Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

Improved Detection of Continuous AE Sources through Time-Reversed Signal Processing

Zuzana Dvořáková
(Joint work with **Jan Kober, Josef Krofta, Milan Chlada, Zdeněk Převorovský, Sigrun Hirsekorn**)

Institute of Thermomechanics, Czech Academy of Sciences

SPMS, 19 - 22 June 2025

Contents

- Green Function
- Basic Principle of Time Reversal Technique
- Principle of Localization by Time Reversal Technique
- Results of Experiment
    - Experiment 1 - thin metal plate
    - Experiment 2 - thick metal plate

Introduction

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

- localization of acoustic emission (AE) sources is a crucial task of AE monitoring in the field of Non-Destructive Testing (NDT) of materials
- classical algorithms based on differences in the signal arrival time and the triangulation method may completely fail e.g., in case of wave dispersion and/or high background noise
- efficient method to localize burst acoustic emission sources is the Time Reversal (TR) approach, but positioning of continuous AE sources is more difficult than locating burst AE sources
- simple Cross-Correlation Function (CCF) approach in the case of continuous AE sources is disputable, but CCF can be used in combination with other techniques
- we suggest the combination of CCFs and the above-mentioned TR method as a new procedure for the positioning of continuous AE sources in order to determine precisely the location of leakage (emitting random acoustic signals) on pipelines, vessels, etc.
- we compare the results with those achieved by using either only TR or only CCFs

Green function

- a simple source like unit impulse at $r = r_0$ (space position) and $t = \tau$ (time instant)
- the vector Green function G represents the displacement in general point (r, t), where $G_i(r, r_0; t, \tau)$ denotes the i-th component of this displacement
- the Green function satisfy the following equation

$$\frac{\partial^2 G}{\partial t^2} = \delta(r - r_0)\delta(t - \tau) + c^2 \nabla^2 G\,, \qquad (1)$$

under zero initial conditions

$$G(r, r_0; t, \tau) = 0, \qquad \text{for } t \leq \tau,$$
$$\frac{\partial G(r, r_0; t, \tau)}{\partial t} = 0, \qquad \text{for } r \neq r_0\,.$$

The solution of (1) can be found in the form

$$G(r, r_0; t, \tau) = \frac{1}{4\pi c^2} \frac{\delta(t - \tau - \frac{\|r - r_0\|}{c})}{\|r - r_0\|}\,.$$

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

Green function

If we have the source $s(t)$ instead of δ pulse, then the Green function is a solution of the following equation

$$\frac{\partial^2 G}{\partial t^2} = \delta(r - r_0)s(t) + c^2 \nabla^2 G \,, \tag{2}$$

again with zero initial conditions. Notice that

$$s(t) = \int_{-\infty}^{\infty} s(\tau)\delta(t - \tau)\mathrm{d}\tau \,,$$

thus, it follows that the resolution of the equation (2) is given by

$$G(r, r_0; t, \tau) = \frac{1}{4\pi c^2} \frac{s(t - \tau - \frac{\|r - r_0\|}{c})}{\|r - r_0\|} \,.$$

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

Time Reversal Technique - Basic Principle & Deconvolution by TR

INSTITUTE OF THERMOMECHANICS
Czech Academy of Sciences

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

- point source $s(t)$ at position r_0 and receiver at position r_i
- measured signal

$$s_G(t) = s(t) * G(r_i, r_0; t, 0), \quad \text{for } t \in [0, T]$$

- time reversation of measured signal

$$s(T - t) * G(r_i, r_0; T - t, 0)$$

- at the position r_0

$$\tilde{s}(t) = s(T - t) * G(r_i, r_0; T - t, 0) * G(r_0, r_i; t, 0)$$

- after calculation

$$\tilde{s}(t) = \frac{1}{16\pi \|r_i - r_0\|^2} s(t) = a \cdot s(t)$$

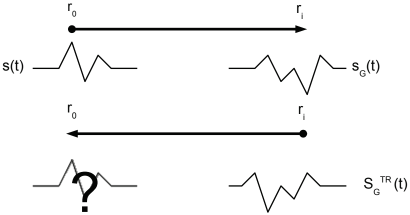
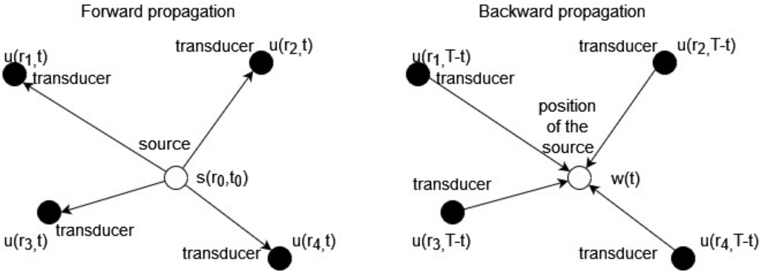


Figure: Scheme of TR process

Localization continuous AE by Time Reversal Technique



1. signals measured by transducers $u(r_1, t), u(r_2, t), u(r_3, t), u(r_4, t)$
2. sending time reversed signals back
   $u(r_1, T - t), u(r_2, T - t), u(r_3, T - t), u(r_4, T - t)$
3. at the roughly estimated AE source position $w_1(t), w_2(t), w_3(t), w_4(t)$
4. calculation of the cross-correlation functions (CCFs)

$$C_{ij} = w_i(t) \star w_j(t), \quad i = 1, \ldots, 4, \quad j = 1, \ldots, 4, \quad i < j.$$

Experiment 1

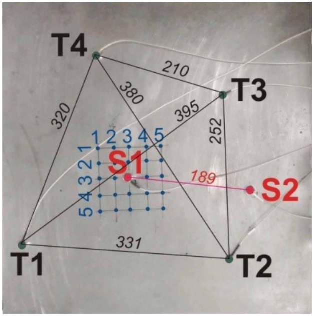


Figure: *Steel plate 500 x 500 x 45 mm^3, the positions of four DAKEL IDK 09 transducers* T1 *to* T4*, and the positions of two excitations of artificial AE sources, $S1$ and $S2$ ($S1$ preferably used).*

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

Experiment 1 - Direct signals + CCF

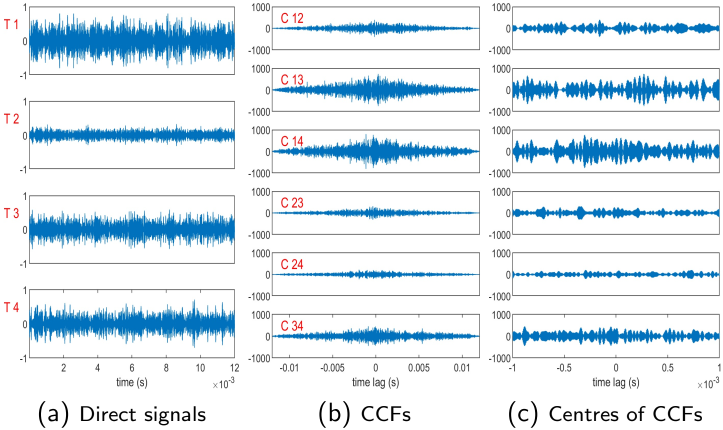
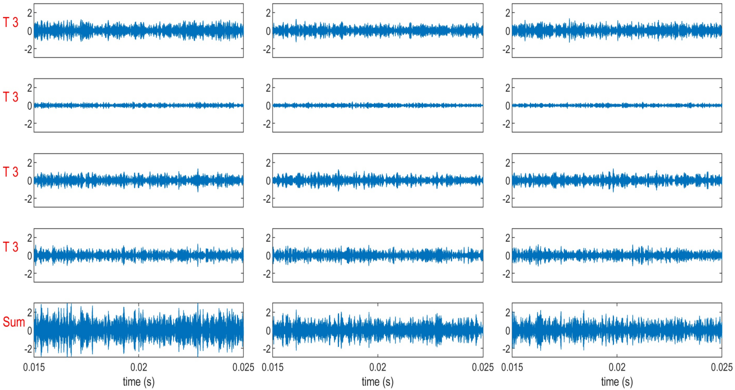


Figure: *Direct signals from the leakage noise source at $S1$ recorded by the four transducers at* T1 *to* T4, *CCFs of all six combinations of two signals $C12$, $C13$, $\ldots$, $C34$, and their zoomed centres around zero lag.*

Experiment 1 - TR signals

INSTITUTE OF THERMOMECHANICS
Czech Academy of Sciences



(a) At signal source (b) 25 mm from $S1$ (c) 50 mm distant from $S1$

Figure: *Time reversed signals picked up by transducers* T1 *to* T4 *at the signal source position* $S1$ *and at positions of 25 mm and 50 mm distant from the source* $S1$*. The fifth line in each column represents the sum of the four TR signals above.*

Experiment 1 - CCFs of TR signals

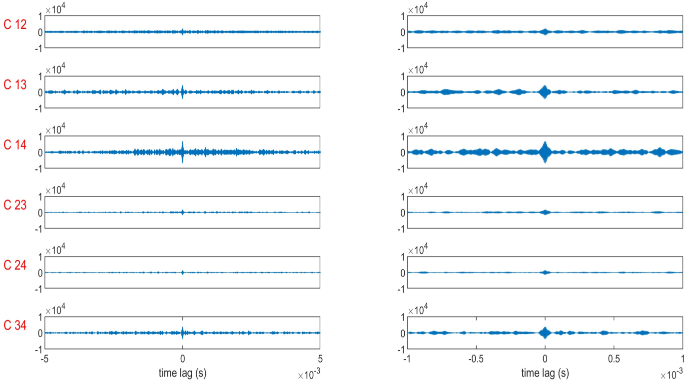
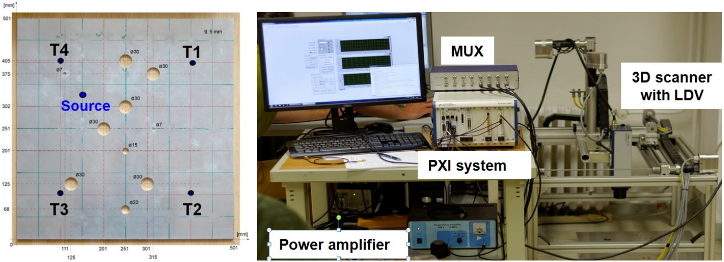


Figure: *(left column) CCFs of all pairs of the TR signals picked up at the source position $S1$. (right column) CCFs zoomed-in around zero lag.*

Experiment 2



(a) The Al sample.   (b) Experimental setup.

Figure: *Sample experimental setup - Al plate of 501 x 501 x 5 mm^3 with circular holes, the position of the artificial AE acoustic source and the positions* T1 *to* T4 *of the four identical broadband transducers are indicated.*

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

Experiment 2 - Signals

INSTITUTE OF THERMOMECHANICS
Czech Academy of Sciences

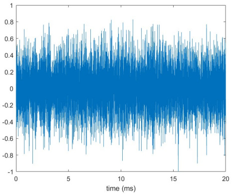


Figure: *Original signal transmitted by the source.*

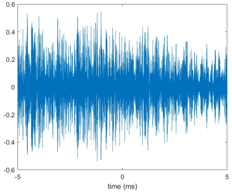


Figure: *Central part of backpropagated signal.*

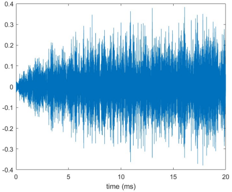


Figure: *The first signal received at the transducer.*

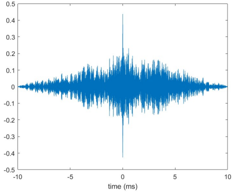


Figure: *CCF of TR reconstructions from two transducers.*

Experiment 2 - Results

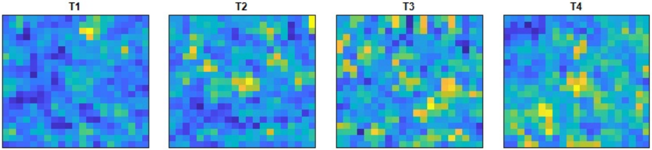


Figure: *TR reconstructions of continuous noise source signals (no indication of the source position).*

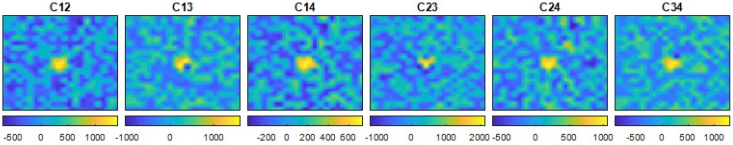


Figure: *Maxima of the CCFs of TR reconstructions of the continuous noise source signal from the six possible pairs of the transducers at* T1 *to* T4 *within the* $30 \times 30\,\text{mm}^2$ *scanning area.*

Conclusions

INSTITUTE OF THERMOMECHANICS
Czech Academy of Sciences

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

- short pulse AE sources require only one transducer to provide precise TR reconstructions of the burst signal at its source in time and space
- continuous random noise sound sources can be located only by cross-correlation functions of TR reconstructions of the source signal of at least two transducers recording simultaneously the source signals at two different positions
- precise sound source localization requires a detailed scanning of the area around the roughly pre-localized source (e.g. by a scanning laser interferometer)
- compared to other techniques (methods based on differences in the signal arrival time, the triangulation method), AE signal processing based on the TR procedure is the most precise method of sound source localization
- our results were published in Insight - Non-Destructive Testing and Condition Monitoring, The Journal of The British Institute of Non-Destructive Testing in March 2025

Introduction
Green function
Basic principle of TR
TR localization
Experiment 1
Experiment 2
Signals in exp.
Conclusion

Thank you for your attention.

Would you like to work with our the NDT team at Academy of Science?

Contact me: **Zuzana.Dvorakova@it.cas.cz**