# Time Reversal in elastodynamics and applications to Structural Health Monitoring

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### Introduction

- 2 The time reversal process
- 3 Damage Identification
- 4 Numerical implementation

### 5 Conclusions

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- 2 The time reversal process
- 3 Damage Identification
- 4 Numerical implementation
- 5 Conclusions

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- Important in SHM systems
- Response recordings at a number of sensors to monitor structural integrity <sup>1</sup>
- Detection : comparison of recordings to a reference (undamaged) state
- Localization : Inverse Problem usually ill-posed
- Solution : Time-Reversal (TR) computational tool introduced by Fink et. al.<sup>2</sup>
- Achieves refocusing of the wave on the source
- Sending back the recorded signals but reversed in time

<sup>1.</sup> GE Stavroulakis, (2000) Inverse and crack identification problems in engineering mechanics 2. Fink et. al., (2000) Time-reversed acoustics

- TR is a physical process
- It exploits the time reversibility (based on spatial reciprocity and time reversal invariance) of linear wave equations
- Robust and Simple technique for source localization
- Has been applied in Acoustics<sup>3</sup>, Elastodynamics<sup>4</sup>, Electromagnetism, Hydrodynamics etc.
- Finds several applications in medicine, telecommunications, underwater acoustics, seismology, engineering structures, etc.
- Example of source localization in acoustic medium here

4. D Givoli, (2014) Time Reversal as a Computational Tool in Acoustics and Elastodynamics.

<sup>3.</sup> L Borcea, G Papanicolaou, C Tsogka and J Berryman, (2002) Imaging and time reversal in random media

- Two step approach :
  - Forward step : waves emitted from some source, travel through the medium and the response is recorded by receivers
  - Backward step : the recorded signals are time reversed and retransmitted
- Ideal Conditions :
  - receivers over the entire domain or it's entire boundary
  - recordings of the field variable and its derivatives
  - recordings during the whole experiment time T
  - absence of noise
- Difficulty : the refocusing time is unknown
- Procedure for the assessment of the refocusing time (stopping criterion)

- Scatterers act as secondary sources
- Emit at every passage of the original pulse
- Multiple in time sources
- Knowledge of the response in the reference (healthy) configuration
- Scattered field  $(p^{scat} = p^{tot} p^{ref})$  results better refocusing
- Example of defect localization in acoustic medium here

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### In the present work

- Description of the numerical implementation of TR
- Elastic medium
- $\bullet$  Bounded domain  $\Omega$
- $\bullet\,$  Excitation produced by  $\mathsf{N}_s$  point sources forming  $\Omega_s\subset\Omega$
- Response recordings at  $\mathsf{N}_r$  receivers forming  $\Omega_r\subset\Omega$
- $\bullet \ \Omega_r \cap \Omega_s = \emptyset \qquad \text{or} \qquad \Omega_r \cap \Omega_s \neq \emptyset \qquad \text{or} \qquad \underline{\Omega_r = \Omega_s}$
- Sensors may form an array or be distributed
- DORT method <sup>5</sup>, <sup>6</sup> for selective refocusing on multiple defect using the SVD of the Impulse Response Matrix

<sup>5.</sup> G Derveaux, G Papanicolaou and C Tsogka, (2007) Time reversal imaging for sensor networks with optimal compensation in time

<sup>6.</sup> E Barbieri and M Meo, (2010) Time reversal DORT method applied to nonlinear elastic wave scattering

### Introduction

#### 2 The time reversal process

3 Damage Identification

#### 4 Numerical implementation

#### 5 Conclusions

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- Simulated Numerically using a mixed finite element formulation <sup>7</sup>
- Wave propagation model Displacement - Stress (second order)

$$\rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} - \operatorname{div} \boldsymbol{\sigma} = \delta(\boldsymbol{x} - \boldsymbol{x}_s) f(t) \boldsymbol{e}_i$$
$$\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon}$$

strain - displacement relationship

$$\varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Velocity - Stress (first order)

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} - \operatorname{div} \boldsymbol{\sigma} = \delta(\boldsymbol{x} - \boldsymbol{x}_s) f(t) \boldsymbol{e}_i$$
$$A : \frac{\partial \boldsymbol{\sigma}}{\partial t} - \dot{\boldsymbol{\varepsilon}} = 0$$

strain rate - velocity relationship

$$\dot{\varepsilon}_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

• Homogeneous Dirichlet boundary conditions and zero initial conditions

- Always performed numerically in SHM applications
- Three alternative forms
  - a) imposed displacements at all  $m{x}_r$
  - b) appropriate initial conditions
  - c) sensors acting as sources introducing right hand side loading terms

$$\begin{split} \rho \frac{\partial \tilde{\boldsymbol{v}}}{\partial t} &-\operatorname{div} \tilde{\sigma} = \sum_{q=1}^{N_r} \delta(\boldsymbol{x} - \boldsymbol{x}_q) \boldsymbol{v}(\boldsymbol{x}_q, T - t), \qquad (\boldsymbol{x}, t) \in \Omega \times (0, T] \\ A &: \frac{\partial \tilde{\sigma}}{\partial t} - \dot{\tilde{\varepsilon}} = 0, \qquad (\boldsymbol{x}, t) \in \Omega \times (0, T] \\ \tilde{\boldsymbol{v}}(\boldsymbol{x}, t) &= 0, \qquad (\boldsymbol{x}, t) \in \partial\Omega \times (0, T] \\ \tilde{\boldsymbol{v}}(\boldsymbol{x}, 0) &= 0 \quad \text{and} \quad \tilde{\sigma}(\boldsymbol{x}, 0) = 0, \qquad \boldsymbol{x} \in \Omega \end{split}$$

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### Introduction

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#### 3 Damage Identification

4 Numerical implementation

#### 5 Conclusions

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• In every time step of the forward propagation



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# Multiple damaged areas

- DORT method imaging procedure for selective refocusing on different targets
- Fourier transform of the IRM P(t) to obtain  $\hat{P}(\omega)$
- Singular Value Decomposition (SVD) of  $\hat{P}(\omega)$  according to

 $\hat{P}(\omega) = U(\omega)S(\omega)V^*(\omega)$ 

• Projection of each column  $\hat{P}^{(l)}$  of the transformed IRM on the k-th singular vector as

$$\hat{P}_{k}^{(p)}(\omega) = \left(U_{k}^{*}(\omega)\hat{P}^{(l)}(\omega)\right)V_{k}(\omega)$$

 $\bullet$  Inverse Fourier transform of  $\hat{P}_k^{(p)}(\omega)$  to obtain  $P_k^{(p)}(t)$ 

 $\bullet\,$  Back-propagation of  $P_k^{(p)}(t)$  to achieve refocusing on one specific defect

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# Stopping Criterion

- Refocusing at the defect during the backward propagation
- The refocusing time is not a priori known
- Stopping criteria based on the minimization of some norm of appropriate field quantities
  - Shannon entropy
  - Bounded variation function of a field variable
  - Mathematical energy
  - Total energy

$$\mathcal{E}(t) = \frac{1}{2} \left( A \sigma, \sigma \right) + \frac{1}{2} \left( \rho v, v \right)$$

- Definition of the discrete energy density
- Normalization by its maximal value
- Computation of its L<sup>1</sup> norm

### Introduction

- 2 The time reversal process
- 3 Damage Identification
- 4 Numerical implementation

#### 5 Conclusions

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# Numerical example

- Geometry : rectangular domain  $L_x = 69.037$  mm and  $L_y = 62.747$  mm
- Mesh : 400  $\times$  400 grid with rectangular elements
- Material : steel with Lamé coefficients  $\lambda =$  96.95 GPa and  $\mu =$  76.17 GPa
- Velocities : pressure waves  $c_p = 5689.9 \text{ m/s}$  and shear waves  $c_s = 3145.2 \text{ m/s}$
- Array of 21 equidistant sensors that act as sources as well
- Two defects : one at  $(0.6L_x, 0.25L_y)$  of area 0.1 mm<sup>2</sup> and second  $(0.6L_x, 0.75L_y)$  of area 0.4 mm<sup>2</sup>
- $\bullet\,$  Damage is considered in the material by the degradation of both Lamé coefficients by 10  $\%\,$
- Excitation function : Ricker pulse with central frequency 1 MHz

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- Forward step and construction of the IRM
- Back-propagation of the field recorded when the source is on the central array element. Response time-history Refocusing
- SVD of the IRM
- Back-propagation of the field recorded when the source is on the central array element after projection on the singular vector corresponding to the
  - first singular value Response time-history Refocusing
    second singular value Response time-history Refocusing
    third singular value Response time-history Refocusing

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### Introduction

- 2 The time reversal process
- 3 Damage Identification
- 4 Numerical implementation

#### 5 Conclusions

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- Time reversal for damage localization in elastic bounded media
- Application of the DORT method for selective refocusing
- Choice of an effective stopping criterion (Total energy)
- Absence of notable differences between array and distributed sensor configurations
- Difficulties in the elastic medium due to the two types of waves (pressure and shear) and their conversions
- Difficulties due to the presence of boundaries

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- Extensive investigation of the distributed sensor configuration
- Propose optimal total experiment time
- Application of imaging techniques<sup>8</sup>
- Investigation of the methodology using passive noisy recordings as input data
- Account for dissipation (damping) and dispersion
- Application to structures with complex geometry

8. L Borcea, G Papanicolaou, C Tsogka and J Berryman, (2002) Imaging and time reversal in random media

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## Scattered field 20.3333 10 12 14 16 18 20 18 4 10 14 16 20

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## Scattered field 22.3333 10 12 14 16 18 20 **k** 18 4 14 16 20

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## Scattered field 23.6667 10 12 2 14 16 18 20 k 0 20 4 10 14 16 18

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#### Scattered field 24.3333 10 12 14 16 18 20 k 0 18 20 4 10 14 16

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#### Scattered field 25.6667 10 12 14 16 18 20 **k** 0 18 14 16 20

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# Scattered field

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20 k 0

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#### 28.3333 10 12 14 16 18 20 k 0 18 14 16 20

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Scattered field



#### Scattered field **k**

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#### Total field



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#### Scattered field



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#### Scattered field



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#### Total field



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TR in Elastodynamics for SHM

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- End of forward step
- Time reverse the recordings and rebroadcast



TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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t=7.8173e-07



TR in Elastodynamics for SHM

May 2015 28 / 35

t=1.5635e-06



May 2015 28 / 35

t=2.3452e-06



t=3.1269e-06



t=3.9086e-06



May 2015 28 / 35

t=4.6904e-06



t=5.4721e-06



TR in Elastodynamics for SHM

t=6.2538e-06



t=7.0355e-06



TR in Elastodynamics for SHM

t=7.8173e-06



t=8.599e-06



t=9.3807e-06



t=1.0162e-05



t=1.0944e-05



t=1.1726e-05



TR in Elastodynamics for SHM

t=1.2508e-05



t=1.3289e-05



t=1.4071e-05



t=1.4853e-05



t=1.5635e-05



May 2015 28 / 35

t=1.6416e-05



t=1.7198e-05



t=1.798e-05


# Backward step

t=1.8761e-05



TR in Elastodynamics for SHM

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# Backward step

t=1.9543e-05



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$$\mathcal{I}(\mathbf{y}) = \int_{0}^{T} \mathcal{E}(\mathbf{y}, t) \mathrm{d}t, \qquad \mathbf{y} \in \Omega$$



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TR in Elastodynamics for SHM

May 2015 29 / 35

t=3.9086e-07



TR in Elastodynamics for SHM

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t=1.1726e-06



TR in Elastodynamics for SHM

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t=1.9543e-06



TR in Elastodynamics for SHM

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t=2.736e-06



TR in Elastodynamics for SHM

May 2015 30 / 35

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t=3.5178e-06



TR in Elastodynamics for SHM

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t=4.2995e-06



TR in Elastodynamics for SHM

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t=5.0812e-06



TR in Elastodynamics for SHM

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t=5.8629e-06



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t=6.6447e-06



TR in Elastodynamics for SHM

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t=7.4264e-06



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t=8.2081e-06



Image: A math a math

t=8.9898e-06



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t=9.7716e-06



TR in Elastodynamics for SHM

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t=1.0553e-05



(日) (四) (三)

t=1.1335e-05



TR in Elastodynamics for SHM

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t=1.2117e-05



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t=1.2898e-05



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t=1.368e-05



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t=1.4462e-05



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t=1.5244e-05



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t=1.6807e-05



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t=1.9934e-05



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$$\mathcal{I}(\mathbf{y}) = \int_{0}^{T} \mathcal{E}(\mathbf{y}, t) \mathrm{d}t, \qquad \mathbf{y} \in \Omega$$



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TR in Elastodynamics for SHM

May 2015 31 / 35

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TR in Elastodynamics for SHM

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May 2015 32 / 35

t=1.5635e-06



TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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t=4.6904e-06



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TR in Elastodynamics for SHM

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Image: A math a math

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TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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t=1.6416e-05



Image: A math a math

t=1.7198e-05



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t=1.798e-05



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t=1.8761e-05



TR in Elastodynamics for SHM

(日) (四) (三)

t=1.9543e-05



(日) (四) (三)



$$\mathcal{I}(\mathbf{y}) = \int_{0}^{T} \mathcal{E}(\mathbf{y}, t) \mathrm{d}t, \qquad \mathbf{y} \in \Omega$$



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main

TR in Elastodynamics for SHM

May 2015 33 / 35

t=3.9086e-07



TR in Elastodynamics for SHM

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t=1.1726e-06



TR in Elastodynamics for SHM

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t=1.9543e-06



TR in Elastodynamics for SHM

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t=2.736e-06



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t=3.5178e-06



TR in Elastodynamics for SHM

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t=4.2995e-06



TR in Elastodynamics for SHM

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t=5.0812e-06



TR in Elastodynamics for SHM

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TR in Elastodynamics for SHM

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t=6.6447e-06



TR in Elastodynamics for SHM

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t=7.4264e-06



TR in Elastodynamics for SHM

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May 2015 34 / 35

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