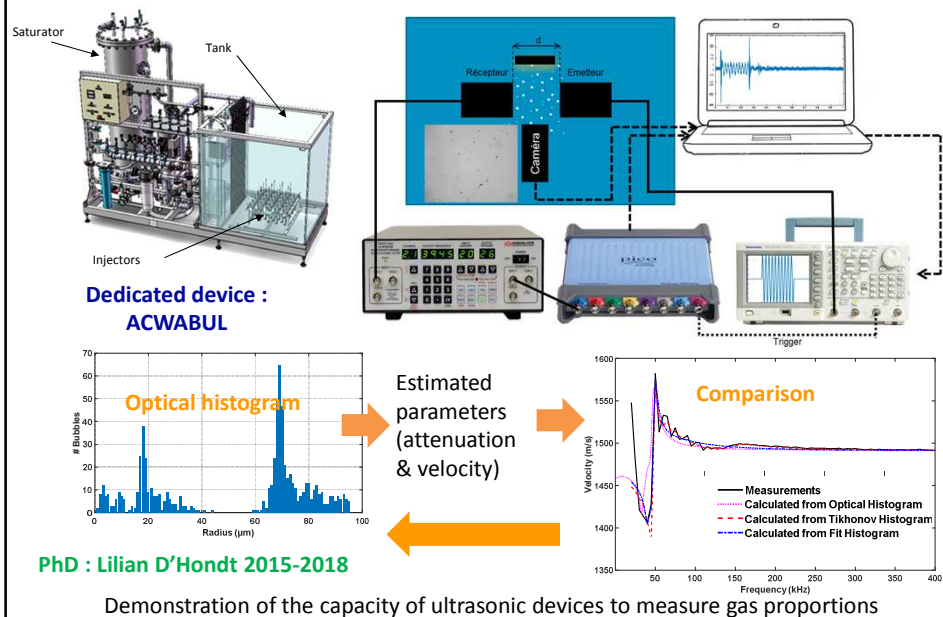
$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = P(t)$$



Nonlinear parameter as a function of void ratio

Nonlinear parameter as a function of frequency for different Gaussian distributions

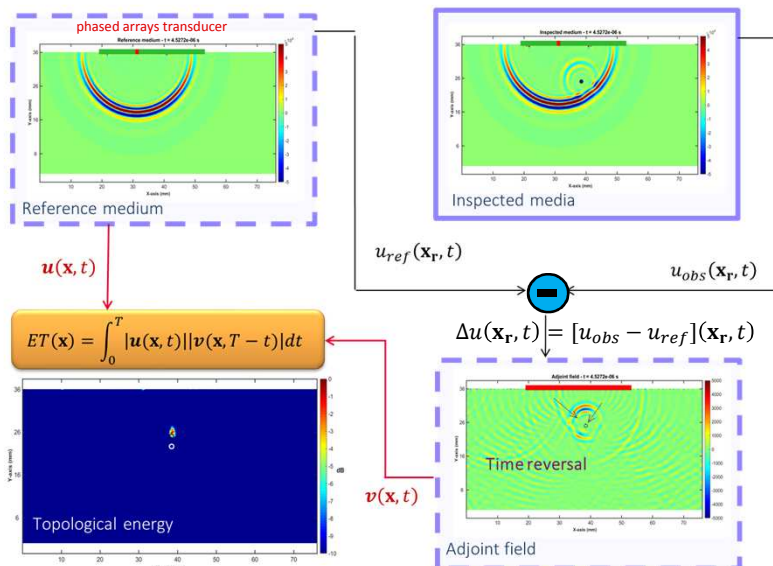
2 Evaluating the gas proportion with acoustics (2/2)



3 Topological imaging for damage localization

General principle

References : Tarantola 1988, Norton 1999, Dominguez 2010



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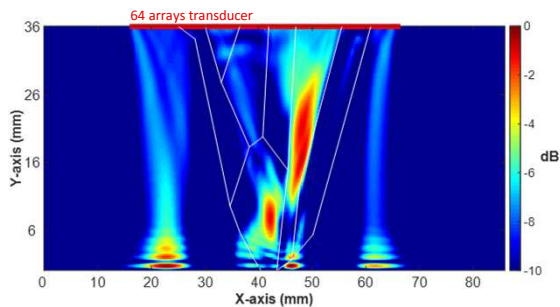
3 Topological imaging for damage localization

Multiple passes austenitic weld

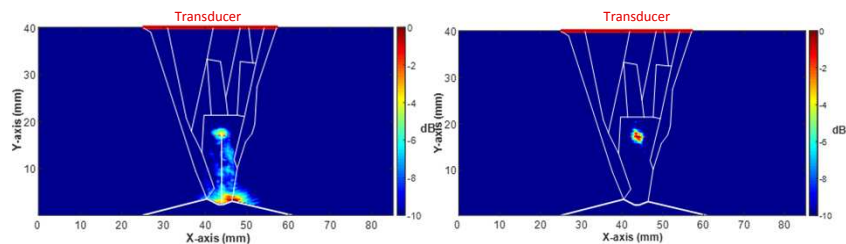
Without anisotropy description



PhD : Emma Lubeigt 2013-2016



With anisotropy description (in sub-areas)



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4 Description of welds for ultrasonic propagation modelling (1/2)

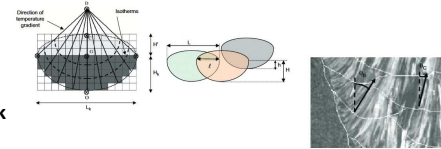
Multipass thick welds are **heterogeneous** and **anisotropic**.

⇒ Detailed **knowledge of the crystalline structure** required to anticipate US propagation.

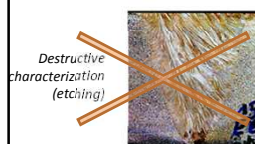
MINA (Modelling anisotropy from Notebook of Arc welding) developed in **collaboration with EDF**

MINA code predicts the **grain orientations** :

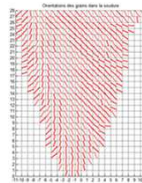
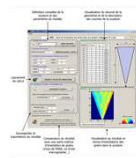
- from phenomenological skills (**epitaxy** and **selective growth**, local **thermal gradient...**),
- and from the information in the **welding notebook** (sequencing **order of the passes**, lateral and vertical **remelting** rates...)



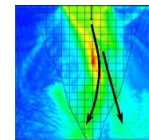
Knowledge of the crystalline structure



MINA modelling from welding notebook



Modelling of US propagation



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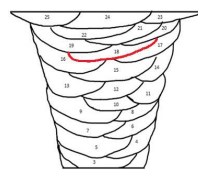
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4 Description of welds for ultrasonic propagation modelling (2/2)

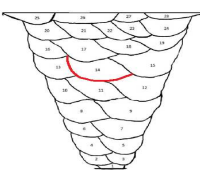
MINA is initially written for **Shielded Metal Arc Welding process**

TIG welds present some fundamental differences

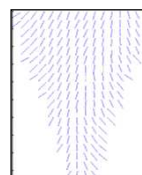
TIG auto sample



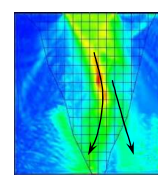
Shielded Metal Arc Welding sample



Ultrasound direction map



Ultrasound deviation



Current PhD : Quentin Marsac 2017-2020

⇒ Aiming at creating **MINA code** for the **TIG** welding process

Subject: "Modelling of the crystalline structure of thick welds. Application to ultrasonic testing for Sodium Fast Reactor primary circuit structures"

✓ In parallel MINA is being implemented in **CIVA** software



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5 Revisiting design codes (RCC-MRx) and inspectability

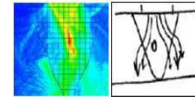
RC-CND (Recommendations of conception from non-destructive testing)

Context: SFR considered in the past as penalized for the in service inspection of the in sodium structures => need of improvement for GEN IV

Creation of a Working Group in 2012 (CEA, FRAMATOME, EDF & LCND-LMA)

=> Prescribed **modifications of RCC-MRx** Appendix A20, with associated "criteria" (justifications)

(recommendations for the choice of materials, assembly, geometry of assemblies, ... dispositions to be taken for future needs of inspection, accessibility...)

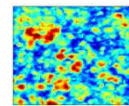
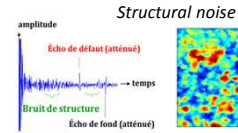
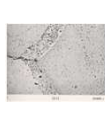
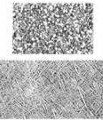


RE-CND (Recommendations of manufacturing from non-destructive testing)

Similar idea: identify the different parameters of the **microstructure** (due to the **manufacturing process**) that influence NDT

And propose recommendations to facilitate / make possible the future testings

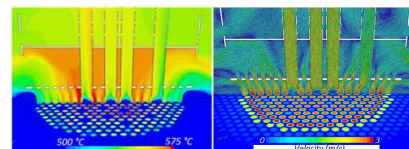
Twinning, dislocation, grain-boundary precipitate, inclusion, crystalline growth...



6 Ultrasonic propagation in heterogeneous medium (1/4)

Intended applications of NDE:

- Ultrasonic telemetry:
 - VISUS: to detect mechanical link between the core and the above core structure.
 - SONAR: to measure the horizontal displacement of the subassemblies.



Temperature and fluid velocity maps (Computational Fluid Dynamics)

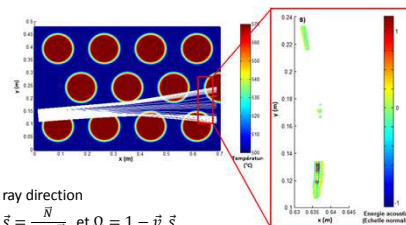
- Ultrasonic thermometry:
 - Measure of the sodium temperature at the outlet of the subassemblies (using the variation of ultrasound speed with the temperature)

Development of a ray code "ACRALIS" to model US propagation considering temperature and flow

$$\begin{cases} \frac{d\vec{x}_p}{dt} = \vec{v}(\vec{x}_p, t) + c(\vec{x}_p, t) \frac{c(\vec{x}_p, t)}{\Omega} \vec{s} \\ \frac{d\vec{s}}{dt} = -\frac{\Omega}{c} \vec{v} \cdot \vec{s} - \vec{s} \wedge (\vec{v} \wedge \vec{s}) - (\vec{s} \cdot \vec{v}) \vec{v} \end{cases}$$

[Cerveny and al. 1982]

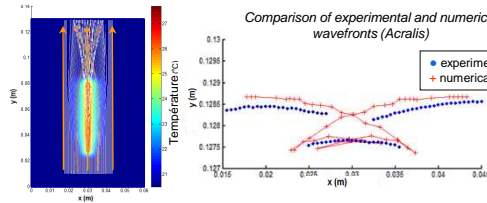
\vec{v} fluid velocity \vec{N} ray direction
 \vec{s} slowness vector $\vec{s} = \frac{\vec{N}}{c + \vec{v} \cdot \vec{N}}$, et $\Omega = 1 - \vec{v} \cdot \vec{s}$.



PhD : Nicolas Massacret 2009-2012

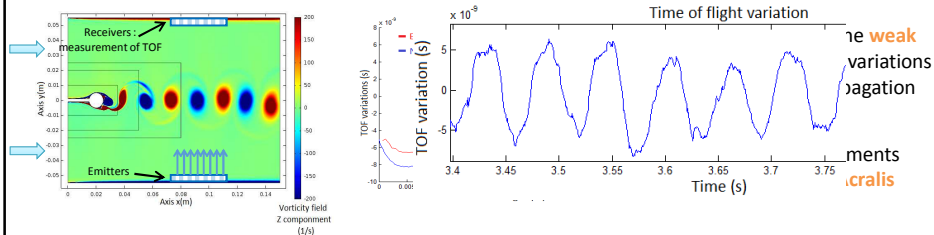
6 Ultrasonic propagation in heterogeneous medium (2/4)

Development of an experimental setup "UPSILON" with temperature heterogeneity And comparison with numerical results (Acralis)



- ✓ Confirmation of the **strong influence of temperature** variations on ultrasonic propagation
- ✓ Good agreement simulation/experiments
=> **validation of Acralis**

Development of an experimental setup "IKHAR" with Von Karman instabilities And comparison with numerical results (Comsol + Acralis)



the **weak** variations in propagation
ments
acralis

6 Ultrasonic propagation in heterogeneous medium (3/4)

Spectral elements to model US propagation at the outlet of the core:

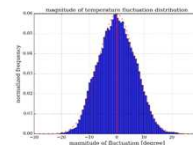
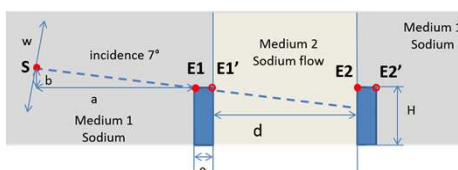
Specfem2D / 3D Numerical Calculation code for seismic wave propagation

PhD : Masaru Nagaso

SEM: Spectral Element Method

Legendre-Gauss-Lobatto-Lagrange interpolation polynomials

Ultrasonic thermometry configuration used in our study.



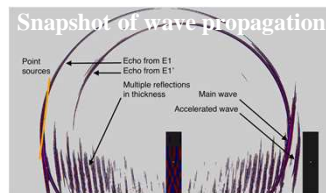
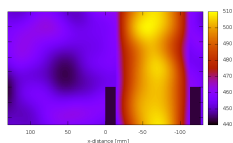
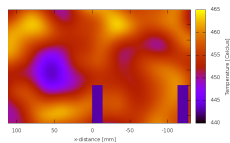
$$l_{\varepsilon} = 0.03 \text{ m}$$

$$\sigma_{\varepsilon} = 0.029$$

Temperature fluctuation
using a Gaussian random field

$$\frac{1}{T(\mathbf{r})} = \frac{1}{T_0} (1 + \varepsilon(\mathbf{r}))$$

σ_{ε}^2 the variance of the random value,
and l_{ε} the characteristic length

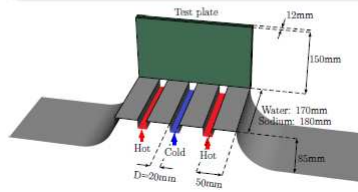


Possible detection of 1% jet temperature difference

6 3D - Ultrasonic propagation in heterogeneous medium (4/4)

Description : PLAJECT experiment (JAEA)


- ▶ Three jets entering a test section
- ▶ Measurements of velocity, temperature and energy spectra



PLAJECT Benchmark Wrap-up: CEA Simulations
P.-E. Angeli

HPC

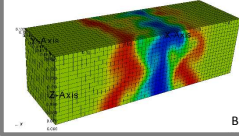
- ▶ Parallel resolution
- ▶ CEA Very Large Computing Center (TGCC)
- ▶ Cluster Curie: 2 petaFLOPS
- ▶ Cluster Airain: 420 teraFLOPS



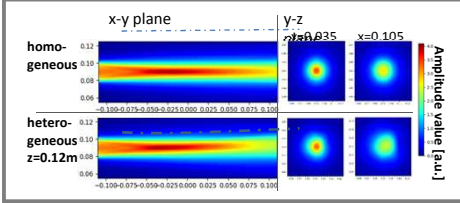
International collaboration JAEA / USDOE / CEA


4D data : 3D + time

Extract a region for acoustic simulation
Interpolation of temperature field
Tetra (TrioCFD) -> Hexa (SPECFEM)



By MEDCoupling

Acoustic field modification





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Conclusions and perspectives


- ✓ A fruitful collaboration
- ✓ An example of **efficient exchanges between industrial partners and academic team**
- ✓ A **lot of research works** during last years between CEA and LCND-LMA
- ✓ Many advances to improve NDT ... especially for the 4th generation of nuclear reactors



improving NDE Performance Evaluation
for safety and sustainability

Dissemination and use of knowledge through **publications, conferences, seminars ...**

- ✓ **Research training** (8 PhD students since 2000, and some of them hired by CEA)
- ✓ Towards a **joint laboratory LMA-CEA : MISTRAL (january 2019)**
 - ❑ Modelling in Mechanics and Mechanical Characterization of Materials
 - ❑ Modelling of structures with a multi-scale multi-physics approach
 - ❑ Acoustics for NDT and Monitoring of Materials and Structures




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