Contactless dependance interactive objects

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Introduction

The time reversal process (TR) developed in our laboratory [1] allows to evaluate the time reversal invariance of wave propagation equations in various isotropic or anisotropic, homogeneous or heterogeneous media, with simple or multiple scattering, with infinite or finite dimension and simple or complex geometry. Except in the case of media with matter flow, this invariance is observed, even in the presence of low attenuation.

In the particular case of a finite medium, experimental results show that the acoustic signature contains the whole information relative to the corresponding source (temporal and spatial shape), even using a single receiver [2]. Thus it is possible to refocus an acoustic wave in a finite medium to its original source using a unique transducer, with a spatial resolution that can reach half the wavelength.

The source localization technique [3] presented in this paper is based on this uniqueness of the acoustic signature. It can be enhanced in order to compensate the temporal excitation of the source.

Acoustic source localisation by correlation

Considering a point-like source located at r_i and a point-like receiver at r_1, the impulse response can be written in the frequency domain as (in all the following, the explicit dependence with frequency f is omitted)

$$R(r_1, r_i) = C(r_1) H(r_1, r_i) E_i(r_i) \tag{1}$$

where R describes the reception function at r_1, C is the transfer function of the receiver, H the impulse response of the propagation medium (Green's function) and E_i the excitation function at r_i.

The acoustic source localisation technique is based on the correlation of the measured signals with those (known by simulation or learning phase) corresponding to particular locations r_i. As shown below, such correlation is equivalent to a time reversal experiment. Based on the assumption that the acoustic signature is unique, the correlation technique allows to identify any new active source in the medium of interest.

For two sources located at r_i and r_j with excitation functions E_i and E_j respectively, the correlation of the received signals at r_1 is (* denotes the complex conjugation)

$$C_{1ij} = R(r_1, r_i) R(r_1, r_j)^* \tag{2}$$

Using the reciprocity $H(r_1, r_i) = H(r_i, r_1)$, we obtain from eqs. (1) and (2)

$$\begin{aligned} C_{1ij} &= |C(r_1)|^2 H(r_1, r_i) H(r_1, r_j)^* E_i(r_i) E_j(r_j)^* \\ &= |C(r_1)|^2 H(r_i, r_1) H(r_1, r_j)^* E_i(r_i) E_j(r_j)^* \end{aligned} \tag{3}$$

Ignoring the term $E_i(r_i)$, this expression represents the signal observed at r_i if we time reverse at r_1 the measured signal generated by a source at r_j. The term $E_i(r_i)$ can be neglected if we consider a wide-band temporal excitation (like a delta function).

In a finite medium, $H(r_i, r_1)$ and $H(r_1, r_j)$ generally differ due to the multiple reflections ; more generally, they can also differ due to scattering or complex paths in heterogeneous media. Consequently, for a given frequency the phases of these two functions f differ if $r_i \neq r_j$. When $r_i = r_j$ we have

$$C_{1ij} = |C(r_1)|^2 |H(r_1, r_i)|^2 E_i(r_i) E_j(r_j)^* \tag{4}$$

The resulting correlation reduces to the correlation of the excitation functions, weighted by $|C(r_1)|^2 |H(r_1, r_i)|^2$. In the time domain, the maximum amplitude of the correlation is high only if the phase difference between the excitation functions is zero or proportional to frequency. Otherwise, the components for different frequencies do not interfere in a constructive manner when back to the time domain.

It results therefore that the temporal shape of the excitation function is important in acoustic source localisation. It is essential to get a formulation of the correlation that does not depend on the phase of this excitation function. To reach this objective, we use a second receiver, whose measured signals are correlated with those of the first receiver. $R(r_2, r_i)$ now corresponds to the signal measured by the second receiver located at r_2 and $C_{12i}(r_i)$ the correlation between the signals measured by the two receivers at r_1 and r_2 for a source at r_i. We have

$$C_{12i}(r_i) = C(r_1) C(r_2)^* H(r_1, r_i) H(r_2, r_i)^* |E_i(r_i)|^2 \tag{5}$$

Any new source located at r_j can be localised by correlating correlation between the two received signals with the same quantity evaluated for a predefined excitation at r_i:

$$\begin{aligned} C_{12ij} &= |C(r_1)|^2 |C(r_2)|^2 H(r_1, r_i) H(r_2, r_i)^* \times \\ &\quad H(r_1, r_j)^* H(r_2, r_j) |E_i(r_i)|^2 |E_j(r_j)|^2 \end{aligned} \tag{6}$$

This last expression shows that the results now only depend on the medium itself, weighted by the bandwidths of the excitation sources and receivers. In the time domain, the maximum amplitude of this correlation is high only if the phase of the product $H(r_1, r_i) H(r_2, r_i)^* H(r_1, r_j)^* H(r_2, r_j)$ is zero ; this happens if $r_i = r_j$.

Experimental results

Figure 1 illustrates the glass plate (400 x 300 x 4 mm^3) on which two piezo-electric receivers are glued. The glass plate lies on a heavy wood plate with an elastomer coupling layer of 5 mm width and 1 mm height. The reception functions have been measured for sources located on a rectangular matrix with a step of 1 cm along the two spatial directions, using an automatic 3D motorized system and a small needle mounted on a vibrating pot. The analyzed bandwidth is between 1500 Hz and 8 kHz.

Figure 2 shows four correlation images corresponding to an impact on the center of the glass plate. Figures 2a and 2c show the corresponding correlations obtained from eqs. (6) and (3), evaluated in the time domain. All measurement signals are normalized in energy, and each image pixel represent a maximum value of the correlation computed in the time domain. Figure 2a shows similar results as 2c, except some side lobes that are higher in amplitude. This is due to the product of the frequency spectrum of the experimental signals on both receivers, that highly reduces the effective bandwidth. To remedy to this problem, eqs. (3) and (6) can be normalized (in complex modulus), thus resulting in a phase correlation only. Figures 2b and 2d show the corresponding results. We clearly observe some similar results in terms of the maximal amplitude of side lobes, but also a more narrow focusing spot.
Remark: to make comparable the results of the two methods – named "classical" and "new" respectively - the correlations obtained from the "classical" method obtained from experimental signals of both receivers are averaged.

Table 1 shows the correlations obtained with various types of impacts. The reception functions are first experimentally determined for 20 arbitrary different impact positions r_i using a pen biro. Then we generate new impacts at the same positions using different impact tools, and the corresponding signals are correlated with those resulting from the previous learning phase. We clearly observe that the results of the "new" technique does not depend on the nature of the impact tool, and the correlation remains stable. Rubbing the pen biro on the glass plate near the reference positions, we obtain a correlation coefficient of 50%, while the "classical" method yields a coefficient of approxima-tively 22%, that corresponds to the mean average value of the side lobes level.

Conclusion

In this paper, a correlation imaging method has been presented, that allows to obtain images in complex media of finite dimension. The inconvenient of this method is that the images we obtain depend i) on the reception functions of the medium when these are experimentally obtained, ii) on the temporal shape of the source to be localised.
The "new" method removes these two difficulties, and allows to apply the correlation technique to the real time tracking of a moving source.

References

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[3] R. K. Ing, N. Quieffin, S. Catheline and M. Fink, "In solid localization of finger impacts using acoustic time-reversal process", Appl. Phys. Lett. 87, 204104, 1-3 (2005).

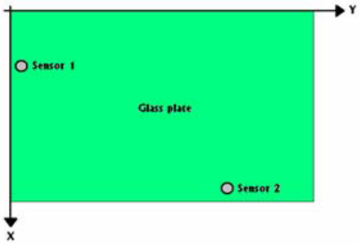

Figure 1: Geometry of the problem.

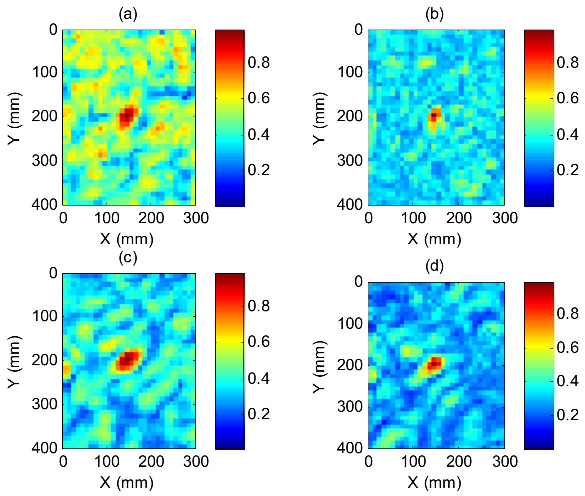

Figure 2: Correlation images from the "new" and "classical" processing techniques.

	Pen biro	PDA stylet	Finger nail	Pulp finger (1)	Pulp finger (2)	Wooden tool	Stainless steel knife	Pen biro friction
"New" processing technique	100 %	92 %	99 %	98 %	98 %	91 %	97 %	50 %
"Classical" processing technique	100 %	63 %	79 %	72 %	74 %	53 %	66 %	22 %

Table 1: Phase correlation results for various tools of realization of impacts