Signal and Image Processing 4.0 for Nonlinear NDT

Serge Dos Santos[1*], Yoshikazu Ohara[2*]

[1]INSA Centre Val de Loire, UMR 1253 « Imaging and Brain », Inserm, University of Tours, 3, Rue de la Chocolaterie CS 23410, F-41034 BLOIS cedex, France

[2]Tohoku University, Sendai, Japan

*Academia NDT International, Brescia, Italy
(*Council Members of the Academia NDT International)

serge.dossantos@insa-cvl.fr
ohara@material.tohoku.ac.jp

Academia General Assembly, 2021 report

Signal and Image processing : data fusion, Artificial Intelligence and ground truth for NDT 4.0

Serge DOS SANTOS , PhD, Hab. Dir. Rech., *Senior Member IEEE*
Full Member of Academia NDT International, Vice-President
INSA Centre Val de Loire, UMR 1253 « Imaging and Brain ». Inserm,
University of Tours, 3, Rue de la Chocolaterie CS 23410, F-41034 BLOIS cedex, France

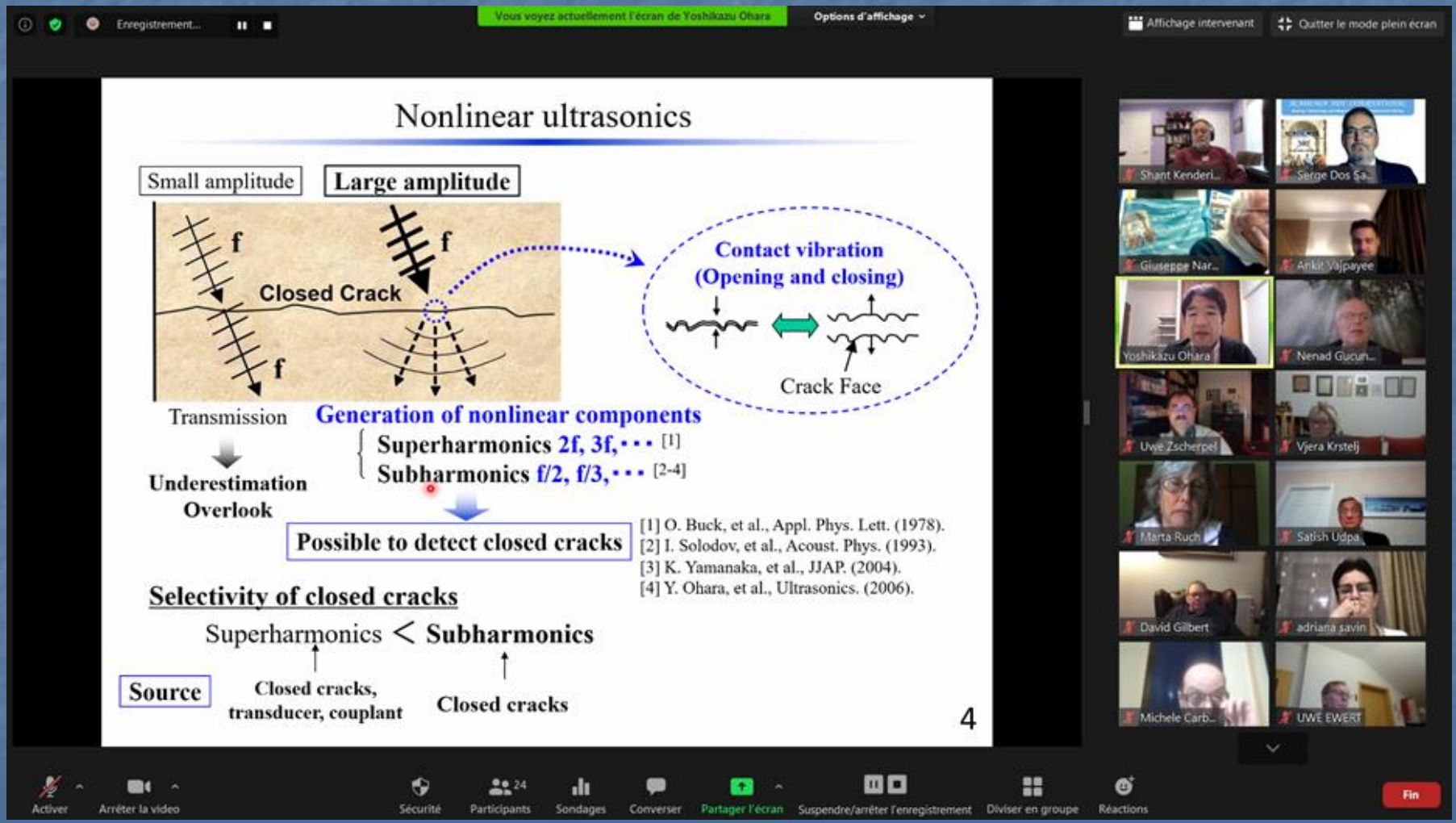
with the inspirations of

Chi Han Chen, Zdenek Prevorovsky, Valeryi Vengrinovich, Norikazu Ooka, Ward Rummel, Krishnan Balasubramaniam and Rainer Link
Full Members of Academia NDT International

serge.dossantos@insa-cvl.fr

Serge Dos Santos, Academia Meeting, October 23, 2021, Brescia, Italy

Academia General Assembly, 2020



Academia meeting : Moscow 2010 !

Nonlinear Acoustics and Signal Processing for Non Destructive Testing : from Symmetry Analysis to Bimodal Imaging

Dr. Serge Dos Santos, PhD

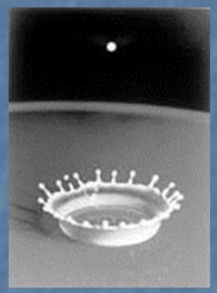
Associate Professor, Hab. Dir. Rech.

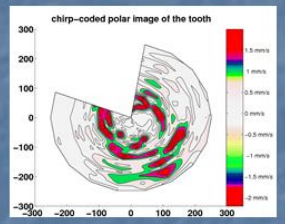
ENI Val de Loire

UMR 930 « Imaging and Brain », INSERM, CNRS, University of Tours

Rue de la Chocolaterie BP 3410, F-41034 BLOIS cedex, France

serge.dossantos@univ-tours.fr





Academia NDT International, General Assembly, June 9 2010, ECNDT2010, Moscow

Academia meeting : Munich 2016 !

The physical meaning of the autocorrelation function in NDT thanks to signal processing

Dr. Serge DOS SANTOS [1], *Hab. Dir. Rech.*
Council Member of Academia NDT International

[1] INSA Centre Val de Loire, campus Blois , UMR 930 « Imaging and Brain ». Inserm, University of Tours, 3, Rue de la Chocolaterie CS 23410, F-41034 BLOIS cedex, France
[2] GREMAN, CNRS, IUT de Blois, 15 rue de la chocolaterie, 41000 Blois, France

serge.dossantos@insa-cvl.fr

19th WCNDT 2016 World Conference on Non-Destructive Testing June 13–17 in Munich Germany

Serge Dos Santos, Academia Meeting, June 15th 2016, Munich, Germany (19th WCNDT)

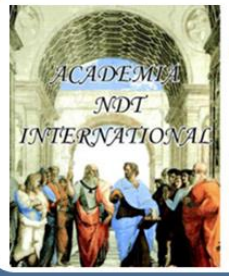
ERD Gothenburg: ECNDT 2018 !

Nonlinear Signal Processing for NDT 4.0

Serge Dos Santos[1*], Zdenek Prevorovsky[2*], Christophe Mattei[3], Valeriy Vengrinovich[4*], Giuseppe Nardoni[5*]

[1]INSA Centre Val de Loire, UMR 1253 « Imaging and Brain », Inserm, University of Tours, 3, Rue de la Chocolaterie CS 23410, F-41034 BLOIS cedex, France
[2]Institute of Thermomechanics AS CR, v.v.i., Dolejskova 5, CZ-18200, Prague 8, Czech Republic
[3] : Creo Dynamics AB; Westmansgatan 37, 582 16 Linköping, Sweden
[4] :Institute of Applied Physics, Minsk, Belarus
[5] : IT Nardoni Institute, Via Della Cascina Pontevica 21, Brescia 25010, Italy
*Academia NDT International, Brescia, Italy
(Full Member of the Academia NDT International)*

serge.dossantos@insa-cvl.fr



12th ECNDT
GOTHENBURG•SWEDEN•2018

For its 10th anniversary, Academia NDT International invites you to attend the European Research Day (June 13th, Room E1)

S. Dos Santos et al, ERD, 12th European conference on Non-Destructive Testing in Gothenburg ECNDT 2018, Sweden, June 11-15, 2018

ENDTCM 2021 keynote : October 2021

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES CENTRE VAL DE LOIRE

Instituts thématiques Inserm Institut national de la santé et de la recherche médicale

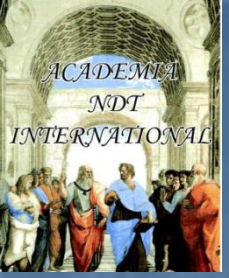
Guidance roadmap for Ultrasonic Nonlinear Imaging within Industry 4.0 : the importance of signal, image and data analysis

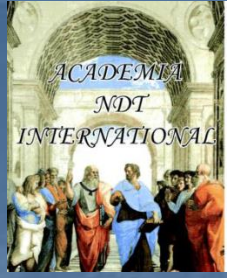
Serge Dos Santos, *PhD, Hab. Dir. Rech., SM'16 IEEE*
Director of the IIAV (2018-2022)

INSA Centre Val de Loire, UMR 1253 « Imaging and Brain », Inserm, University of Tours, 3, Rue de la Chocolaterie CS 23410, F-41034 BLOIS cedex, France
Full Member of Academia NDT International, Brescia, Italy

Member of the NDE4.0 Ambassador Group
serge.dossantos@insa-cvl.fr

Serge Dos Santos, keynote lecture, European Conference NDT&CM 2021, October 4-7, Prague

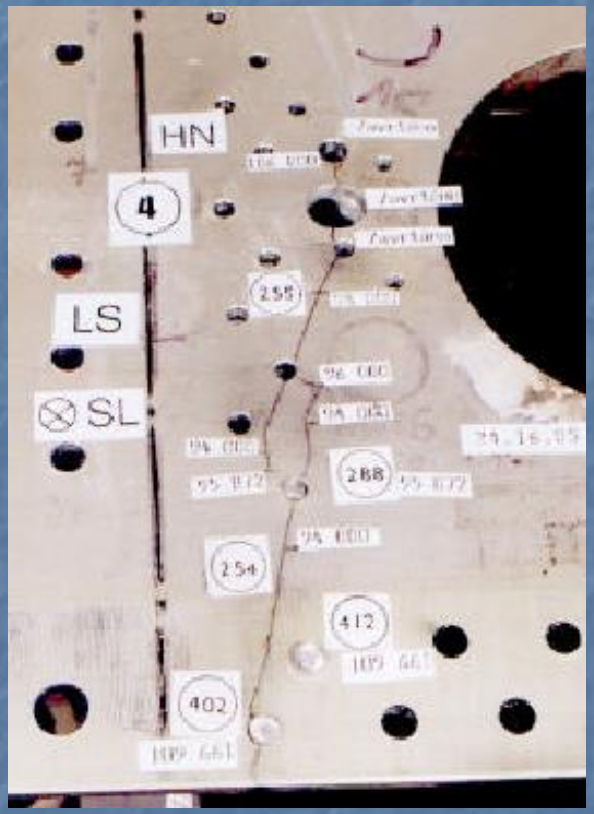


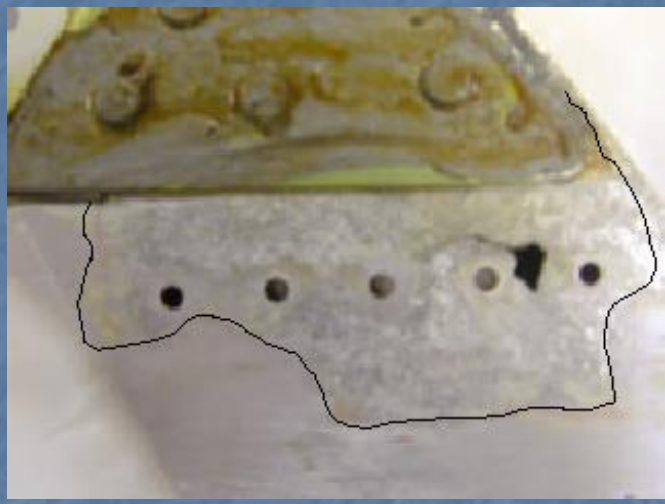


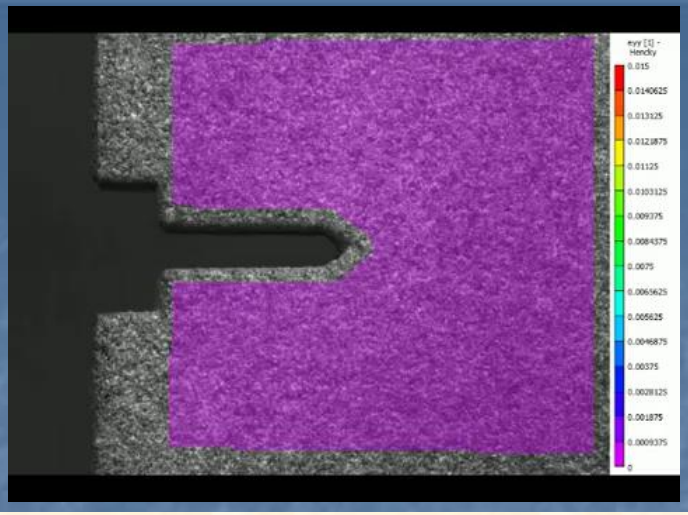
Outline

- Introduction
  - The growing interest for nondestructive testing (NDT) methods based on nonlinear acoustic effects
  - nonlinear ultrasonic (US) has become increasingly important due to the increase of higher sensitivity of electronic instrumentation and its associate signal processing algorithms
  - Instrumentation for NDT Integrity Engineering needs basics from applied physics and will concern all disciplines of engineering, including applied mathematics, computer science, modern automation and robotics, big data and artificial intelligence for Industry 4.0
- Methodology
  - One of the strategic plan of the international NDT community is to define standards for developing nonlinear NDT for automated set-up in mass production
  - The objective of this workshop is to define **the future of NDT 4.0** including **modern signal processing tools** such as big data reduction performed with an Artificial Intelligence (AI) and mapping of reduced data for modern NDT
  - The objective of this workshop will be used to prepare a guideline for application of nonlinear techniques. The working plan is to analyze strengths, weaknesses, opportunities and threats (SWOT) within the area of experimental nonlinear NDT.
- Conclusions, Discussion and Perspective

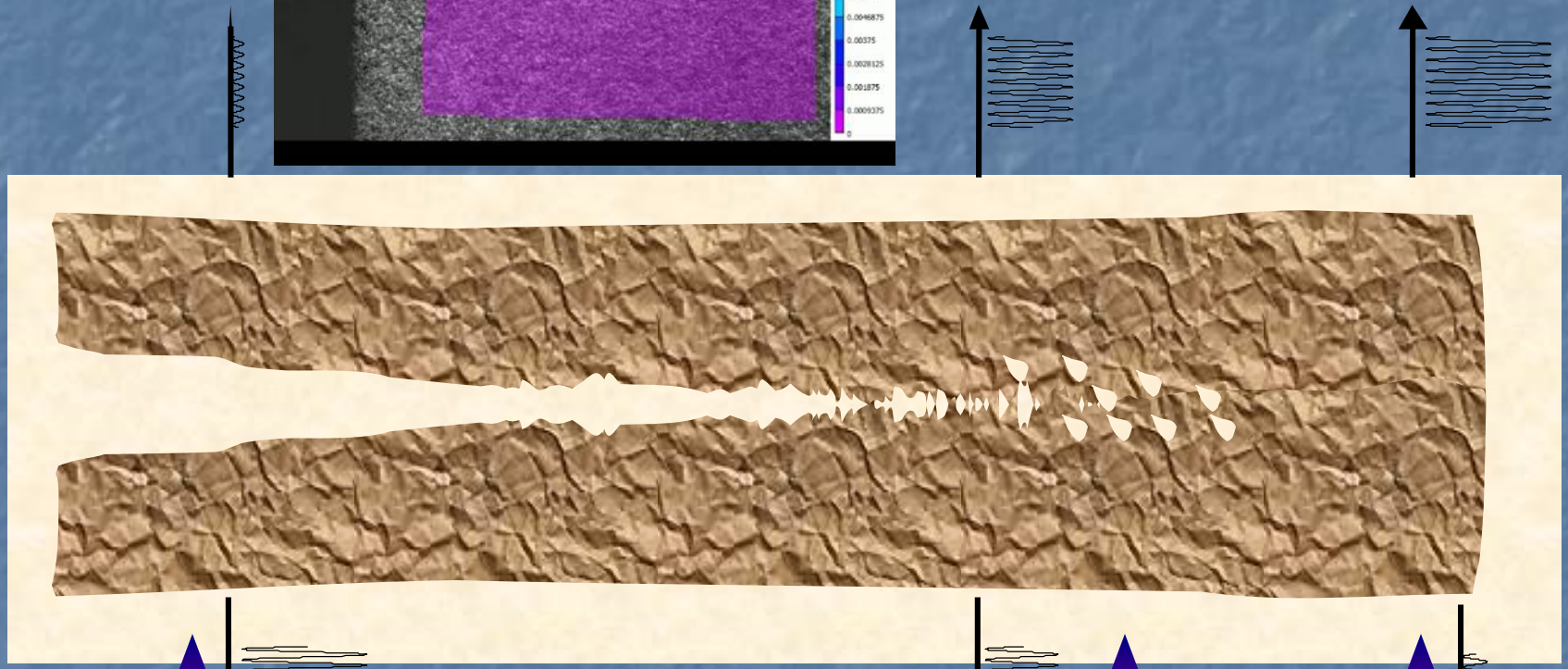
Damaged structures : macroscopic aspects

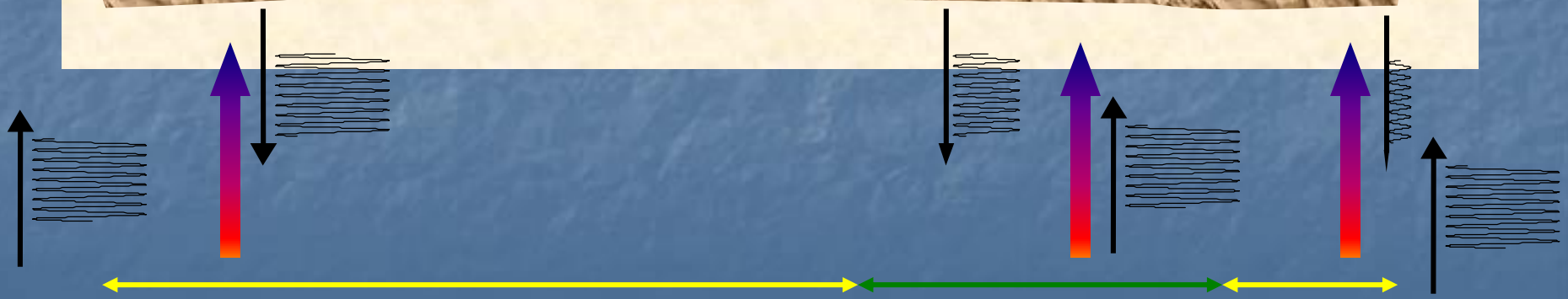






degradation ---> cracks

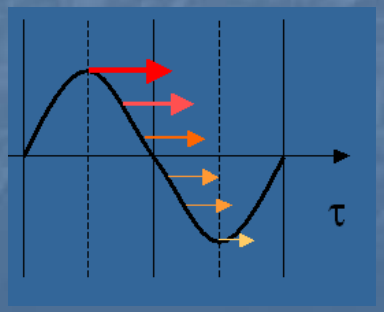


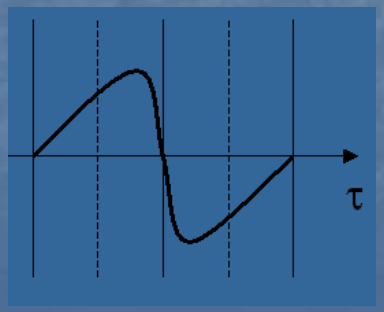


Linear region Nonlinear region Linear region

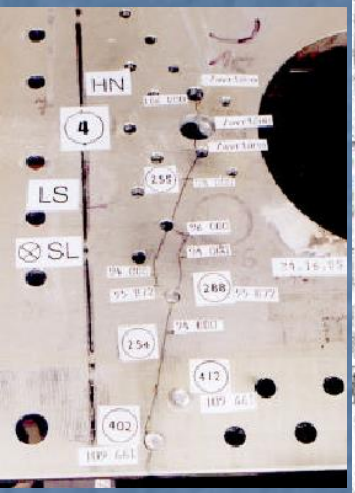
Advantage of ultrasonic nonlinear waves

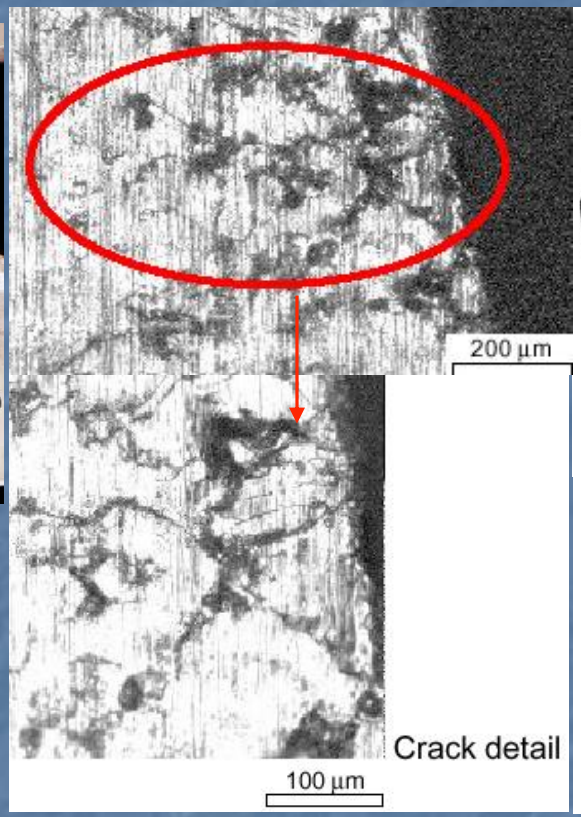
- How to detect smaller cracks :
  - Increase the frequency of ultrasound …
  - consequence : increase of attenuation …
- Solution :
  - … increase the ultrasonic power …
  - consequence : nonlinear effets are created (harmonics)
- Advantage :
  - « Natural » increase of the frequency thanks to harmonics

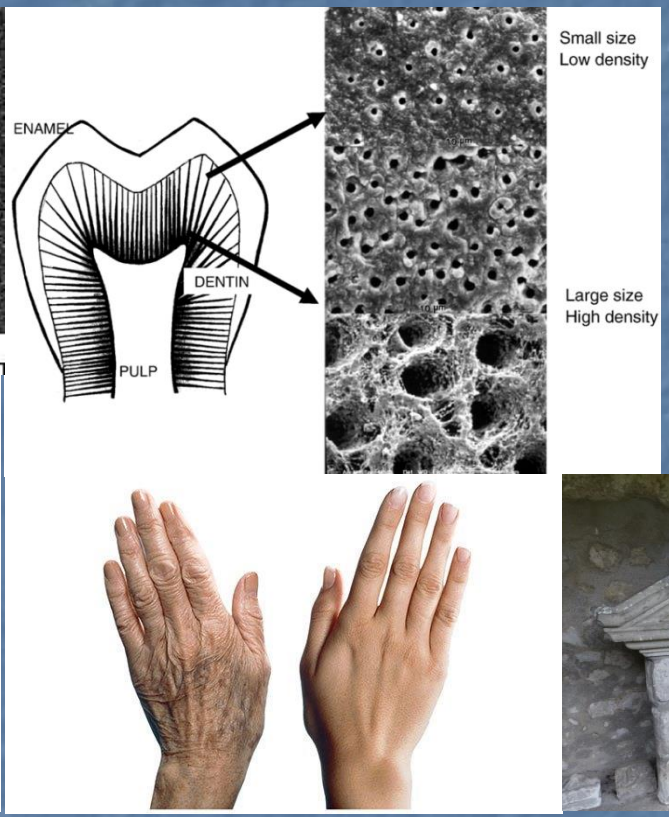




The (old) problem of aging !



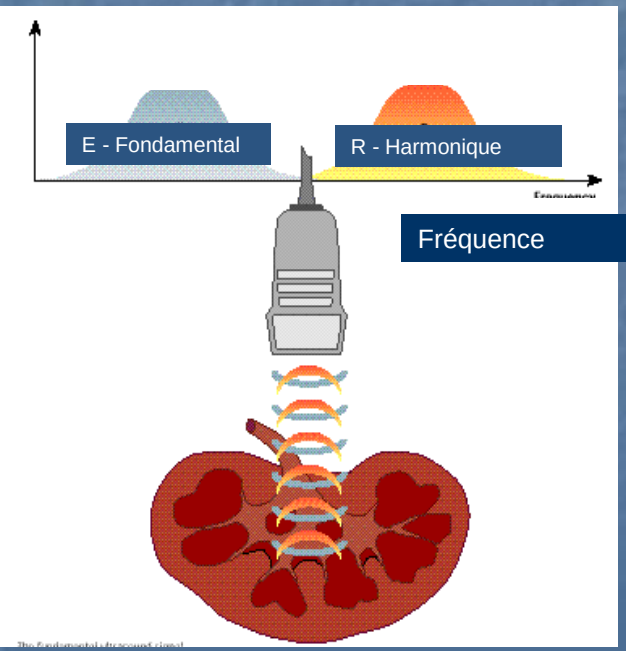


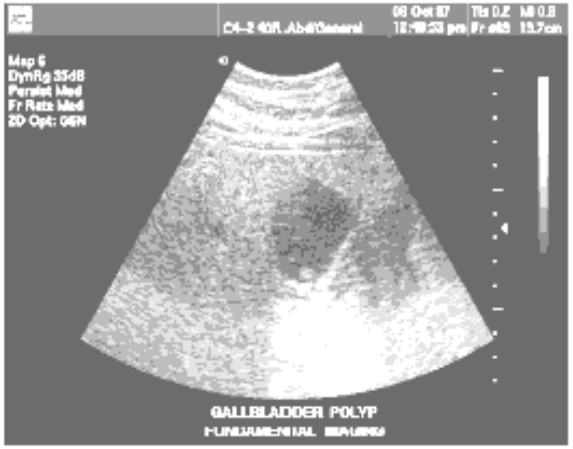


- What is the link between complex cracked structure from aeronautic industry, a human damaged tooth, the ancient stones, or skin …
- The internal complex structure …

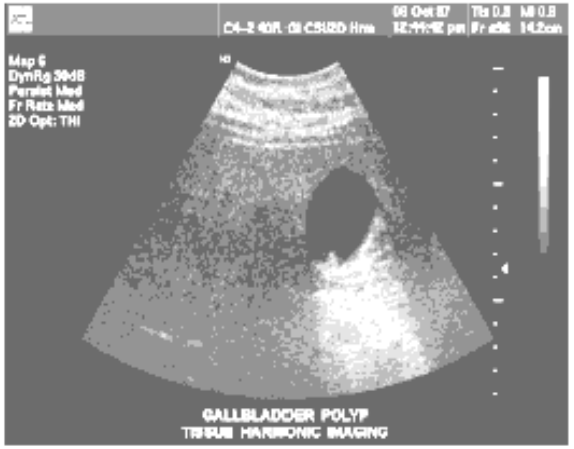
Medical applications of ultrasonic nonlinear waves

- **Harmonic Imaging**

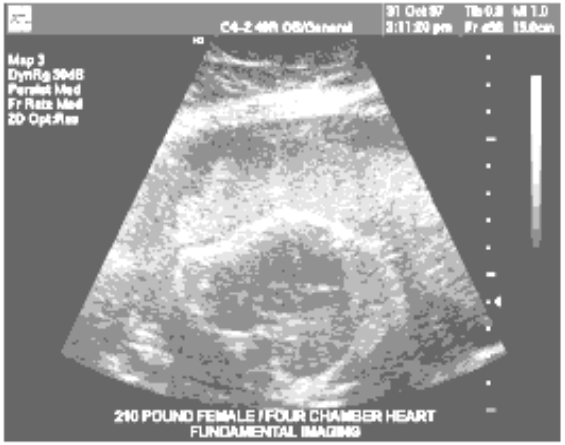




Fondamental



Harmonic



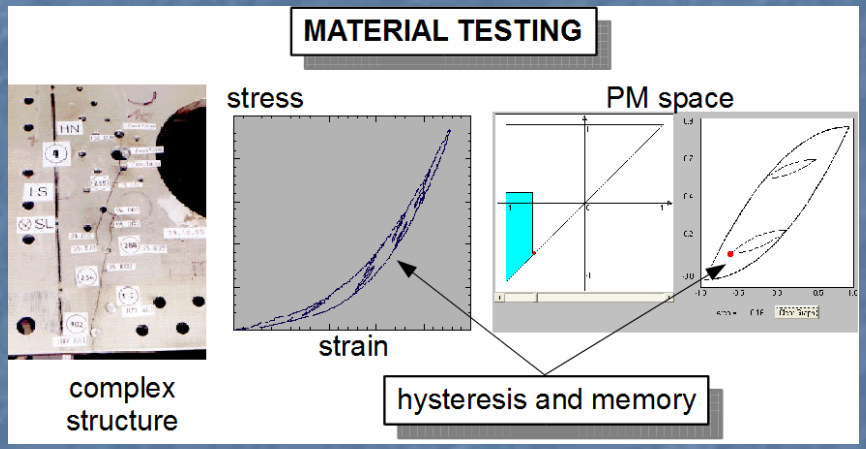
Nonlinear signature
Signal processing

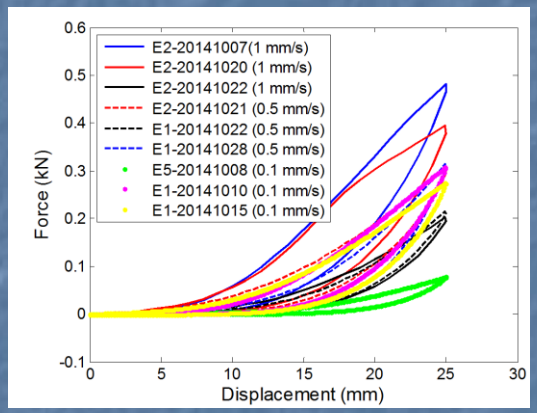
- harmonics generation
- intermodulation
- modulation, auto-modulation
- amplitude dependance of "classical linear signatures"
  - resonance frequency
  - attenuation
- sub-harmonics with arithmetical skeleton
- low frequency effects <-> slow dynamics
- chaos...

nonlinearity level

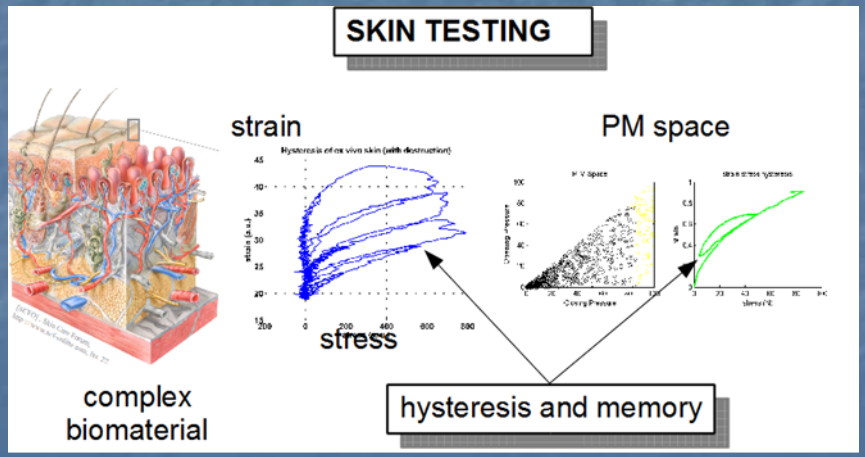
- <u>generic signature</u> in various physical systems
  - Mechanics, optics, electronics, acoustics, control
  - Lots of data ! ----→ BIG DATA !

Aging, memory, nonlinearity and hysteresis networks

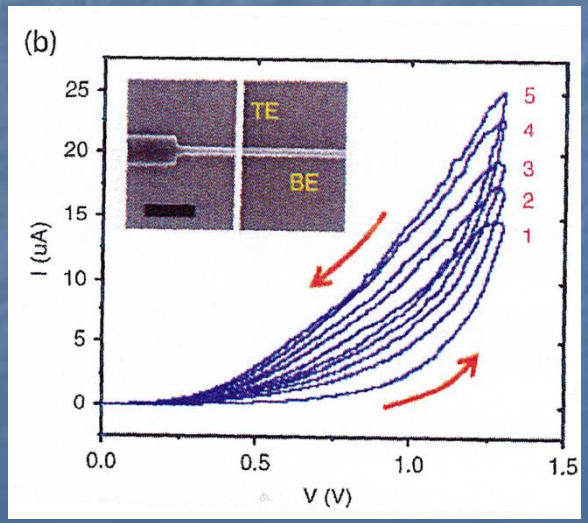




Plasticity and memory properties



Serge Dos Santos *et al*, IFSCC 2014, Paris



Memristor networks :
T. Chang, Y. Yang, W. Lu, IEEE Circuits and Systems Magazine 13, 56 (2013)

Excitation of Nonlinear Systems : concept

- Linear systems

$E(t) = A\cos(2\pi f t)$ → R(t) → S(t)

$$S(t) = R(t) * E(t)$$
$$S(f) = R(f).E(f)$$

R(t)* not dependant of amplitude *A

  - output spectrum properties are « invariant » with respect to excitation
  - lots of invariants including scaling effects, reciprocity and time reversal

- Nonlinear systems
  - spectrum is modified : spectrum representation in not an « invariant »
  - is it still interesting to look at frequency components ?
  - what is the next "invariant" candidate instead of sine wave excitation?
    - time evolution of frequency representation : wavelets and second order tools …

⇒
- It depends on the system
- how to find such invariant ?

Excitation of Nonlinear Systems : experiments

- Linear systems (amplitude is not critical)
  - time domain : pulse
  - frequency domain : sine waves are eigen-functions
- Nonlinear systems (amplitude is critical)
  - time domain : pulse amplitude must be known (calibration)
  - frequency domain : sine waves are not eigen-functions (modulation)
  - attenuation and frequency are time-dependant (slow dynamic)
  - scaling effects : how to take into account them systematically

- It depends on the system
- how to find such excitations ?

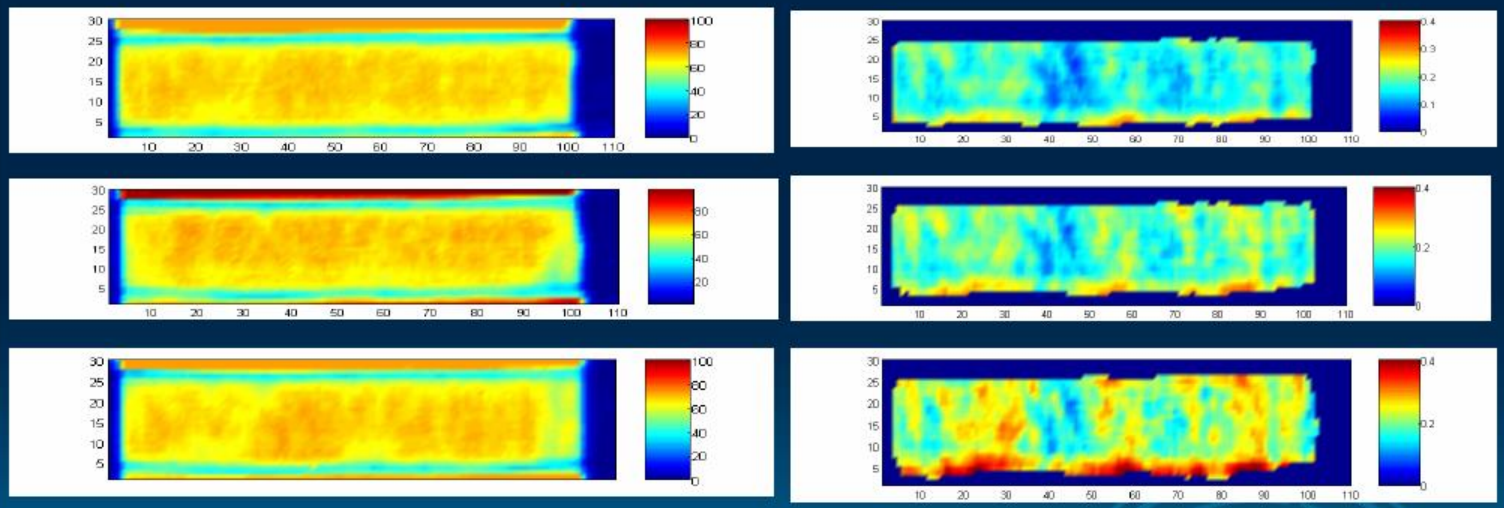
Basic Results (2002)

Example:
C-scan Imaging of fatigued CFRP samples

0 fatigue cycles
15000 fatigue cycles
17000 fatigue cycles

Classical C-scan

"2nd Harmonic Imaging"



AERONEWS

Bodycote Materialteknik, Sweden

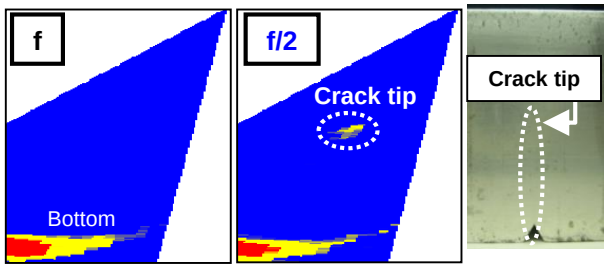
Nonlinear Ultrasonic Phased Array (2007-present)

Nonlinear ultrasonic phased array for closed-crack imaging

Phased array (PA)
for internal imaging
+
Nonlinear ultrasonics utilizing crack opening/closing behavior

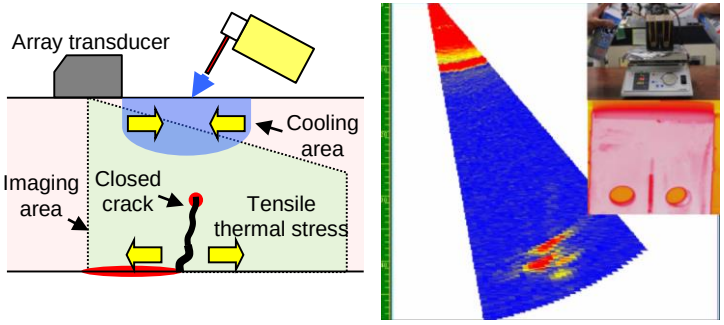
✓ SPACE (Subharmonic Phased Array for Crack Evaluation)

- Y. Ohara, et al., ***Appl. Phys. Lett.***, 90 (2007) 011902.



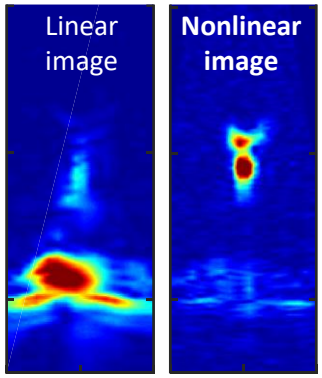
✓ GPLC (Global Preheating and Local Cooling)

- Y. Ohara, et al., ***Appl. Phys. Lett.***, 103 (2013) 031917.



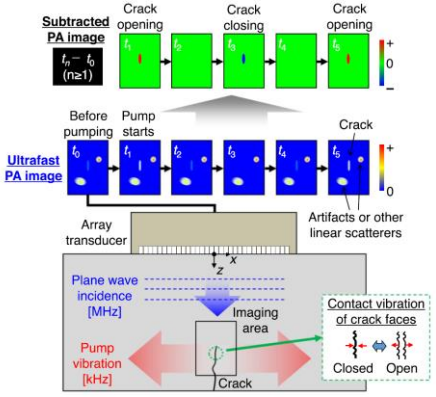
✓ FAD (Fundamental wave Amplitude Difference)

- Y. Ohara, et al., ***J. Acoust. Soc. Am.***, 146 (2019) 266.



✓ Ultrafast imaging with pump excitation

- Y. Ohara, et al., ***Appl. Phys. Express***, 14 (2021) 126505.

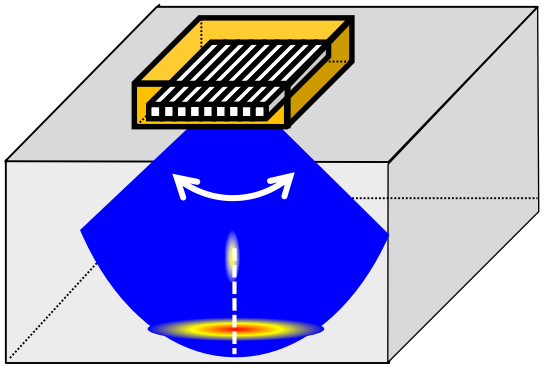


Accurate measurement of closed-crack depth

https://www.linkedin.com/feed/update/urn:li:activity:6986694457895051265?utm_source=share&utm_medium=member_desktop

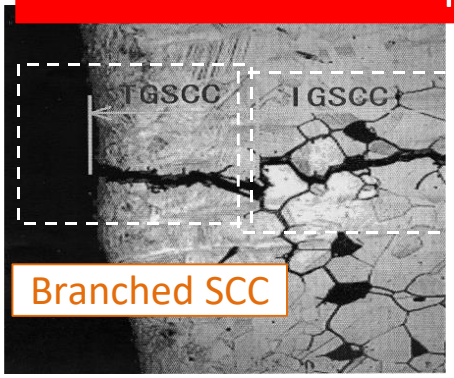
Toward 3D ultrasonic imaging

1D array transducer

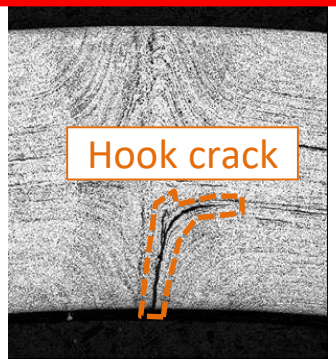


(Averaging within the elevation width)

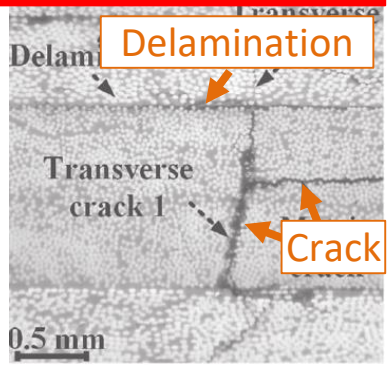
Many defects generated in various industrial fields have complicated 3D geometries



Power plants



Welds in automobile components



CFRP

If we can achieve **3D imaging,**

Efficient and reliable evaluation based on 3D defect geometries

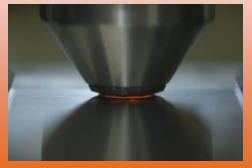
Energy

Car

Airplane

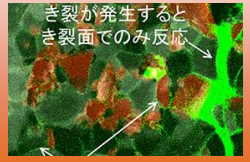
Other academic fields

Bonding engineering

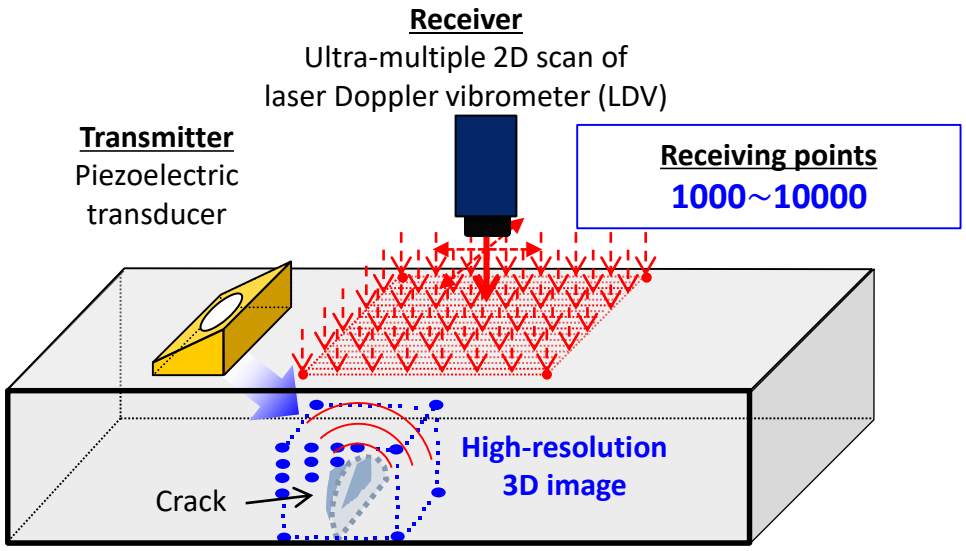


Fracture mechanics

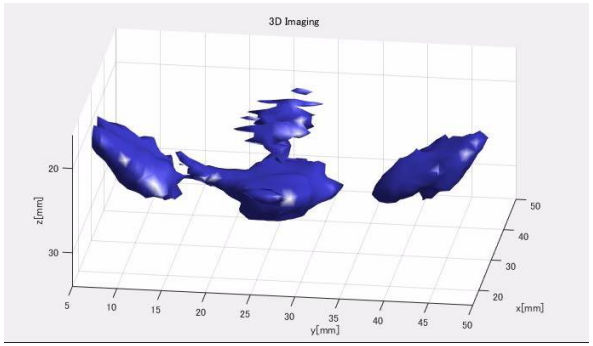
Self healing material



Piezoelectric and Laser Ultrasonic System (PLUS)

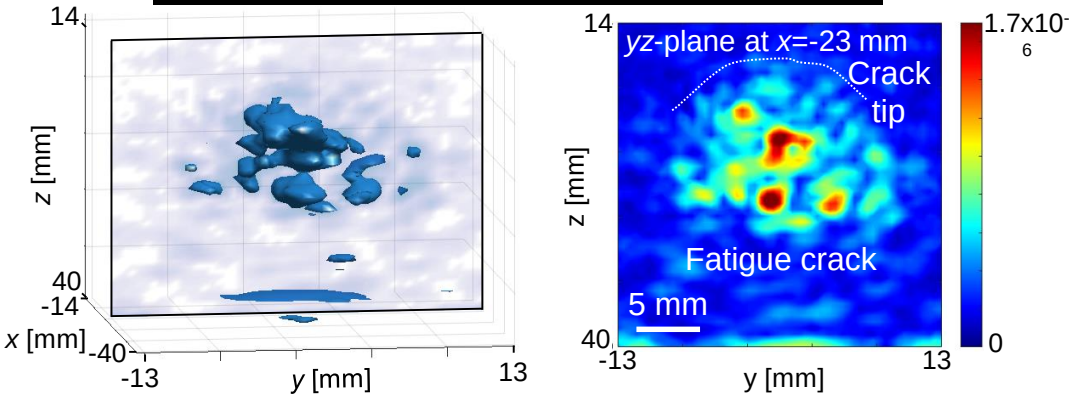


Branched SCC
3600 receiving points (100 × 36)



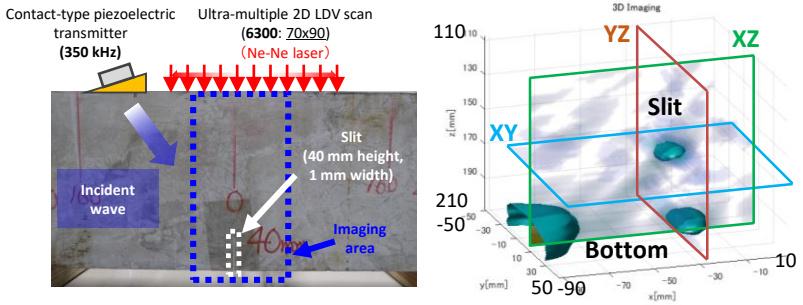
Y. Ohara, et al., ***Appl. Phys. Lett.*** 117 (2020) 111902.

Fatigue carck
4118 receiving points (71 × 57)



Y. Ohara, et al., ***Jpn. J. Appl. Phys.***, 61 (2022) SG1043. [**Best Paper Award**]
Y. Ohara, et al., ***Sci. Rep.***, 12 (2022) 8291.

Slit in concrete
6300 receiving points (70 × 90)



Y. Ohara, et al., ***IEEE IUS***@Venice, Italy (2022).

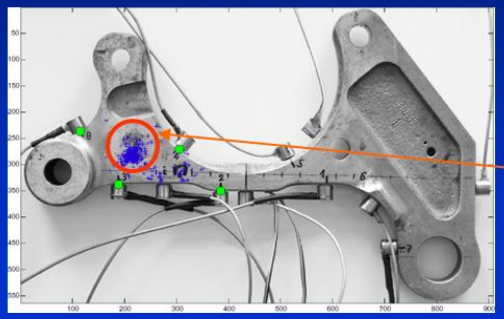
In future, PLUS can be extended to nonlinear version for 3D closed-crack imaging

Nonlinear Signal Processing for characterization of aeronautic structures

FATIGUE TESTS WITH NLTRM – ESAM on the STEERING ACTUATOR BRACKET

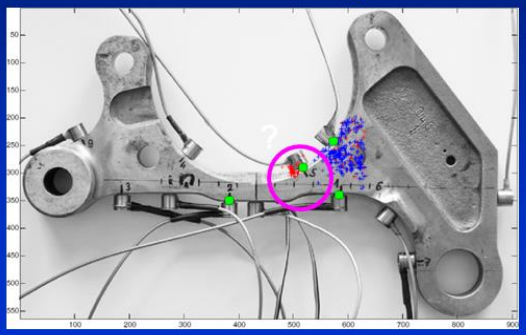
9th LOADING PERIOD (125 000 - 135 000 cycles)

AE left-clusters

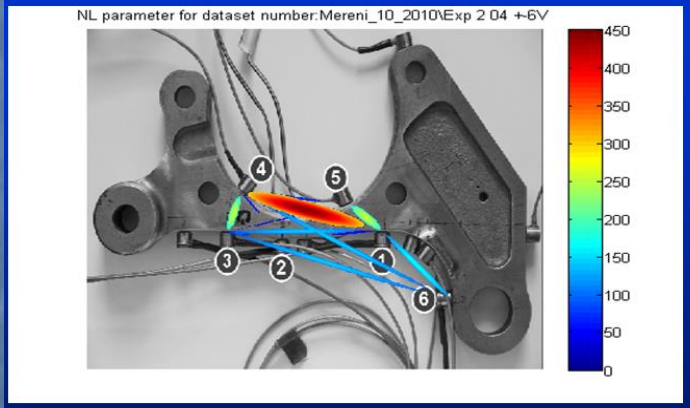


Damage of loading pinhole is one AE source cluster

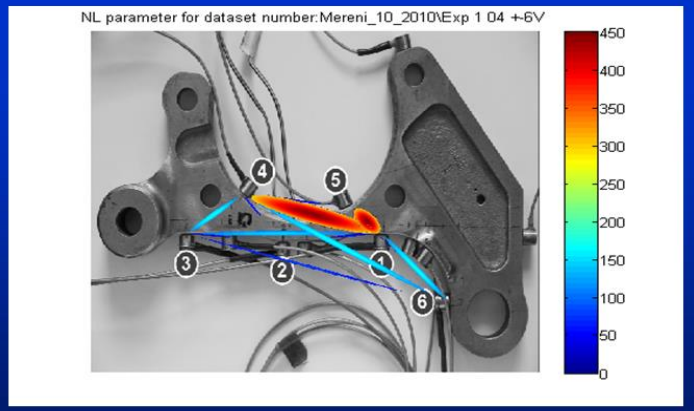
AE right-clusters



NLTRM – config. 1



NLTRM – config. 2



ACADEMIA NDT International
Durban, 17 April 2012

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Nonlinear ultrasonic time reversal mirrors in NDT, Zdenek Prevorovsky, Czech Academy of Science, Academia NDT lecture at WCNDT, Durban (2012)

TR-NEWS : the physical meaning of the autocorrelation function

Convolution equation

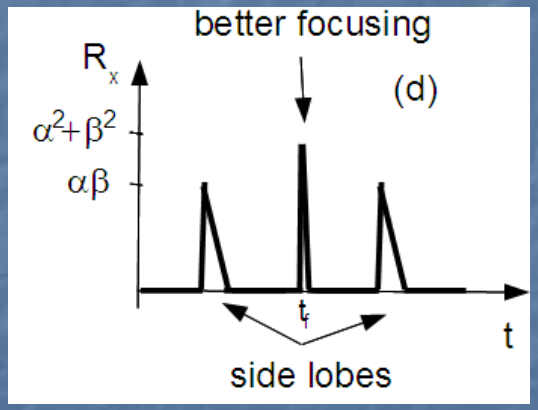
$$y(t) = c(t) * h(t) = \int_{\mathbb{R}} h(t-t')c(t')dt',$$

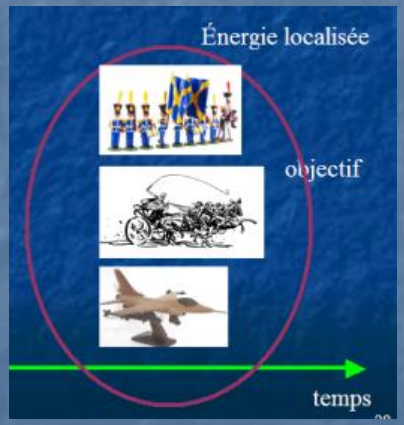
Correlation fonction

$$\gamma_{xx}(\tau) = \int_{\mathbb{R}} x(t)x^*(t-\tau)dt,$$

TR-NEWS

$$y_{TR}(t) = \Gamma(-t) * h(t) = \Gamma_h(-t),$$

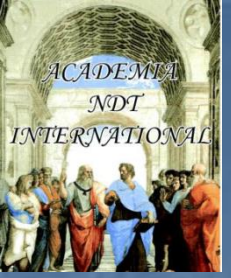


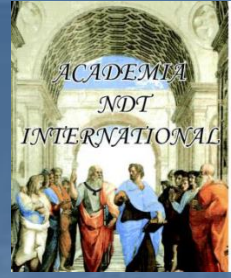


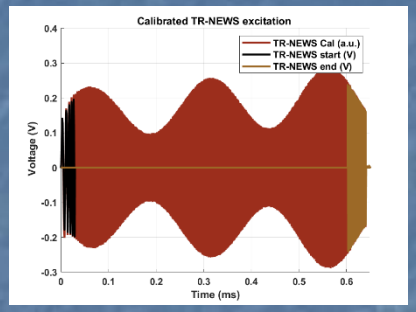
TR-NEWS process is a way to understand the physical interpretation (energetically) of the autocorrelation function of a complex medium

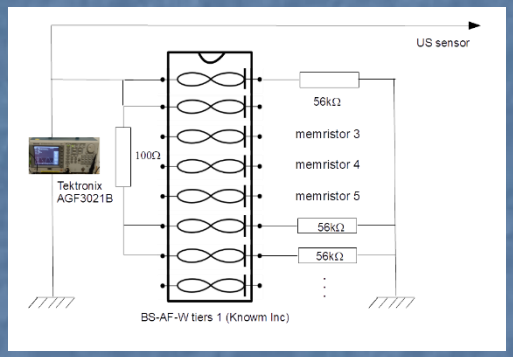
http://www.academia-ndt.org/admin/Downloads/Topo_Academia-Munich2016-V2.pdf

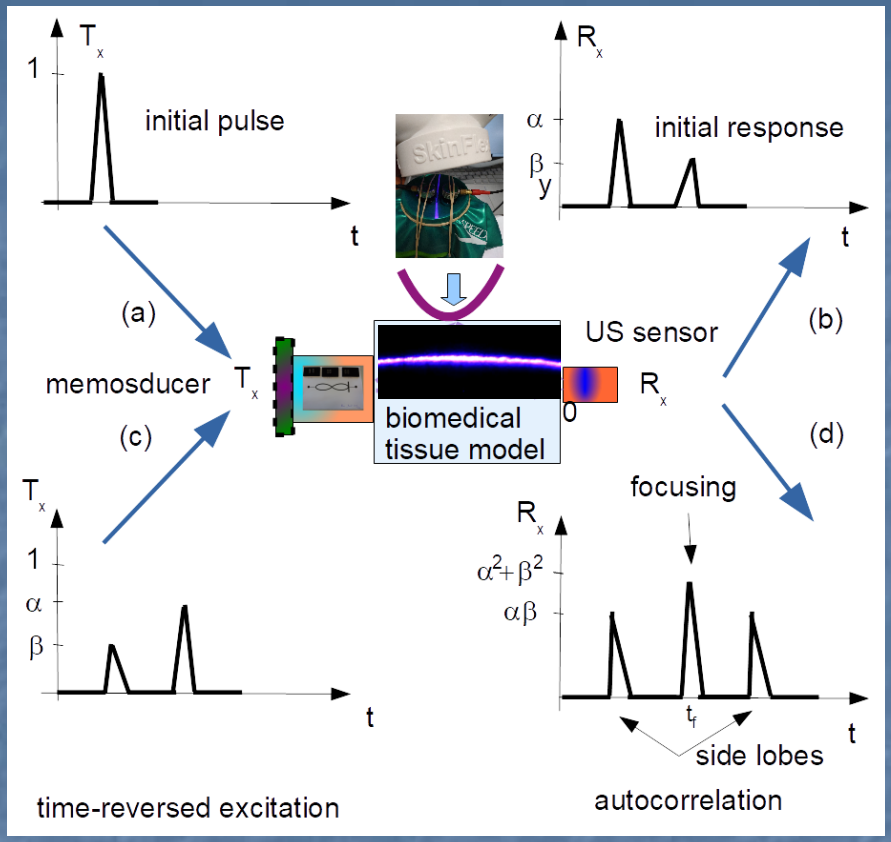
Signal Processing 4.0 Implementation

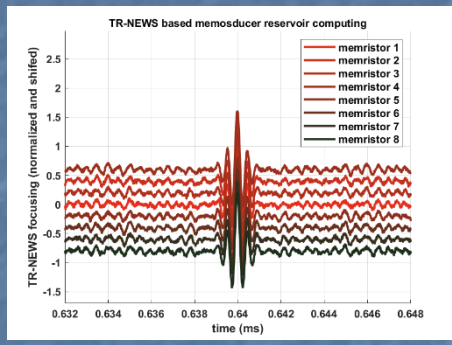


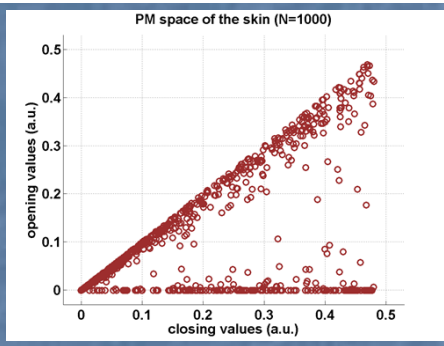


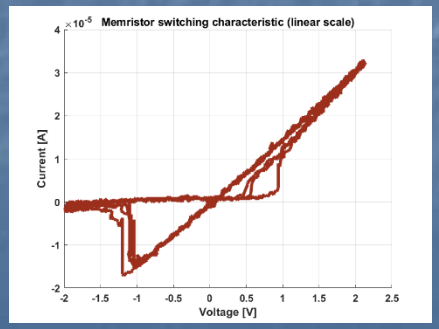


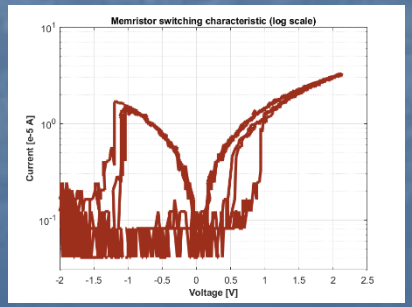


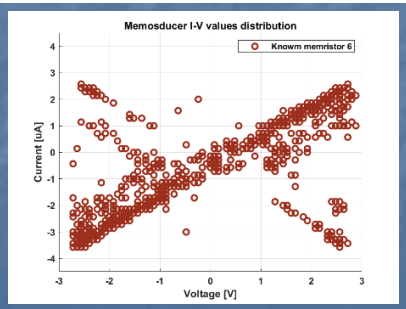








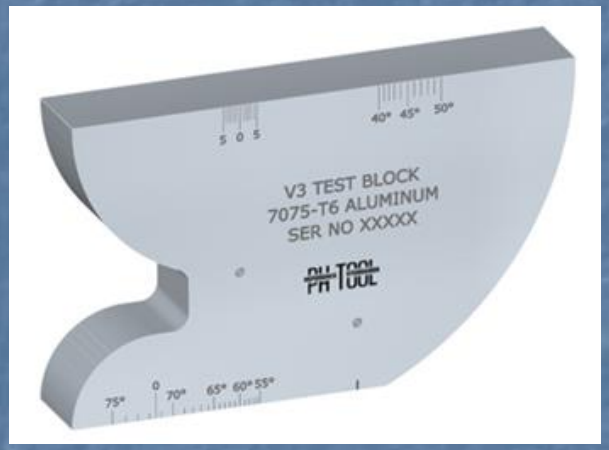


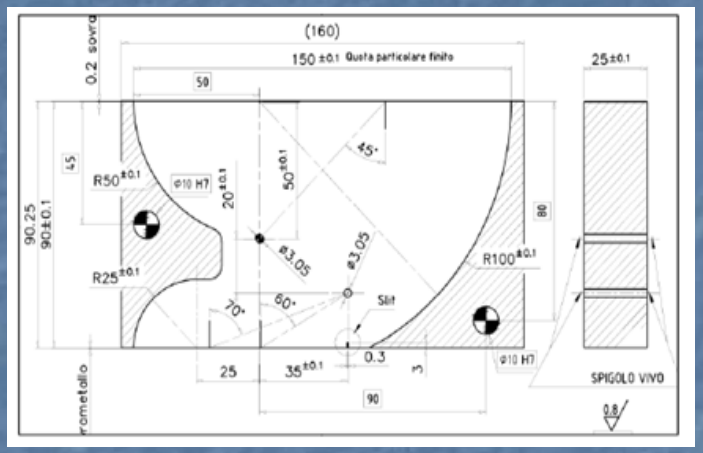


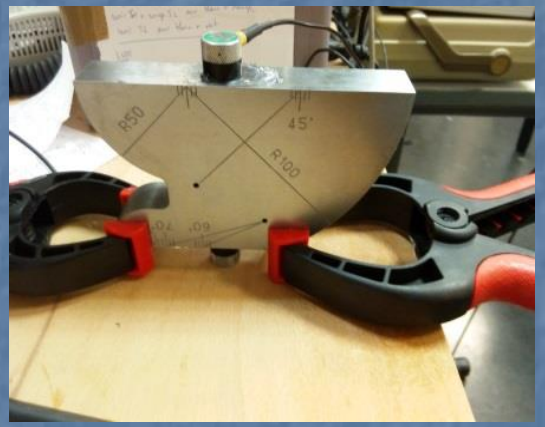
S. Dos Santos et al., *"Optimization of memristor based ultrasonic transducers for mesoscopic characterization of biomaterials,"* 2022 IEEE International Symposium on Applications of Ferroelectrics (ISAF), 2022

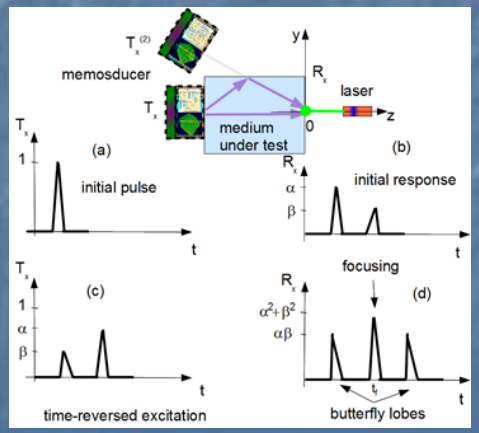
Signal Processing 4.0
BIG DATA

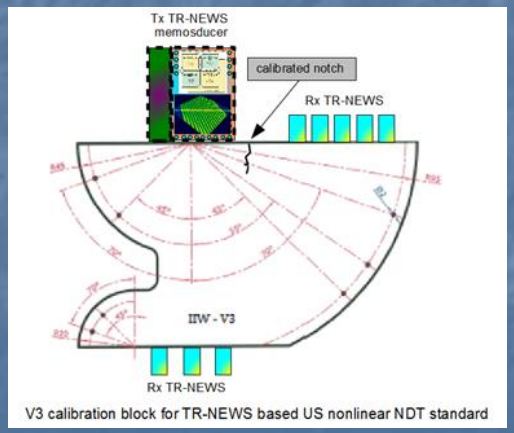
Standardisation with the V3 calibration block











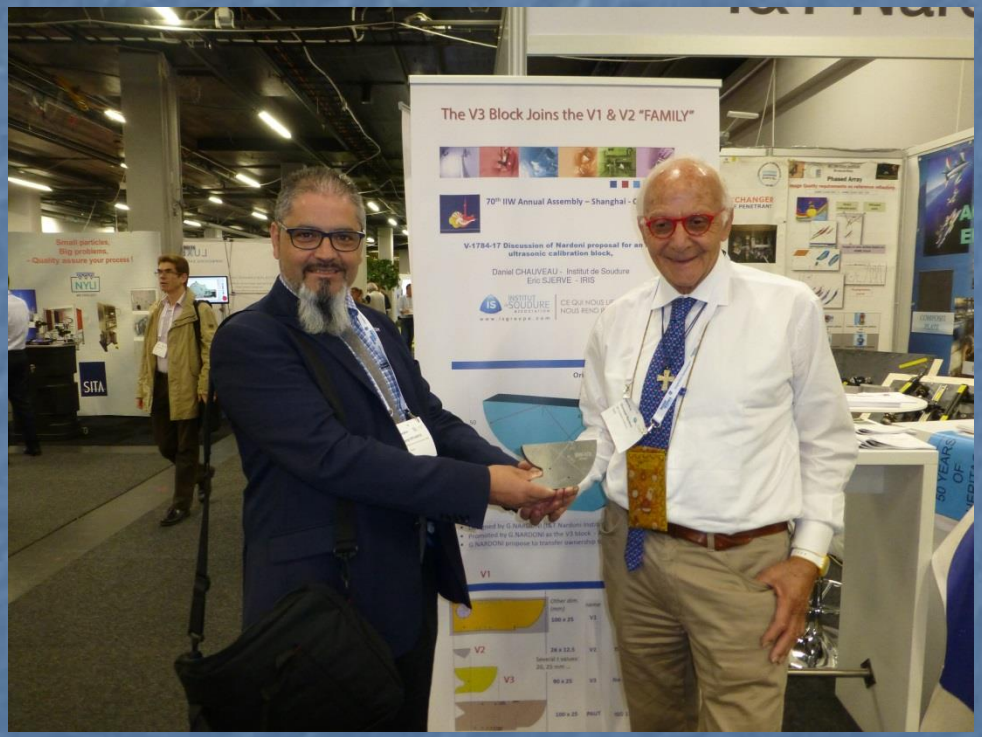
V3 calibration block for TR-NEWS based US nonlinear NDT standard

Download ECNDT 2018 papers under session Nonlinear Ultrasonics 1 :

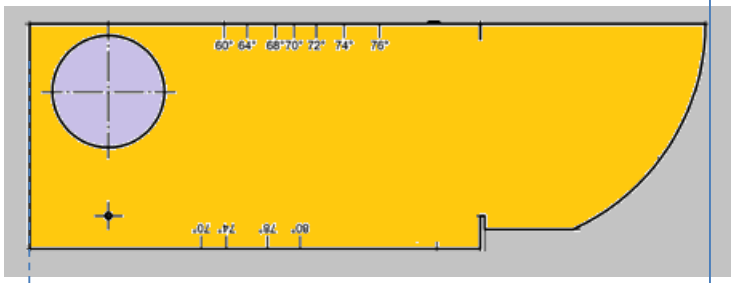
http://www.ecndt2018.com/abstract/acousto-mechanical-evaluation-of-multiscale-hysteretic-parameters-of-complex-material-with-nonlinear-time-reversal-imaging/

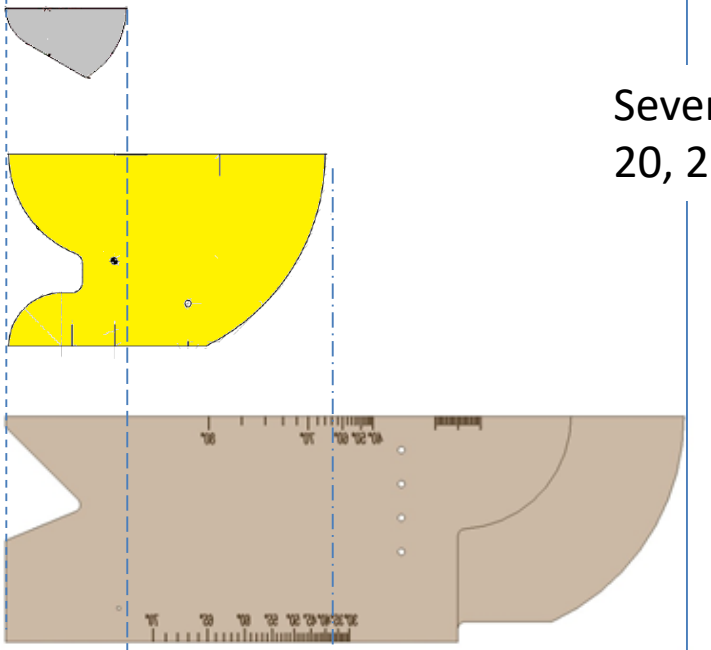
http://www.ecndt2018.com/abstract/acousto-mechanical-evaluation-of-multiscale-hysteretic-parameters-of-complex-material-with-nonlinear-time-reversal-imaging/

ECNDT 2018, Gothenburg



> UT calibration blocks comparison





Other dim. (mm)	*name*	*ISO standard*	*weight* (St)
100 x 25	**V1**	**ISO 2400**	**5070 g**
26 x 12.5	**V2**	**ISO 7963**	**212 g**
90 x 25	**V3**	**No standard**	**< 2500? g**
100 x 25	**PAUT**	**ISO 19675**	**4660 g**

Several t values:
20, 25 mm …

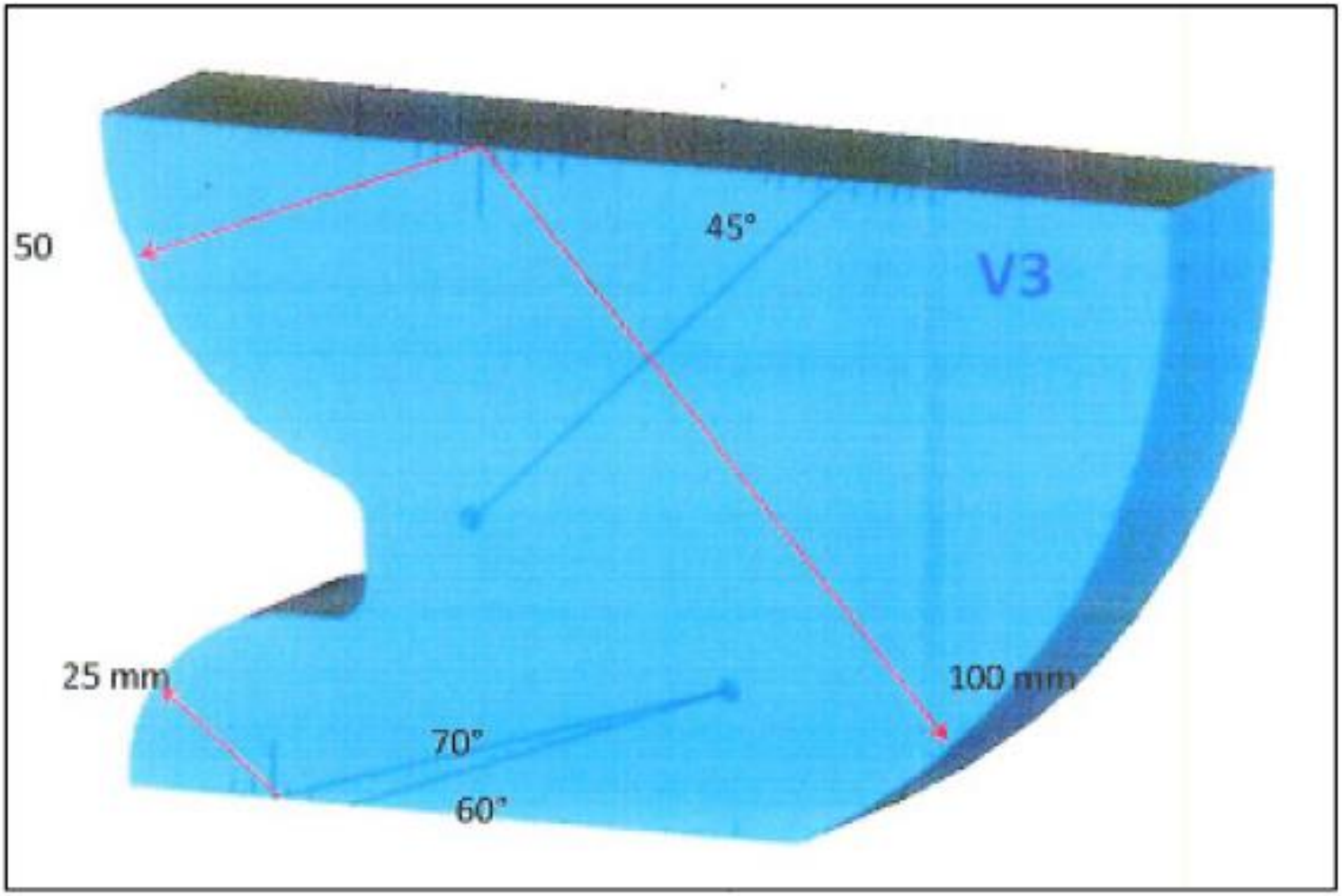
45 **150** **300**

length(mm)

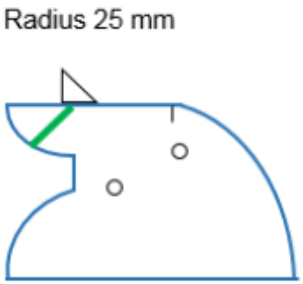
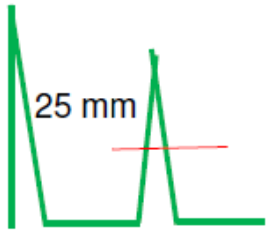
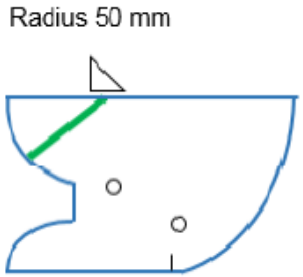
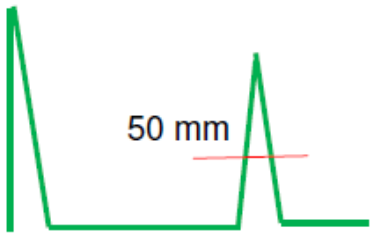
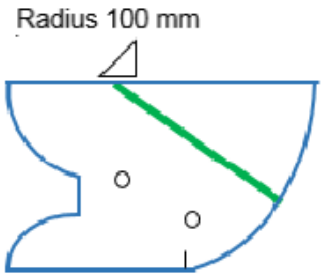
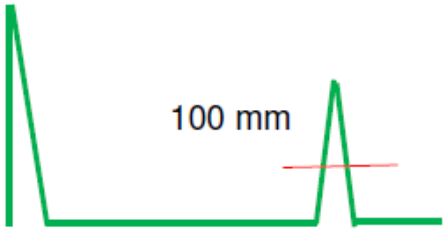
Main functions:

1. Three direct reflections: 25mm – 50mm – 100 mm
2. Two multi-reflections: 200mm – 250mm
3. Index point measurement for an angle beam probe
4. Incident angle measurement for an angle beam probe
5. Limited ability to set sensitivity on the 3 mm holes
6. Surface breaking slit for surface and sub-surface indications
7. Creeping wave calibration

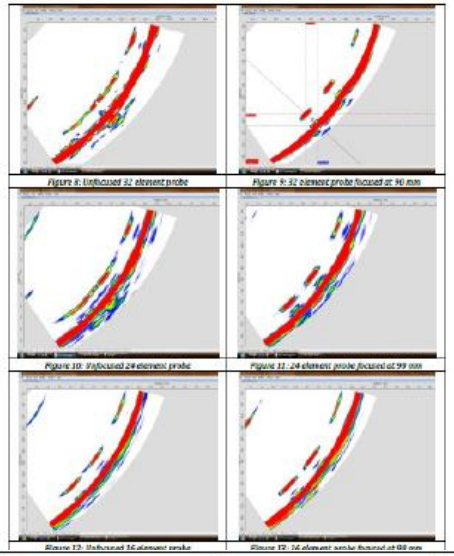
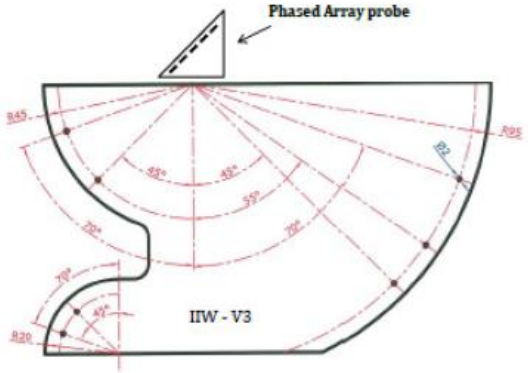
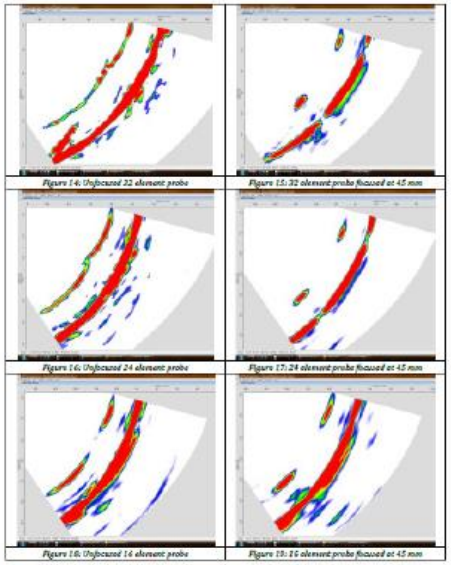
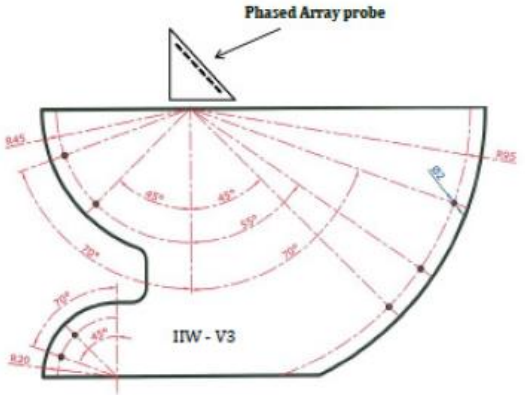
V3 – main functions



V3 – main functions

Main Functions	V3 Block	A-Scan
25 mm direct reflection		
50 mm direct reflection		
100 mm direct reflection		

V3 – other possible functions

Non-Focused Beam	Focused Beam	Probe Position
		Beam focus at 95 mm  Ultrasonic path at 100 mm
		Beam focus at 45 mm  Ultrasonic path at 50 mm

> Why a calibration is needed ?

Action Plan 4: Education & Research

- ***Continue to promote register of Research organisations***
- ***Review when to update Research and Education Guides***
- ***Prepare a list of NDT books with commentary on their suitability***
- ***Draw up a list of Universities offering courses in NDT, categorizing them as in the Guide***
- ***Sponsor International Specialist Groups, each hosted by a Member society***, internet meetings
  - –a) Full matrix capture - BINDT
  - –b) Teraherz imaging – BINDT
  - –c) Microwave NDT – ASNT
  - –d) Magnetic Memory Method- RSSNDT
  - –e) NDT of Art and Heritage - BINDT
  - –f) NDT Reliability – DGZfP
  - –g) Non-linear UT – KSNT
  - –h) Guided Wave UT – KSNT?
  - –ISGs will be open to all members of NDT Societies in ICNDT
- ***Promote more widely ICNDT Guide on importance of NDT and NDT research***
- ***Link to Academia NDT***
  - ***–Offer place for advertising Professorships and Studentships***
- ***Link to WFNDEC***

ICNDT
The World Organisation for NDT

Strategic Plan 2016-2020

The calibration is based on the selection of uncertain model parameters and the data that form the calibration metric together with an efficient optimization routine based on measurements

To obtain informative data, the excitation signal is designed to be optimized (sinusoidal, multisinusoidal, frequency chirp, etc.) and the resulting steady-state (linear and nonlinear) response data are measured

ICNDT Working Group on NDT Education and Research

ICNDT Working Group 3 is the focal point in ICNDT for activities relating to research, education and links to higher education. At a meeting held during the 19th WCNDT, Dr Manfred Johannes stepped down after four years of service as Chairman and Professor Younho Cho was elected as his successor.

Current members of the ICNDT Working Group on NDT Education and Research are:

- Professor Steve Holland, Iowa State University, USA
- Ekaterina Cheprasova, Russian Society for NDT, Russia
- Professor Vjera Krstelj, Croatian NDT Society, Croatia
- Harold Jansen, SAIW, South Africa
- Professor Marc Kreutzbruck, University of Stuttgart, Germany
- Kevin Smith, ASNT, USA
- Professor Uwe Ewert, BAM, Germany
- Dr Tony Erhard, DGZfP, Germany
- Professors Robert Smith and Keith Newton, BINDT, UK
- Dr Serge Dos Santos, INSA, France
- Mike Farley, ICNDT PGP Chairman.

Thursday, 14 June		
Authors lounge	08:00 – 17:00	Room 26
ICNDT GA	08:00 – 12:00	Room E1
ICNDT AC	12:00 – 15:00	Room E1
ICNDT WG3	15:00 – 17:00	Room E1

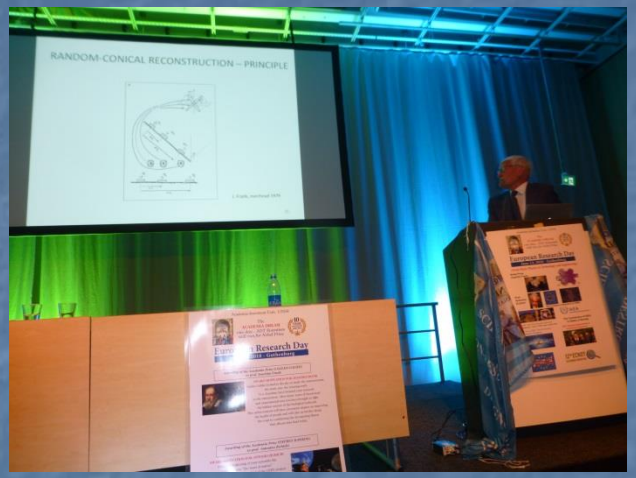
INSTITUT de SOUDURE ASSOCIATION

Academia document Univ. 1/2018

General scenario of the NDT methods and fields of application Presented at the 19th Wordl Conference Münich 2016

1 Acoustic Methods
2 Automotive Spot Welds
3 Aviation
4 CFRP Aircraft Structures
5 Civil Engineering
6 Composite Materials
7 Computed Tomography
8 Condition Monitoring
9 Corrosion Detection
10 Cultural Heritage
11 Digital Radiology and Radiography
12 Eddy Current
13 Energy Generation
14 Energy Nuclear
15 Guided Waves
16 ICNDT WG3
17 Image Processing
18 Imaging
19 Infrared and Optical
20 Laser Ultrasonic
21 Laser Ultrasonic and New Methods
22 Leak Testing
23 Lifetime Management
24 Magnetic and Penetrant
25 Microwaves and Terahertz
26 Modelling and Data Processing
27 Nano-Technologies and High Resolution NDT
28 NDT Adhesive Bonding
29 Non-Contact Ultrasonic
30 Non-Linear Acoustic
31 Nuclear Storage Casks Inspection
32 Other Applications
33 Pipeline In-Service Inspection
34 Process Monitoring
35 Project MAIzfp
36 Public Security and Humanitarian Safety
37 Qualification and Certification
38 Radiography/Computer Tomography
39 Railway
40 Reliability
41 Resonance Technology
42 Robotics Assisted NDE
43 Semi-finished Products
44 Sensor Concept
45 Standardization
46 Marine
47 Material Degradation
48 Materials Characterization
49 Medicine and Biology
50 Metal Magnetic Memory Technique
51 Stress Analysis
52 Structural Health Monitoring
53 Surface
54 Synchrotron Applications
55 Thermography
56 Ultrasonic
57 Underground Infrastructure
58 Welding

Advanced Signal Processing during the Gothenburg European Research Day



Joachim Frank, *Nobel Prize in Chemistry, 2017*

Peter Trampus

Christian Boller

Victor Udintsev

Conclusion and perspectives

- One of the strategic plan of the international NDT community is to define standards for developing nonlinear NDT for automated set-up in mass production
- The objective of this Academia Chapter is to define the future of NDT 4.0 including modern signal processing tools such as big data reduction performed with an Artificial Intelligence (AI) and mapping of reduced data for modern NDT
- The objective Academia Chapter will be to prepare a guideline for application of nonlinear techniques. The working plan is to analyze strengths, weaknesses, opportunities and threats (SWOT) within the area of experimental nonlinear NDT

Acknowledgements and Collaborations

- Development of TR-NEWS based approach in NDT and medical imaging
  - USA : A. Sutin and A. Sarvazyan (TR-NEWS experimentation for NDT and bubbles)
  - Belgium : K. Van den Abeele (AERONEWS EU project ,TR-NEWS methods for cracks)
  - Spain : V. Sanchez Morcillo (TR-NEWS optimization of focusing with phononic cavities)
  - France : O. Bou Matar (TR-NEWS simulations), V. Gusev (Nonlinear Acoustics), M. Caliez (TR-NEWS for skin)
  - Czech Rep : Z. Prevorovsky and V. Kus (TR-NEWS and AE, ESAM-DORT signal processing)
  - Germany : M. Kreutzbruck (TR-NEWS for CFRP, multi-modality), Johannes Vrana (NDE 4.0)
  - Italy : G. Nardoni (V3 calibration block for TR-NEWS ISO standardization)
  - UK : T. Stratoudaki (bimodality laser/US for TR-NEWS, invited researcher)
  - Germany : S. Hirsekorn (nonlinear NDT; invited researcher at INSA Centre Val de Loire)
  - Spain : V. Sanchez Morcillo (Nonlinear acoustics /nonlinear optics, inv. researcher)
  - Latvia : V. Kurtenoks (TR system instrumentation; electronics)
  - USA : Leon O. Chua (memristive effects ; nonlinear systems), R. Singh (NDE 4.0)
  - Japan : S. Furui (symmetry analysis of memristor based TR-NEWS systems)
  - Estonia : A. Salupere, M. Lints (solitonic and delayed TR-NEWS), T. Rang (INSA students)
- U1253 « Imaging and Brain : iBrain », Inserm-Université de Tours (GIP Ultrasons), Greman UMR 7347 CNRS-CEA, Lamé
  - Abellard A.-P., Arruga D., Bouakaz A., Caliez M., Callé S., **Chaline J.**, Domenjoud M., **Farova Z.**, Feuillard G., Fortineau J., Girault JM, Guilloteau D., **Goursolle T.**, Gratton M., Haumesser L., **Hemmati P.**, Kozena C., Lethiecq M., **Lint M.**, Masood A., Novell A., Papouskova J., Patat F., Plag C., Poirot, N., Pourcelot L., Remenieras J.P., Tauber C., Tran P., Vander Meulen F., **Vila M.**
- Council Members (2010) of Academia NDT International (www.academia-ndt.org)
  - Dr. G. Nardoni (President), Prof. Vladimir V. Klyuev, Dr. Baldev Raj, Prof. Vjera Krstelj
  - Dr. Ing. Rainer Link, Dr. Sotirios J. Vahaviolos

Academia NDT Signal Processing Chapter

Academia NDT International
President: G Nardoni
Via D.C. Pontevia n21
25010 - Folzano - Brescia - Italy
http://www.academia-ndt.org/

Signal Processing for Non Destructive Testing (NDT)

Serge Dos Santos [1,2] and Academia NDT International Members [2]

[1] INSA Centre Val de Loire, Unité Inserm U930 -Université de Tours, 3 Rue de la chocolaterie, BP3410, 41034 Blois cedex, FRANCE

[2] Via D.C. Pontevia n21 - 25010 - Folzano - Brescia , ITALY
Email: serge.dossantos@enivl.fr, Authors@academia-ndt.org

Abstract. A review of modern signal processing methods is suggested. All standard NDT methods are described form the signal processing point of view, beginning form historical ideas and systems, and ending with promising modern approaches.

Key words: non destructive testing, signal processing.

1 Introduction

Chapter supported by

- V. Vengrinovich
- B. Raj
- Z. Prevorovsky
- W. Rummel
- and new members …

Signal processing : a « new » area (Shannon, 1948) compared to mathematics, physics, medicine, chemistry, …

Thank you ! Questions ?

https://filesender.renater.fr/?s=download&token=078cb0f2-06c2-41e7-b8f4-123d15e9c0f3