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Impact detection in anisotropic materials using a time reversal approach

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Abstract

This paper presents an *in-situ* imaging method able to detect in real-time the impact source location in reverberant complex composite structures using only one passive sensor. This technique is based on the time reversal acoustic method applied to a number of waveforms stored in a database containing the impulse response (Green's function) of the structure. The proposed method allows achieving the optimal focalization of the acoustic emission source in the time and spatial domain as it overcomes the drawbacks of other ultrasonic techniques. This is mainly due to the dispersive nature of guided Lamb waves as well as the presence of multiple scattering and mode conversion that can degrade the quality of the focusing, causing poor localization. Conversely, using the benefits of a diffuse wave field, the imaging of the source location can be obtained through a virtual time reversal procedure, which does not require any iterative algorithms and a priori knowledge of the mechanical properties and the anisotropic group speed. The efficiency of this method is experimentally demonstrated on a stiffened composite panel. The results showed that the impact source location can be retrieved with a high level of accuracy in any position of the structure (maximum error was less than 3%).

Keywords: time reversal, imaging method, acoustic emission localization, complex composite structures.

1 Introduction

The growing use of composite materials in aerospace structures has attracted much interest to the development of real-time, accurate and cost-effective ultrasonic structural health monitoring (SHM) systems for the localization of impact points due to their poor impact resistance properties. Traditionally, the estimation of the acoustic emission (AE) source is achieved by optimization methods based on *wave propagation* approaches. These techniques can be employed for both isotropic [1, 21] and anisotropic [13, 14] materials and are usually divided in two steps. First, the time of arrival (TOA) of the stress waves is measured by a network of transducers and the signals are evaluated through a suitable time-frequency analysis. Then, a resolution algorithm is used to convert this information into the impact location [19]. However, these methods require a relatively large number of transducers, especially in composite materials, wherein the group velocity is not constant but dependent of the frequency and the heading angle [$V_g = V_g(f, \theta)$] [26]. Moreover, only the coherent part of the wavefield that arrives first to the sensors (ballistic wave) is used, regardless the contribution of multiple scattering and reflection from the boundaries (known from seismology as coda). In fact, the dispersive characteristics of guided Lamb waves in thin plate-like structure and the presence of scatterers as rivets, holes and stiffeners, can alter the resulting signal, leading to a wrong estimation of the TOA. That is, the wave field of complex structures excited over a finite frequency band is incoherent diffuse [7]. In fact, a fully diffuse wave field is characterized by a superposition of modes having the same

level of energy (“equipartition principle”) and uncorrelated random amplitude, phase and direction of propagation [24].

Nevertheless, the propagation of AE can be described as a linear system with different impulse responses. When an impact is applied on a generic point of the structure, the impulse response (Green’s function) can be retrieved from the correlation of the reverberant diffuse wave field at the sensor location [2, 6, 11, 23]. This concept was widely used in seismology and civil applications, and only recently it was examined through a time reversal process (TRP). Due to the time invariance and spatial reciprocity of linear wave equation, in a time reversal acoustic (TRA) experiment, an input signal can be focused back on the original source if the output received by a set of transducers, is time-reversed and emitted back to the excitation point. TRA behaves as a spatio-temporal matched filter that maximizes the ratio between the amplitude of the output and the square root of the energy of the input [4]. However, a perfect localization would require a totally covering array of sensors (closed cavity), which is impossible to obtain in practise. Hence, the closed cavity is usually replaced by a time reversal mirror (TRM) of finite aperture and bandwidth that limits the focus quality. However, it was demonstrated by Derode et al. [3] that the reverberations of a diffuse wave field in a complex medium improve the spatial resolution of the focusing. From a physical point of view, the presence of scatterers within the medium allows the evanescent waves to propagate in the far field, where the TRM is located. These modes, carrying the information of the AE source, can participate to the focusing process [8]. Therefore, the angular aperture of the sensor array is virtually enhanced (kaleidoscopic effect) and the number of sensors of the TRM can be drastically reduced. The limit case was illustrated by Draeger and Fink [5], where all the information where recorded by only one sensor

bonded in a highly reverberant closed cavity of silicon wafer showing ergodic properties and negligible absorptions. Time reversal process has also been widely used in medical applications and non-destructive evaluation (NDE) techniques like pulse-echo methods for damage detection in pipes [9] and in both aluminium [22, 25] and quasi-isotropic composite [15] structures.

The layout of the paper is as follow: in Section 2 the algorithm for the imaging of the impact location using a time reversal approach is presented. Section 3 reports the experimental set-up whilst Section 4 illustrates the imaging results. Then, the conclusions of the method adopted are discussed.

2 One-channel impact localization algorithm using time-reversal

This paper reports a one-channel imaging method of the AE source (impact event) in geometrically complex anisotropic media with diffuse field conditions (Fig. 1). The proposed technique is aimed to overcome the limitations of most impact detection methods and to obtain the optimal focusing of the source in real-time, by using only one passive sensor placed on a generic point of the structure (focusing plane). The methodology was divided in two steps. In the first step, the impulsive responses of the structure were acquired and stored into a computer. Then, exploiting the benefits of multimodal conversion and scattering effects, a simulated time reversal experiment was carried out in order to obtain the optimal refocusing. To validate this method, a number of experiments on a carbon-fibre composite panel reinforced with stiffeners and connected with rivets were carried out.

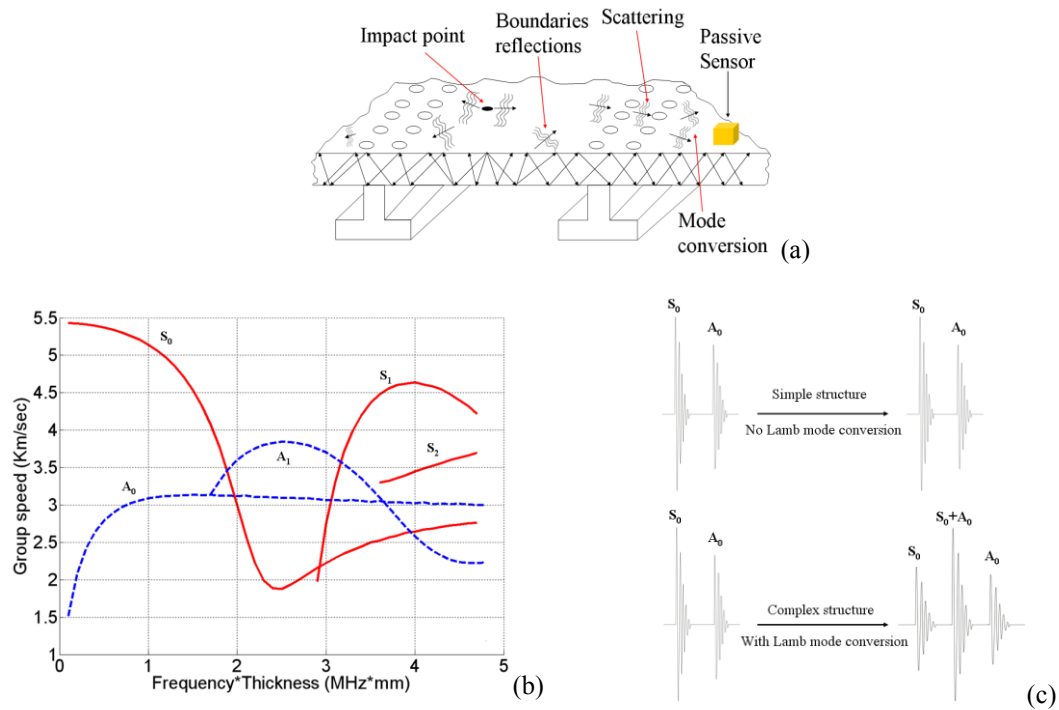


Figure 1 (a) (b) (c) Complex structure with diffused wave field conditions (a), dispersion curves for a quasi-isotropic composite plate with 3mm of thickness (b) and the effects of mode conversion for the fundamental Lamb waves in complex structures (c).

The idea of using the time reversal concept for impact detection was originally developed by Ing et al. [10] for the detection of a finger knock on a glass plate. Then it was used for the source localization in open spaces [17] and wireless communication systems [12]. Here, we apply TRA for acoustic emission source identification in SHM systems with complex anisotropic structures. According to [10], the experimental process was divided in two steps. Initially, the structure was entirely divided in $M = 50 \times 15$ “observation points” distributed along a grid at interval of 2 cm. At each point, the acoustic emission was generated by impact loads. (Fig. 2).

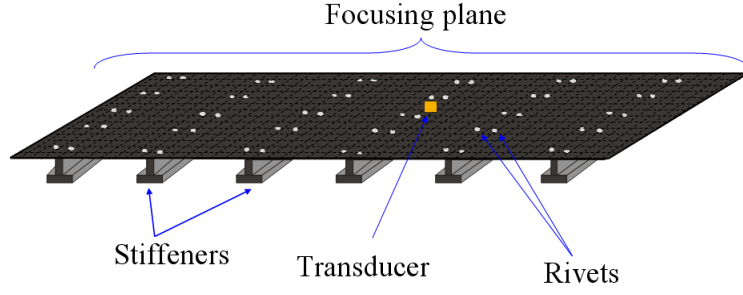


Figure 2 Experimental set-up

Due to linearity, the acoustic field measured by the transducer from the m^{th} observation point is:

$$f(t) = \sum_{m=1}^M \mathbf{h}_m(t) \otimes \mathbf{e}_m(t) = \int_{-\infty}^{\infty} \sum_{m=1}^M \mathbf{h}_m(\tau) \mathbf{e}_m(t - \tau) d\tau \quad (1)$$

where the symbol “ \otimes ” represents a temporal convolution and $\mathbf{h}_m(t)$ ($1 \leq m \leq M$) is the linear propagator operator defining the Green’s function measured by the sensor. This term includes all the propagation effects through the medium from the m^{th} observation point to the receiver (included its acoustic-electric response). $\mathbf{e}_m(t)$ is the column vector of the input signal sent by the m^{th} source on the focusing plane and $f(t)$ is the output signal measured by the transducer at each instant in time. In the frequency domain, equation (1) is:

$$F(\omega) = \sum_{m=1}^M \mathbf{H}_m(\omega) \mathbf{E}_m(\omega) \quad (2)$$

which can be written in matrix form as:

$$\underbrace{F(\omega)}_{1 \times 1} = \underbrace{\mathbf{H}_m(\omega)}_{1 \times M} \underbrace{\mathbf{E}_m(\omega)}_{M \times 1} \quad (3)$$

where the matrix $\mathbf{H}_m(\omega)$ is the transfer function of the system (Fourier transform of the Green’s function) and represents the amplitude of the i -th guided Lamb mode associated to the i -th eigenfrequency. For the spatial reciprocity condition, the transpose of \mathbf{H}_m

(\mathbf{H}_m^T) corresponds to the propagation between the transducer and the observation points (Fig. 3):

$$\mathbf{E}_m(\omega) = \mathbf{H}_m^T(\omega)F(\omega) \quad (4)$$

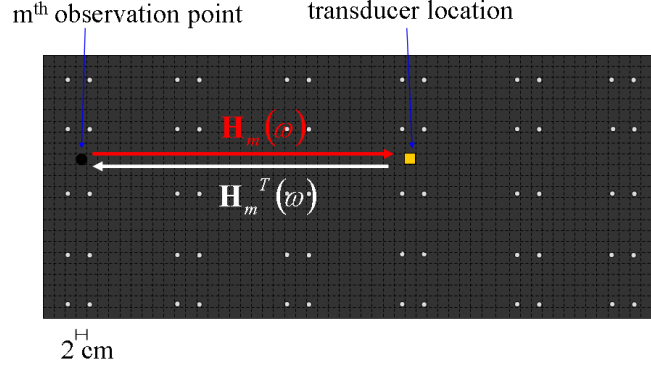


Figure 3 Schematic outline of the propagator operator

Hence, the M signals representing a library of impulse responses $\mathbf{H}_m(\omega)$ of the structure were recorded by the transducer and stored.

The second step consisted in recognition of the optimal refocusing procedure at the source location. The basic idea was to time reverse not only the Green's function associated to the AE source, but also to the neighbouring points (observation points). Thereby, a new impact was applied in one of the points (of unknown location) of the focusing plane and its impulse response was measured by the sensor. Assuming that the impact source in the second step is located at m_0 , the input column vector $\mathbf{e}_{m_0}(t)$ from the m^{th} observation point can be mathematically approximated to a temporal delta function $\delta(t)$ only when $m = m_0$. In the frequency domain, the emitted signal is $\mathbf{E}_{m_0}(\omega) = \{0, \dots, 0, 1, 0, \dots, 0\}$. According to (3), the wave field received by the transducer is:

$$F_{m_0}(\omega) = \mathbf{H}_{m_0}(\omega)\mathbf{E}_{m_0}(\omega) \quad (5)$$

and the Time Reversal (TR) operation of the Green's function $[\mathbf{h}_{m0}(-t)]$ in the time domain is equivalent to taking its complex conjugate in the Fourier domain. Hence, time reversing the spectrum of the transducer output, we have:

$$F_{m_0}^*(\omega) = \mathbf{H}_{m_0}^*(\omega) \mathbf{E}_{m_0}^*(\omega) = \mathbf{H}_{m_0}^*(\omega) \mathbf{E}_{m_0}(\omega) \quad (6)$$

where the superscript '*' denotes complex conjugate and $\mathbf{E}_{m_0}(\omega)$ is real. Combining equations (4) and (6), the back-propagated signal at the source is:

$$\mathbf{E}_{TR}(\omega) = \mathbf{H}_m^T(\omega) F_{m_0}^*(\omega) = \mathbf{H}_m^T(\omega) \mathbf{H}_{m_0}^*(\omega) \mathbf{E}_{m_0}(\omega) \quad (7)$$

and $\mathbf{H}_m^T(\omega) \mathbf{H}_{m_0}^*(\omega)$ is called the TR operator. Since equation (7) has a maximum at the focus point, the information associated to the AE source location can be extracted from a "virtual" TR experiment. Fig. 4 illustrates the procedure for obtaining the imaging focusing.

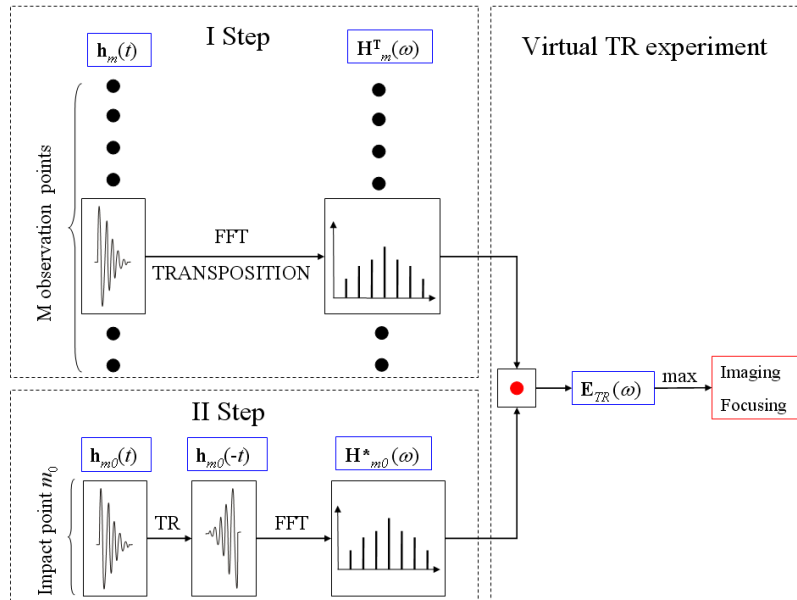


Figure 4 Architecture of the imaging focusing

3 Experimental set-up

The experiments were carried out on a reverberant carbon-fibre composite plate (100cm x 30 cm x 3 mm) reinforced with six vertical stiffeners and connected with rivets (7.9 mm of diameter) (see Fig. 2). For the library of signal needed to implement the technique, the impacts were applied to 750 observation points spaced 2 cm apart using a hand-held modal hammer, manufactured by Meggit-Endveco. The experimental Green's function from each observation point was acquired using an acoustic emission sensor instrumented with an oscilloscope (Picoscope 4224) with a sampling rate of 25 MHz. The passive sensor employed was a surface bonded acoustic emission sensor with a central frequency of 300 kHz. The transducer output was connected to a pass-band filter with a frequency bandwidth between 200 and 400 kHz and a preamplifier. According to the d_{31}/d_{32} electromechanical coupling mechanism of the acoustic emission sensor, at the mentioned finite bandwidth, only the fundamental antisymmetric Lamb wave A_0 was measured. The time histories of the signal received by the sensor were stored on a computer and processed using a Matlab software code implemented by the authors. All the impacts were carried out manually (with different forces applied) in order to avoid damaging the structure. In addition, as it can be seen from Fig. 5, the signals were normalized in amplitude and averaged in the first step. Due to the long reverberation present in the waveform, the time window of the signals was chosen at 100 ms (Fig. 5).

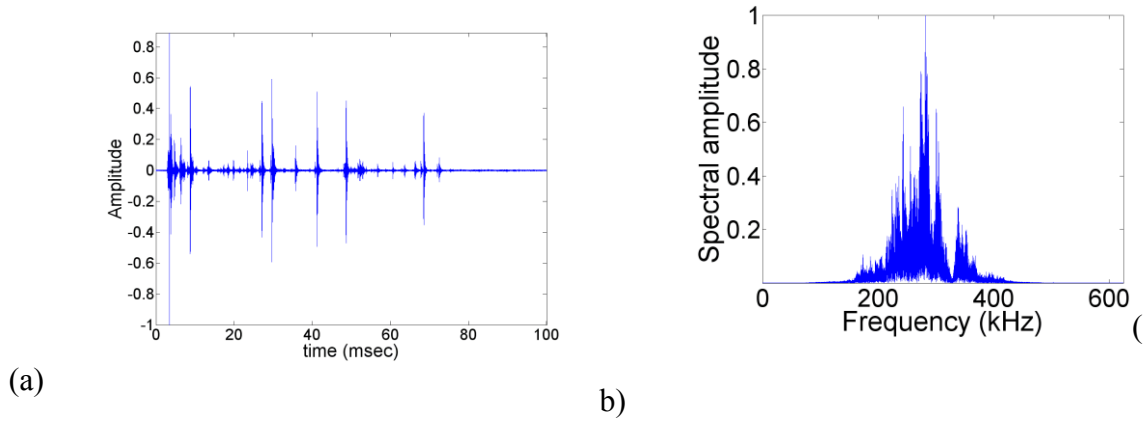


Figure 5 (a) (b) Normalized time history (a) in one of the observation points and its frequency content (b). In this figure, a reverberant impulse response is clearly visible.

Sensor locations and impact source coordinates are reported in table 1 for two different cases (referred as impacts I1 and I2 in the article).

Table 1 Sensors and impact coordinated in case I1 and I2

	X-coordinates [cm]	Y-coordinates[cm]
Sensor position (case I1)	60	16
Sensor position(case I2)	24	14
Impact I1	40	10
Impact I2	80	26

4 Imaging localization results and discussions

The imaging results are illustrated in Fig. 6. According to Section 2, the refocusing diffused wave field at the source location is represented by a 2-D map and the maximum of $E_{TR}(\omega)$ [Eq. (7)] is deduced from the values nearest to 1 (characterized by a dark red colour) with a computational time lower than 1 sec.

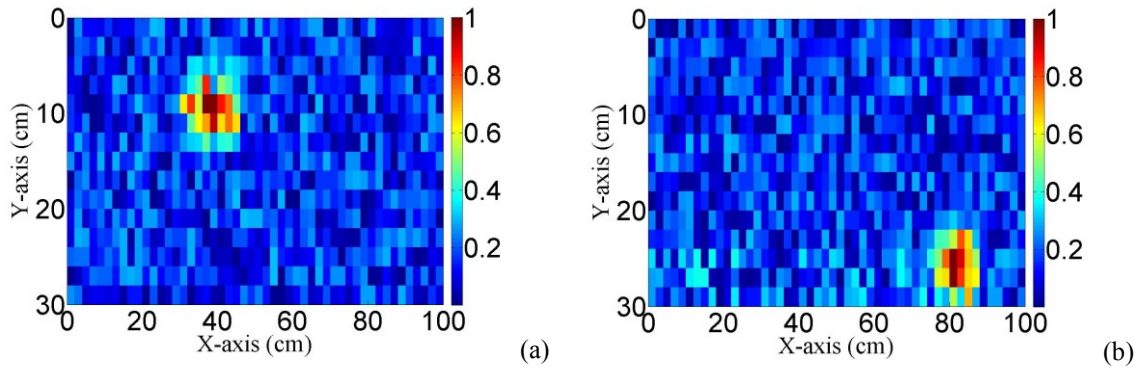


Figure 6 (a) (b) 2D map of the optimal refocusing with a simulated TRA experiment for impact I1 (a) and I2 (b).

From the above figure, it can be clearly seen that the TRA method provides an optimal focusing with reasonable accuracy and the maximum error in estimation of the source location was less than 3% (maximum percentage error given by the error function expressed in [14]) for all the case tested. In fact, as it can be observed from Fig. 6, a maximum value of the refocusing equal to 1 was found even in points close to the true impact source (see the points at $x = 38$ cm and $y = 10$ cm for case I1 and $x = 80$ cm and $y = 28$ cm for case I2). Such ambiguity might be due to the non-linear attenuation with the wave amplitude that induces distortions of the wave front propagating in the structure [20]. Although this phenomenon is present at low frequencies, it becomes critical at higher frequencies, especially in composite materials, where the anisotropy can distort the propagating wave front and cause signal loss, making the focusing images difficult to interpret. Hence, a combination of the physical principles of a correlation diffuse field (CFD) technique [6, 7, 23] with the advantages of a time reversal process, has shown to provide an optimal re-focusing at the impact location.

In other words, the “benefits” of multiple scattering from rivets and modal conversion due to the presence of stiffeners (ultrasonic diffused wave field) allow achieving a high refocusing quality of the recompressed waves without the need to

increase the number of sensors for improving the spatial resolution [18]. In fact, from Fig. 7, the correlation coefficients pattern along the X and Y-axis shows that a high resolution can be achieved even using only one passive transducer. Therefore, a very simple configuration is needed for the identification of the AE source, leading to an effective decrease of the number of sensors employed, resulting into costs savings and weight reduction.

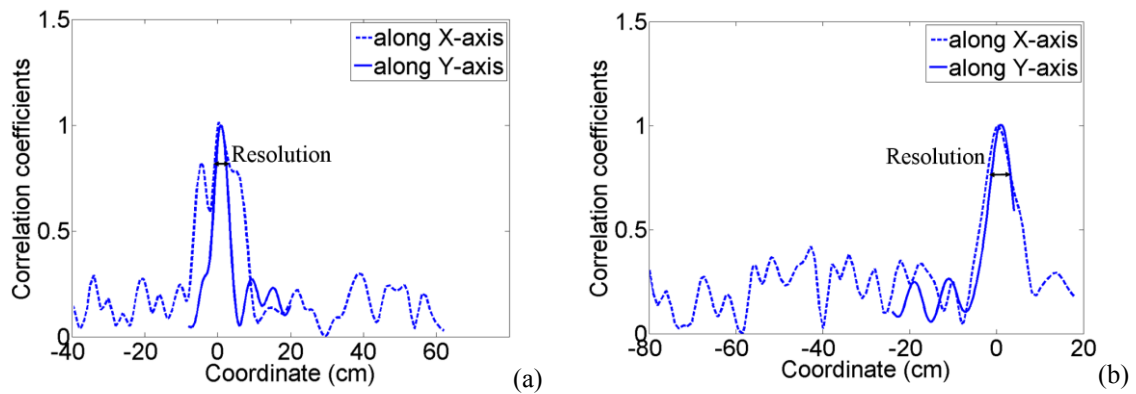


Figure 7 (a) (b) Correlation coefficients pattern along the X and Y-axis with the maximum at the focus point for impact I1 (a) and impact I2 (b).

Nevertheless, during the experiments it was observed that a decrease of the number of observation points led to an increase of the maximum error in retrieving the impact location, with lower values of $\max E_{TR}(\omega)$ compared to the previous case (Fig. 8).

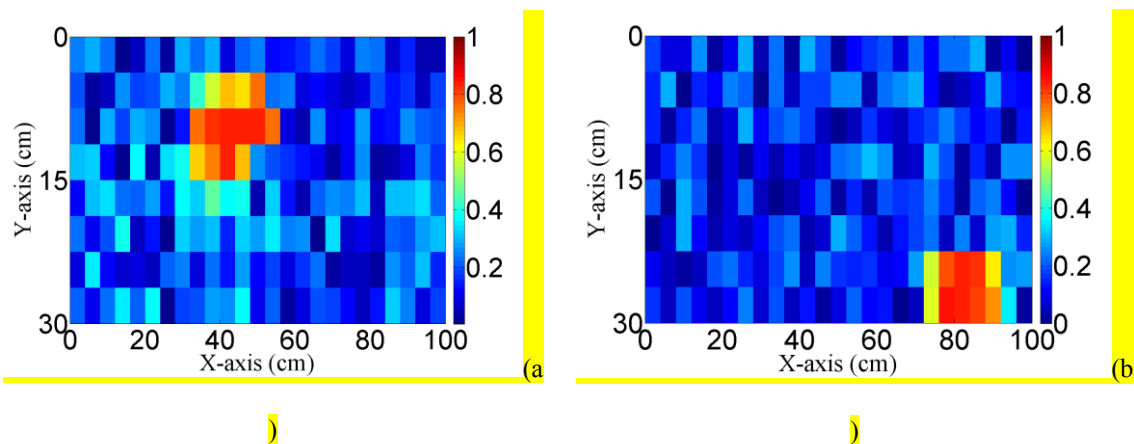


Figure 8 (a) (b) 2D map of the optimal refocusing with a simulated TRA experiment for impact I1 (a) and I2 (b) with 200 observation points.

In particular, assuming 200 observation points the location error was found nearly 10% for impact I1 (Fig. 8-a) and approximately 12% for impact I2 (Fig. 8-b). Hence, unlike other impact localization systems, this method presents the great advantage that it does not require any iterative algorithms as well as a priori knowledge of the mechanical properties, lay-up and anisotropic angular-group velocity pattern of the medium. In addition, with this technique the dispersive behaviour of guided Lamb waves was compensated [16].

5 Conclusions

This paper proposes an in-situ Structural Health Monitoring (SHM) system for the localization of the impact source in complex anisotropic structures with diffuse field conditions. This technique, based on one-channel time reversal acoustic (TRA) approach, is applied to a number of waveforms recorded by a passive sensor containing the impulse response of the medium. Unlike conventional ultrasonic impact localization systems, with the present method the benefits of scattering, mode conversions and boundary reflections allow achieving the focusing of the source with high resolution. Since the imaging of the source is obtained through a virtual focusing procedure, this system does not require any iterative algorithms and a priori knowledge of the mechanical properties of the structure and the anisotropic group speed. Good agreement between theoretical and experimental results has shown that the imaging of the impact source on a carbon fibre stiffened panel can be predicted with a reasonable level of accuracy (maximum error was less than 3%).

Further work is ongoing to better improve the imaging focusing in order to avoid any ambiguities due to the effects of distortions in complex dissipative structures.

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