Acoustic wave focusing in complex media using Nonlinear Time Reversal coded signal processing

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Content

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  - Principle of the Bi-modal Time Reversal (TR) based NEWS technique
    - Future trends for NDT (Non Destructive Testing) and potentiality for medical imaging

- **Methods and Materials**
  - The human tooth as a reverberating complex media
  - The nonlinear ultrasound (US) signature as an indication of degradation
  - Nonlinear Signal Processing: Pulse Inversion (PI) method

- **Results**
  - TR-NEWS used for tooth and skin applications: experimental set-up
  - Polar imaging of internal human tooth with TR-NEWS

- **Conclusions, Discussion and Perspective**
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 effects are created (harmonics)
- Advantage:
  - « Natural » increase of the frequency thanks to harmonics
Time Reversal for NEWS

M. Fink, France
IEEE Trans on UFFC (1992)

K. Van Den Abeele, P.A. Johnson, and A. Sutin.

- NEWS: Nonlinear Elastic Wave Spectroscopy
  - What is the nonlinear signature due to damaged area?
  - A high level of ultrasound is needed
  - How to localize sources of nonlinearity?

- Time Reversal
  - Retrofocused signal with high level of ultrasound (for NL effects)
  - Temporal focusing: reconstruction of coherent tone-burst signals
  - Spatial focusing: analysis on localized point: the focused region
    (practically measurements are done with laser interferometers)
Nonlinear Acoustics and TR

- TR: Time Reversal (M. Fink, France). It combines advantages:
  - of increasing the acoustic pressure stress localization
  - The local evaluation of the medium (which could be highly nonlinear) using global complex and dispersive response of the whole medium (which is mostly linear)

- It assumes a powerful symmetry between sources and receivers: reciprocity
  - Localized power!
  - Power not localized!
Multi-modal TR-NEWS: the objective!
Nonlinear Time Reversal for localization of nonlinear sources


Nonlinear Time Reversal in a chaotic system for extraction of localized nonlinear electromagnetic signatures

Synopsis: Alice and Bob Go Nonlinear

Perspectives: symbiosis between Time Reversal Techniques, chaotic waves, nonlinear dynamics and NDT of local activity

New area of Research and New innovations: cryptography and secured and coded communications
Coded Signal processing from Medical applications and Symmetry Analysis
Nonlinear Signal Processing: Symmetrization of Excitation with Pulse Inversion (PI)

Nonlinear medium

\[ y(t) = NL[x(t)] = N_1 x(t) + N_2 x^2(t) \]

Nonlinear signature

Experiments: measurements in the time domain!!
Symmetry associated to chirp-coding

\[-1\]
\[y(t) = c(t) * h(t) = \int_{\mathbb{R}} h(t - t') c(t') dt',\]

- linear response of systems

- chirp-coded response and correlation

\[1\]
\[\Gamma(t) = y(t) * c(-t) = h(t) * c(t) * c(-t),\]

\[\Gamma_c(t) = c(t) * c(-t) = \delta(t)\]

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

TR-NEWS

Nonlinear signature extraction with Pulse Inversion : addition of responses

Nonlinear signature extraction with Chirp coded Pulse Inversion : substraction of responses
Pulse Inversion (PI) method
Inversion group ($C_2$) interpretation

\[ y(t) = NL[x(t)] = N_1 x(t) + N_2 x^2(t), \]

where $N_1$ and $N_2$ are respectively linear and second order coefficients. If $X_E = x(t)$ and $X_I = -x(t)$ are applied separately to (S), one can extract $N_1$ and $N_2$ using the respective nonlinear response $Y_E(t)$ and $Y_I(t)$ with:

\[ N_1 = \frac{Y_E(t) - Y_I(t)}{2x(t)}, \quad (2) \]
\[ N_2 = \frac{Y_E(t) + Y_I(t)}{2x^2(t)}, \quad (3) \]

Extension for the 3rd order nonlinearity

Multiplication table (left) and character table (right) for the point group $C_2$. The top row of right table labels the group elements, and the first column the one-dimensional irreducible even $A_g$ and odd $A_u$ representations. $E$ is the identity, $I$ denotes inversion or rotation by an angle $\pi$. 
Higher order Pulse Inversion (PI) method : ESAM

\[ y(t) = NL[x(t)] = N_1 x(t) + N_2 x^2(t) + N_3 x^3(t), \]

C3 character table and irreducible representation

\[
\begin{array}{c|ccc|c|ccc|c|}
C_3 & E & \epsilon & \epsilon^* & C_3 & E & \epsilon & \epsilon^* \\
\hline
E & E & \epsilon & \epsilon^* & A_1 & 1 & 1 & 1 \\
\epsilon & \epsilon & \epsilon^* & E & A_2 & 1 & -1 & -1 \\
\epsilon^* & \epsilon^* & E & \epsilon & E_1 & 2 & -1 & 0 \\
\end{array}
\]

Multiplication table (left) and character table (right) for the point group \(C_3\). \(E\) is the identity, \(\epsilon = e^{2i\pi/3}\) denotes rotation by an angle \(2\pi/3\), \(\epsilon^* = e^{-2i\pi/3}\) denotes rotation by an angle \(-2\pi/3\).

\[
\Rightarrow \text{ New « symmetrized » excitations}
\]

Application of ESAM signal processing

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

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

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TR-NEWS imaging of the tooth

chirp-coded polar image of the tooth
B-scan echodentography

Imaging of the tooth before focusing

TR-NEWS polar image of the tooth

Imaging of the tooth after focusing

TR-NEWS polar image after focusing

Nonlinear signature

Future work: include tooth topography data with other modality

Efficiency of TR-NEWS in complex medium:

reverberant medium is an advantage!!
Strategies for TR-NEWS focusing improvement and nonlinear measurements: chaotic transducer

For TR-NEWS based focusing, “long time coda” is needed:

- Reverberation (or dispersion or memory) should be present in the “transducing device”
- Chaotic cavities should be preferred in order to reduce “symmetry” effects

Bou Matar et al., On the use of a chaotic cavity transducer in nonlinear elastic imaging, Applied Physics Letters 95, 141913 2009
Strategies for TR-NEWS focusing and nonlinear measurements: the phononic transducer
Results on the TR-NEWS focusing

The phononic cavity decreases the "focusing properties" of the compressed signal.

Localisation and classification

Classification and localization of bubbles and Ultrasound Contrast Agent (UCA) in bio-medium

Experimental setup – 2 parts:

- 3 different sources of nonlinearities in water tank are measured – small bubbles, big bubbles and Ultrasound Contrast Agent (UCA) flow in a capillary
- small bubbles – measured at 4 different positions \([0,0], [10,0], [10,10] \) and \([0,14]\)


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Classification of nonlinear signatures

Nonlinear and localized signatures of material can be classified.

TR-NEWS signal

Classification Clusters

φ-divergence parameters of measured signals

Result of the Fuzzy divergence method
TR-NEWS for skin US imaging

- NDT
- Degradation ⇔ memory of the material (memristor for NDT?)
- Ageing ⇔ memory of the skin (see Leon Chua lecture)
TR-NEWS for skin (PLET project)

S. Dos Santos et al, Viscoelastic and hysteretic properties of the skin: Acousto-mechanical evaluation using nonlinear time reversal imaging, to be presented at IFSCC, Oct. 2014, Paris
Nonlinear acoustics for complex composites structures

- Complex composite: 144 layers!
- Dispersive properties ...
- Damaged composite: nonlinear behavior ...
- Nonlinearity + dispersion = soliton propagation ...

M. Lints et al (see presentation Th.D.4.5)
Delayed TR-NEWS for solitonic excitation
Strategies for TR-NEWS focusing improvement and nonlinear measurements: memristive transducer

Figure 2: Principle of the memory based transducer. Putting memory into transducer induce the possibility of breaking any symmetry in the excitation device leading to a unambiguous superfocusing properties needed for TR-NEWS based experiments[12, 13]

Nonlinear Time Reversal and complex medium
2D simulations: ISNA17, 2005

A. Sutin et al., ISNA17, PennState, 2005

3D simulations: T. Goursolle et al., JASA 2007

TR-NEWS
Conclusion

- Some TR-NEWS innovations have been presented for ultrasonic testing (UT) of nonlinear, complex media and complex pattern
  - The concept of “focused TR-NEWS” using a focused sensor as a receiver
    - Surface TR-NEWS method could be investigated for volumic tomography of complex media
  - Experiments with 2D and 3D phononic cavities as a reverberant media
    - Consequently, TR-NEWS is better for complex medium and does not work for “regular” ones!
  - New TR-NEWS device (40 MHz)
    - New perspectives for Medical Imaging and NDT in complex samples using coded solitonic excitations (see Martin Lints paper in these conference)

- Perspective
  - Practical implementation of these results for complex media, like bubbles localisation using statistical analysis
  - Potential applications for underwater detection of nonlinear scatterers like bubbles (seagrass, diver, etc.) and damage and ageing signature of human organs (bone, skin, brain)
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Questions!

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