Acoustic emission localization in complex dissipative anisotropic structures using a one-channel reciprocal time reversal method — **Source link** ☒

Francesco Ciampa, Michele Meo

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Abstract Page

Title:

Acoustic emission localisation in complex dissipative anisotropic structures using a one-channel reciprocal time reversal method.

Authors:

Francesco Ciampa and Michele Meo[1]

Material Research Centre, Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, UK

Running title:

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[1] Correspondent author: m.meo@bath.ac.uk

Abstract

This paper presents an imaging method for the localization of the impact point in complex anisotropic structures with diffuse field conditions, using only one passive transducer. The proposed technique is based on the reciprocal time reversal approach (inverse filtering) applied to a number of waveforms stored into a database containing the experimental Green's function of the structure. Unlike most acoustic emission monitoring systems, the present method exploits the benefits of multiple scattering, mode conversion and boundaries reflections to achieve the focusing of the source with high resolution. Compared to a classical time reversal acoustic (TRA) approach, the optimal re-focusing of the back propagated wave field at the impact point is accomplished through a "virtual" imaging process. The robustness of the inverse filtering technique is experimentally demonstrated on a dissipative stiffened composite panel and the source position can be retrieved with a high level of accuracy in any position of the structure. Its very simple configuration and minimal processing requirements make this method a valid alternative to the conventional imaging Structural Health Monitoring systems for the acoustic emission source localization.

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Article

I. INTRODUCTION

Advanced composite structural components are susceptible to impacts loadings due to a variety of causes (hail stones, tool drop etc…). Such events not only weaken the structure undergone to continuous service load, but also may generate different types of flaws before full perforation, i.e. delamination, cracks or barely visible impact damage (BVID). Over time, these effects may induce variations in the material mechanical properties, thus leading to possible catastrophic failure conditions. Hence, a quick detection of impact events is a major concern for civil and aerospace industries. Due to their versatility and sensibility, Structural Health Monitoring (SHM) systems based on ultrasonic guided waves can be used for the identification of the impact source. These methods are particularly suitable for probing components with different geometries, ensuring structural reliability and a global inspection of large structures.

Traditionally, the determination of the impact location is an inverse problem based on the time of arrival (TOA) and the group velocity recognition of the *ballistic waves* (direct waves from the source to the receiver) recorded by a network of passive transducers. The waveforms are usually analyzed with advanced signal processing techniques and then optimization algorithms can be employed to obtain the impact coordinates. Even though most of these methods are able to find the impact source with satisfactory accuracy in isotropic [1] and anisotropic [2] structures, a number of issues still need to be addressed. At first, they require a relatively large number of transducers, especially in composite materials, wherein the group velocity due to structural anisotropy is angular dependent. Then, the dispersive nature of guided Lamb waves, as well the presence in geometrically complex structures of multiple scattering, reflections from the boundaries

and mode conversion (known from seismology as *coda*) can alter the resulting signal, leading to a wrong estimation of the TOA. That is, the wave field of complex structures (with stiffeners, rivets, holes and voids), excited over a finite bandwidth, becomes diffuse incoherent. From a statistical point of view, fully diffuse wave fields are globally equipartitioned and are characterized by a superposition of modes having uncorrelated amplitude, phase and direction of propagation [3, 4]. This makes the impact localization problem with elastic diffuse conditions difficult to be solved with analytical algorithms.

However, the acoustic emission (AE) propagation can be described in terms of signal processing as a linear system with different impulse responses. Lobkins and Weaver [5] showed that the structural impulse response (Green's function) could be retrieved from the cross-correlation of the elastic diffuse wave field (CDF) at the sensors location. This concept was widely used in seismology [6], ocean acoustics [7], open media [8] and ultrasonic applications [9], and only recently it was examined through a time reversal (TR) process. The idea of using TR as an imaging method of the impact source was originally developed by Ing et al. [10] for the detection of a finger knock on a glass plate. Then, this concept was extended to the localization of the reverberated sounds in a human skull in order to understand the spatial positioning of pulses emitted by a loudspeaker [11].

This study, in its physical principle, is closer to a recent work presented by Sabra et al. [12] consisting on the estimation of the local Green's function of aeronautical structures with a CDF technique. However, in that work, all the information contained in the reverberant acoustic wave field was recorded using two passive sensors and the experimental impulse response was compared to theoretical predictions. Here, we combine the CDF method with the advantages of a TR process, already used in

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conventional pulse-echo [13] and imaging [14] damage detection. Nevertheless, loss information induced to either limited bandwidth or a nonlinear attenuation with the wave amplitude break the time reversal invariance [15]. These aberrations generate phase and amplitude distortions of the propagating wave front, and the behaviour of a TRM becomes very difficult to be predicted. However, Tanter et al. [16] showed that the inverse filtering (IF) approach allows recovering the optimal focusing, even in dissipative media.

This paper reports a one-channel imaging method aimed to detect in real time the impact source in complex anisotropic structures with diffuse field conditions. The proposed technique, based on the reciprocal time reversal (IF) approach, allows achieving the optimal focalization of the AE source (impact event) as it overcomes the drawbacks of most impact identification methods. In a first step, the impulsive responses of the medium were acquired and stored into a computer. Then, exploiting the benefits of multimodal conversion and scattering effects, a virtual focusing procedure was performed by using only one passive sensor placed on a generic point of the structure. Compared to a classical TR process, the robustness of this approach is experimentally demonstrated on a dissipative stiffened carbon-fibre composite panel.

The layout of the paper is as follow: in Section II, the imaging method for the localization of the impact source is theoretically presented with a classical time reversal process and the inverse filtering technique. Section III reports the experimental set-up whilst Section IV compares the robustness and focus quality of both methods, showing the imaging results for two different impact points. Then, the conclusions of the paper are presented.

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II. ONE-CHANNEL IMPACT LOCALIZATION METHOD

Based on the principle of time-reversal invariance and spatial reciprocity of the acoustic wave equation in a lossless medium, in a TR experiment, the elastic waves diverging from a point-like target can be focused back to the original source if the output measured by a set of transducers is time reversed and re-emitted back onto the excitation point [17]. Nevertheless, a perfect localization would require a totally covering array of sensors (closed cavity), which is impossible to obtain in practise. Hence, the closed cavity [18] is replaced by a time reversal mirror (TRM) of finite bandwidth and aperture that limits the focusing quality. However, it was illustrated by Derode et al. [19] that the reverberations of a diffuse wave field in a complex medium enhance the focusing resolution of the re-emitted signal. This phenomenon, called *super-resolution* [20, 21], is mainly due to the presence of scatterers within the medium that allow the evanescent modes (waves that decay exponentially with the distance to the source) to be converted into propagating modes. These waves, carrying the information of the impact source to the far field, where the TRM is located, can participate to the focusing process. The result of such operation creates a virtual enlargement of the transducers angular aperture (*kaleidoscopic effect*) and the number of sensors of the TRM can be drastically reduced (Fig. 1). The limit case was reported by Draeger and Fink [22] wherein the benefits of a reverberant closed cavity, showing ergodic properties and negligible absorptions, were used to perform TR experiments with only one sensor surface bonded.

This work presents an imaging technique of the AE source (impact event) in geometrically complex anisotropic structures with diffuse field condition (Fig 2). Such method is based on the reciprocal time reversal (inverse filtering) approach applied to a number of waveforms recorded by a passive transducer containing the impulse response

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of the medium. Hence, in order to obtain the optimal re-focusing at the impact source, the transfer matrix of the structure $\mathbf{H}(\omega)$ is first introduced, and then both time reversal and reciprocal time reversal imaging techniques are analyzed.

A. The structural transfer matrix H

The imaging process was split into two steps. In a first step, the surface structure ("focusing plane") was entirely divided in M = 50 x 15 "excitation points" distributed along a grid at interval of 2 cm. At each point, the acoustic emission was generated by impact loads. (Fig. 3).

Due to linearity, the acoustic field measured by the transducer from the m-th excitation point is:

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

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 excitation point to the receiver (including 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, Eq. (1) is:

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

which can be written in matrix form as:

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

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where the matrix $\mathbf{H}_m(\omega)$ is the *transfer matrix* 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 excitation points (Fig. 4):

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

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

B. Time reversal focusing approach

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 neighbouring points (excitation 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. TR behaves as a spatio-temporal matched filter that maximizes the ratio between the amplitude of the output signal (waveform acquired) and the square root of the input energy (impulse applied). Hence, assuming that the impact source in the second step is located at m_0, the input column vector $\mathbf{e}_{m0}(t)$ from the m-th excitation 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 $\mathbf{E}_{m0}(\omega) = \{0,\ldots 0,1,0,\ldots 0\}$. According to Eq. (3), the wave field received by the transducer is:

$$F_{m0}(\omega) = \mathbf{H}_{m0}(\omega) \mathbf{E}_{m0}(\omega) \qquad (5)$$

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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:

$$F_{m0}{}^*(\omega) = \mathbf{H}_{m0}^*(\omega)\mathbf{E}_{m0}^*(\omega) = \mathbf{H}_{m0}^*(\omega)\mathbf{E}_{m0}(\omega) \tag{6}$$

where the superscript '*'denotes complex conjugate and $\mathbf{E}_{m0}(\omega)$ is real. Combining equations (4) and (6), the back-propagated signal at the source is:

$$\mathbf{E}_{TR}(\omega) = \mathbf{H}_m{}^T(\omega)F_{m0}{}^*(\omega) = \mathbf{H}_m{}^T(\omega)\mathbf{H}_{m0}^*(\omega)\mathbf{E}_{m0}(\omega) \tag{7}$$

and $\mathbf{H}_m{}^T(\omega)\mathbf{H}_{m0}^*(\omega)$ is called the TR operator. Since Eq. (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. 5 illustrates the procedure for obtaining the imaging focusing with a TR analysis.

C. Reciprocal time reversal (inverse filtering) focusing approach

The reciprocal time reversal (IF) approach is based on the inversion of the transfer matrix $\mathbf{H}(\omega)$. Compared to a classical time reversal acoustic (TRA) experiment, the inverse filtering technique is able to increase the contrast, i.e. as the ratio of the averaged energy of the refocused signal at the time $t=0$ and the averaged energy of the recompressed signal at all other times [23]:

$$C = \frac{\left\langle \mathbf{e}_X{}^2(t=0) \right\rangle}{\left\langle \mathbf{e}_X{}^2(t \neq 0) \right\rangle} \tag{8}$$

where $\mathbf{e}_X(t)$ is the back-propagated field at the impact source (in the time domain) and the subscript X indicates either TR or IF operation. As the TR experiments, a new impact was applied in m_0 and its experimental Green's function was recorded by the transducer. In

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the general case of *M* excitation points and an array of *N* receivers (*N*>1), Tanter et al. [16] showed that the inversion of the transfer matrix **H** could be performed through a Singular Value Decomposition (SVD) in order to avoid singularity problems (propagator operator ill conditioned). In our case, the field distribution $F_{m0}(\omega)$ of a single receiver, when the acoustic emission propagation is generated by an impact $\mathbf{E}_{m0}(\omega)$, is obtained multiplying both members of Eq. (4) for the complex conjugate of $\mathbf{H}_{m0}(\omega)$ as follows:

$$\mathbf{H}_{m0}^{*}(\omega)\mathbf{E}_{m0}(\omega)=\mathbf{H}_{m0}^{*}(\omega)\mathbf{H}_{m}^{T}(\omega)F_{m0}(\omega)=\left|\mathbf{H}(\omega)\right|^{2}F_{m0}(\omega) \qquad (9)$$

Hence we obtain:

$$F_{m0}(\omega)=\widetilde{\mathbf{H}}(\omega)\mathbf{E}_{m0}(\omega) \qquad (10)$$

where $\widetilde{\mathbf{H}}(\omega)=\dfrac{\mathbf{H}_{m0}^{*}(\omega)}{\left|\mathbf{H}(\omega)\right|^{2}}$ is the inversion of the propagation operator and $\left|\mathbf{H}(\omega)\right|^{2}$ is the squared norm of the vector $\mathbf{H}_{m}^{T}(\omega)$ which represents the square of the modal energy of the system. Thereby, the optimal focusing with the reciprocal time reversal method is:

$$\mathbf{E}_{IF}(\omega)=\mathbf{H}_{m}^{T}(\omega)F_{m0}(\omega)=\mathbf{H}_{m}^{T}(\omega)\widetilde{\mathbf{H}}(\omega)\mathbf{E}_{m0}(\omega) \qquad (11)$$

and the operator $\mathbf{H}_{m}^{T}(\omega)\widetilde{\mathbf{H}}_{m0}(\omega)$ is referred to as the IF operator. As Eq. (7), also Eq. (11) has a maximum at the focus point, i.e. when $m=m_0$. Therefore, the imaging focusing of the impact location can be obtained through a "virtual" IF experiment (Fig. 6).

III. 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) (Fig. 7). For the library of signal needed to implement the technique, the

impacts were applied to 750 excitation 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 [24], 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. In accordance with the AE sensors frequency bandwidth and Nyquist theorem, due to the long reverberation present in the signal, a 100 ms duration time window was chosen (Fig. 8).

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

	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

IV. IMAGING LOCALIZATION RESULTS

Since the imaging method is based on a "virtual" focusing process, spatial resolution and localization precision (accuracy) are highly related. In particular, accuracy is defined as the degree of closeness of the maximum value of the normalized correlation coefficients obtained for the m-th excitation point with respect to the true impact point (located in m_0). It can be expressed (in percentage) by the ratio between the localization error ψ given by the formula $\psi = \left(x_m - x_{m_0}\right)^2 + \left(y_m - y_{m_0}\right)^2$ and the total length of the plate, where x_m and y_m are the coordinated of the m-th excitation point and x_{m_0} and y_{m_0} are the coordinates of the true impact source. On the other hand, resolution is the system's ability to distinguish neighbouring points and it can be defined as the -3dB width of the normalized correlation coefficients patterns at the focus point [10]. The imaging results are illustrated in Fig. 9 and 10 for the two different cases I1 and I2, showing a comparison of focalization between the IF method and TR analysis. According to Section III, the refocusing wave fields at the source location are represented by a normalized gray-scale 2-D map and the maxima of $\mathbf{E}_{TR}(\omega)$ and $\mathbf{E}_{IF}(\omega)$ [Eq. (7) and (11)] are deduced from the values nearest to 1, with a computational time lower than 1 sec. From the above figures, the TRA experiments provided a maximum value of the normalized correlation coefficient equal to 1, even in points close to the true impact source (see the points at x = 38 cm and y = 10 cm for case I1 in Fig. 9b and x = 80 cm and y = 28 cm for case I2 in Fig. 10b). Such ambiguities might be due to the effects of distortion (nonlinear attenuation) in the complex dissipative structure. Conversely, in the IF technique an optimal focusing with a 0% error on the estimation of the impact location was achieved. This can be explained as follows [25]. In the TRA process [Eq. (7)] only the flexural Lamb modes with higher

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energy are used for the refocusing process, whilst the modes with lower energy are vanished (see Fig. 5). On the other hand, in the IF approach, contrast is enhanced through the introduction of the modes weighted by the inverse of the energy at each eigenfrequency [Eq. (11)]. Indeed, the modes with weak amplitude are re-emitted at higher energy, whilst the modes with bigger amplitude are back propagated at lower energy (Fig. 6). Hence, the reciprocal TR technique can be assumed as a "whitening process", wherein the number of modes (and thus the quantity of information) employed for the back propagation at the focal point can be increased. Such effect is fundamental to understand the significant improvement of the contrast with the IF technique compared with the TR method in reverberant dissipative media. Indeed, assuming the linear propagator operator $\mathbf{h}_m(t)$ for the m-th excitation point as a non-stationary Gaussian signal with zero mean and variance $\sigma^2(t)$, it can be defined for a dissipative medium with diffuse field conditions as:

$$\mathbf{h}_m(t) = \sum_{i=0}^{\infty} \alpha_i \sin(\omega_i t) e^{-\frac{t}{\tau_a}} \tag{12}$$

where α_i are the amplitudes of the i-th Lamb mode contained in the wave field associated to the i-th eigenfrequency ω_i, and τ_a represents the decay time of the elastic field which depends on the scattering properties and the elastic attenuation of the structure [4]. Under the hypothesis of diffusive wave field, substituting expression (12) in the inverse Fourier transform of Eq. (7), according to the analytical formulation obtained by Quieffin [25], the contrast defined in Eq. (8) becomes:

$$C = \frac{8\pi^{3/2} Bn}{a} \tag{13}$$

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where *B* is the frequency bandwidth of the acoustic emission transducers, *n* is the modal density of the structure, *a* is the flatness factor, i.e. the ratio of mean fourth power of a mode amplitude to the square of the mean square. The product *Bn* represents the number of modes contained in the retro-focused signal, whilst *a* for dissipative media varies between 2 and 3 [26]. Since the effect of IF is to increase the number of modes for the back propagation at the focal point (*a* remains the same for TR and IF), according to Eq. (13), with such method the contrast can be significantly enhanced [27]. Therefore, from the normalized correlation coefficients patterns along the X and Y-axis in Fig. 11 and 12 two main conclusions were drawn:

- since the maximum error reported for TRA and IF experiments was less than 3% and 0%, respectively, in accordance with the benefits of a diffuse wave field, a high spatial resolution was obtained and the number of sensors used did not need to be increased.

- the real effect of IF method was to improve the accuracy of the impact location (compensation of the distortions effects in a dissipative medium in combination with the benefits of a diffuse wave field) and to enhance the contrast and thus the focusing efficiency (accuracy) up to 0% localization error even using one passive transducer.

Hence, compared to other ultrasonic 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 TOA, mechanical properties, lay-up and anisotropic angular-group velocity pattern of the medium. In addition, since only one passive transducer is needed

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for the imaging of the impact source, an effective decrease of the number of sensors, resulting in significant costs and weights savings, can be accomplished.

V. CONCLUSIONS

In this paper, an *in situ* imaging method able to detect in real-time the impact source in dissipative complex composite structures with diffuse field conditions is presented. This technique based on the reciprocal time reversal (inverse filtering) approach, is directly applied to the experimental impulse responses of the structure recorded by only one passive sensor and stored into a database. The proposed method allows achieving the optimal focalization of the acoustic emission source as it is able to compensate the distortion effects in a dissipative medium. Moreover, exploiting the benefits of a diffuse wave field, a high refocusing quality, with only one sensor can be accomplished. Compared to a simple time reversal process, the robustness of this approach is experimentally demonstrated on a stiffened composite plate and the results have shown that the IF technique provides an optimal focusing with a 0% error on the estimation of the impact location. Moreover, for the imaging process, no iterative algorithms as well as a priori knowledge of the mechanical properties, lay-up, thickness and the dispersive and anisotropic group velocity pattern of the medium are required.

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Figure captions:

Figure 1 Kaleidoscopic effect.

Figure 2 Complex structure with diffuse field conditions and a representation (inset) of the mode conversion effects for the flexural Lamb waves A_0 and A_1.

Figure 3 Experimental set-up.

Figure 4 Reciprocity condition of the transfer matrix $\mathbf{H}(\omega)$.

Figure 5 Architecture of the time reversal imaging process.

Figure 6 Architecture of the inverse filtering imaging process.

Figure 7 Top and bottom view of the stiffened carbon-fibre composite panel used in the experiments.

Figure 8 (a) (b) Normalized time history (a) of one the focusing point and its frequency content (b). In figure (a), a reverberant impulse response is clearly visible.

Figure 9 (a) (b) 2-D map of the maxima normalized correlation coefficients with the IF approach (a) and the TR analysis (b) for the case I1.

Figure 10 (a) (b) 2-D map of the maxima normalized correlation coefficients with the IF approach (a) and the TR analysis (b) for the case I2.

Figure 11 (a) (b) Normalized correlation coefficients patterns along the X and Y-axis with the maximum at the focus point with IF method (a) and TR approach (b) for case I1.

Figure 12 (a) (b) Normalized correlation coefficients patterns along the X and Y-axis with the maximum at the focus point with IF method (a) and TR approach (b) for case I2.

Table caption:

Table 1 Sensors and impact coordinated in case I1 and I2