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# In solid localization of finger impacts using acoustic time-reversal process

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Time reversal in acoustics is a very efficient solution to focus sound back to its source in a wide range of materials including reverberating media. It expresses the following properties: A wave still has the memory of its source location. The concept presented in this letter first consists in detecting the acoustic waves in solid objects generated by a slight finger knock. In a second step, the information related to the source location is extracted from a simulated time reversal experiment in the computer. Then, an action (turn on the light or a compact disk player, for example) is associated with each location. Thus, the whole system transforms solid objects into interactive interfaces. Compared to the existing acoustic techniques, it presents the great advantage of being simple and easily applicable to inhomogeneous objects whatever their shapes. The number of possible touch locations at the surface of objects is shown to be directly related to the mean wavelength of the detected acoustic wave. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2130720]

Draeger[1] experimented the time reversal invariance of acoustic waves in chaotic cavities. In this experiment, an ultrasonic pulse is sent from a transducer (the source) and propagates inside a silicon plate. The acoustic trapped energy is reverberated a very long time. The acoustic field, measured on a second transducer (the receiver) lasts hundreds of times the initial pulse duration. This long and complex field is then time reversed and re-emitted from the receiver. The acoustic field is shown to propagate back to the source, recreating the short initial pulse. This experiment, transposed in the audible frequency range, is shown to be an efficient localizing technique.

In the following interactive experiment, the source transducer used in the ultrasonic experiment is replaced by a mechanical impact at the surface of an object. Once the impact position is determined, any corresponding action is executed. For example, a virtual keyboard can be drawn on the surface of an object; the sound made by fingers when a text is captured, is used to localize impacts. Then, the corresponding letters are displayed on a computer screen.

In the following example, the sound propagates through a glass plate, with the dimensions $400 \times 300 \times 5$ mm$^3$. The receiver is a passive sensor (Murata PKS1-4A type), with a working bandwidth ranging from 0.1 to 5 kHz. The sensor is glued next to one side and connected to the input line of a personal computer, 700 MHz with a 256 Mo random access memory. Typically, 100 ms acoustic signals are digitized by a standard sound card, with a 44.1 kHz sampling rate, and a 16-bit dynamic. This signal can mathematically be expressed as a convolution product between the emitted signal $e(t)$ from the touched point $P$, and the impulse response to the sensor $S, h_{PS}(t)$:

$$S(t) = e(t) \otimes h_{PS}(t). \tag{1}$$

Since the touch is brief enough in consideration with the working frequency bandwidth, the emitted signal can be approximated to a delta function $\delta_P(t)$. Thus, Eq. (1) becomes:

$$S(t) \cong h_{PS}(t). \tag{2}$$

It means that the signal measured by the sensor is simply the impulse response between points $P$ and $S$.

The first step of the experiment is a training step. At the surface of the plate, a $35 \times 28$ "tactile points" are chosen on the nodes of a 1 cm square grid, Fig. 1. These 980 tactile points $P_i$ are sequentially knocked; $i = 1, \ldots, 980$ is defined as the point index. The corresponding impulse responses, $h_{P_iS}(t)$, detected by the sensor are recorded in the computer.

In a second use step, as one of the previous points is knocked again, say $P_j$, the new impulse response $h_{P_jS}(t)$, is transferred to the computer. Then, a time reversal experiment is processed in the computer. The new impulse response is time reversed and virtually reemitted by the sensor as if it

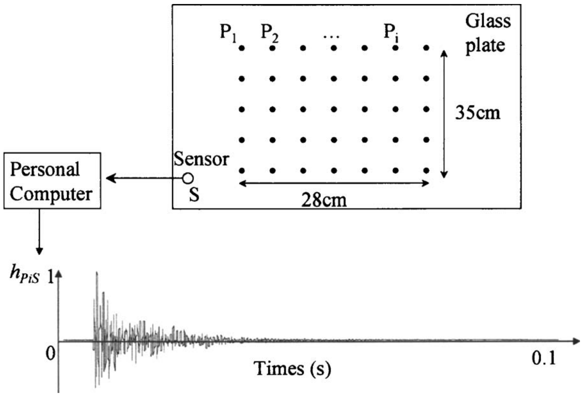

FIG. 1. Training step of a time reversal interactive experiment. Tactile points in a $35 \times 28$ matrix are sequentially knocked on a glass plate. Detected by a sensor S, 980 acoustic signals $h_{P_iS}(t)$, are stored in the computer memory.

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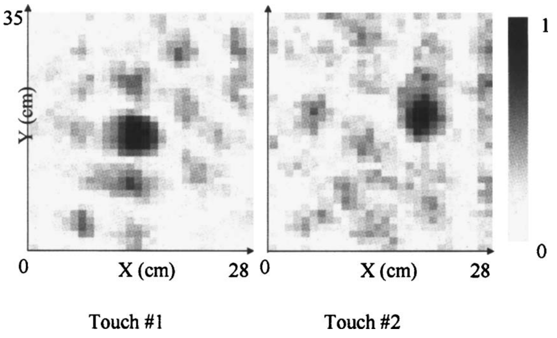

FIG. 2. During the use step, the signal from a new touch impact is correlated to the acoustic signals recorded in the training step. On the correlation map, the localization of two touch impacts clearly appears as black dots.

was able to act as a source. The acoustic field $S_i(t)$ that would be observed with sensors on points $P_i$ is deduced from Eq. (1) where the emitted signal $e(t)=h_{PjS}(-t)$:

$$S_i(t) = h_{P\,j\,S}(-t) \otimes h_{P\,i\,S}(t). \tag{3}$$

The field $S_i(t)$ is entirely computed in software. It is indeed a correlation of impulse responses with a maximum when $i=j$. This is a consequence of the reversibility property of the wave equation which implies that a maximum of energy is found on the point where the source was. From another straightforward point of view, the correlation can be interpreted as a recognition processing that does identify the touched point among the reference signals.

This is illustrated on the normalized correlation map (i.e., the focusing acoustic pattern) represented on a grey scale, Fig. 2. Black dots indicate a correlation coefficient bigger than 0.95 whereas white areas correspond to a correlation coefficient smaller than 0.55. The technique can clearly localize the two touch impacts, moreover in real time since the whole computation in this example takes 20 ms.

Figure 3 represents the correlation coefficient along a line of Fig. 2 at $Y=17$ cm. The impact point is centered at $X=14$ cm. Such focusing patterns of acoustic waves involving time reversal technique have been described quantitatively in numerous papers.[2,3] Its −3 dB width and the maximum peak to ground level ratio are the two main characteristics. They define the resolution and the contrast respectively. The resolution is highly related to the question of the maximum number of tactile points. Indeed, it sets a boundary limit between points having different acoustic signatures with a correlation coefficient smaller than an arbitrary value chosen here at 0.7 (−3 dB). In other words, it defines a resolution surface.

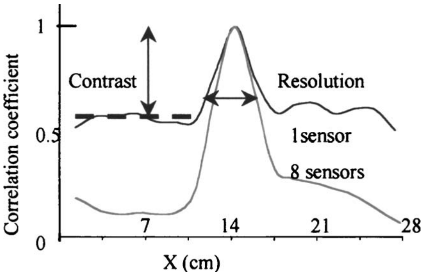

FIG. 3. Typical normalized correlation pattern centered on a touched point at 14 cm. Compared to a single sensor, using eight sensors mostly improve the contrast.

The acoustic energy mostly propagates as antisymmetric Lamb waves and more precisely as flexural waves for low value of the frequency-thickness product. In this experimental configuration, the flexural wave speed, absorption time, and wavelength at a 4 kHz frequency range are ≈230 ms$^{-1}$, ≈25 ms, ≈5.7 cm, respectively. The latter figure is almost twice the −3 dB width observed in Fig. 3. This is in perfect agreement with the diffraction theory, stating that the resolution limit is reached when the −3 dB width equals half of the wavelength. Indeed, thanks to multiple reflections on boundaries (more than 30 in the plate experiment), there is a whole set of virtual sensors surrounding the focal spot and responsible for its shape (cylindrical symmetry) and its width (one-half of a wavelength). This observation is crucial since it states that the surface of resolution can be deduced from the flexural wavelength estimate $\lambda_F$. Theoretically, this latter value depends on the central frequency, the width, the transverse, and compression sound speeds of the plate. As a consequence, the maximum number of tactile points increases with the surface of the object (which is obvious) and with the frequency whereas it decreases with thickness. It may be noted that dispersive effects of the flexural wave improve the efficiency of the localization.[4]

The question of the number of receivers in time reversal experiments has been extensively studied on a wide class of multiple scattering media as well as in parallel steel rod immersed in water,[5] two-dimensional silicon wafer,[6] or reverberant room.[7] In order to investigate this question in time reversal interactive experiments, we used a Soundscape system (SS810-3 type). Simultaneous acoustic fields on different points (up to eight receivers) could be recorded. The contrast increases but the resolution remains unchanged by adding sensors. The contrast enhancement can be explained by the superposition principle: When $N$ emitters focus their energy on the same point, the amplitude on the focal point is the sum of the amplitudes of each individual emitter. Since the resulting acoustic field of each individual emitter is uncorrelated, the amplitude increases according to the square root of the number of emitters everywhere else. The resulting contrast is the ratio of the amplitude on the focal point and the average amplitude elsewhere that is to say $N/\sqrt{N}=\sqrt{N}$. The reciprocity property of the wave equation stipulates that the same result applies to the number of receivers. Indeed, from Fig. 3, the contrast with eight sensors, ≅4.9, is roughly $\sqrt{8}$ times better than the estimation of the contrast with one sensor, ≅1.8. As far as the resolution is concerned, no improvement is expected in nicely reverberating objects. However, for weak reverberating media, the focal spot only partially surrounded by virtual sensors, may lose its cylindrical symmetry and be enlarged. Adding sensors in such situation can help to improve the resolution.

In this letter, a new acoustic time reversal technique has been proposed to transform most of everyday life objects as interactive interfaces. It appears that the number of tactile points is dependent on the mean wavelength of acoustic waves involved in the experiments. Since in numerous cases the acoustic energy propagates as flexural waves, the tactile points are centimeter sized, which is ideal for finger uses. A single receiver is sufficient for localizing impacts, but others can be added to improve the correlation map contrast.

Compared to time-of-flight techniques, the time reversal technique presents the great advantage of being efficient in most solids where sounds propagate, without any knowledge of sound speed or receiver positions. Moreover, the technical and processing requirements make the experiment possible in real time with a basic personal computer.

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[1] C. Draeger and M. Fink, Phys. Rev. Lett. **79**, 407 (1997).
[2] D. Cassereau and M. Fink, Acoust. Imaging **19**, 141 (1991).
[3] N. Quieffin, S. Catheline, R. K. Ing, and M. Fink, J. Acoust. Soc. Am. **115**, 1955 (2004).
[4] R. K. Ing and M. Fink, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **45**, 1032 (1998).
[5] A. Derode, A. Tourin, and M. Fink, J. Acoust. Soc. Am. **85**, 6343 (1999).
[6] C. Draeger and M. Fink, J. Acoust. Soc. Am. **105**, 611 (1999).
[7] S. Yon, M. Tanter, and M. Fink, J. Acoust. Soc. Am. **114**, 3044 (2003).