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RECONSTRUCTION OF IMPACT ON COMPOSITE AIRFOIL SEGMENT USING PIEZOELECTRIC SENSORS

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ABSTRACT

The presented study focuses on structural health monitoring technique with the goal to predict induced damage and assess the residual strength of impacted structure. Herein, the primary problem of impact force reconstruction is investigated on an airfoil segment (part of a propeller blade for a large fan) made of laminated composite with attached piezoelectric transducers. The segment is made from carbon textile using RTM technology. The reconstruction is based on deconvolution method and transfer functions. The efficiency of the proposed approach is tested for all impact locations used to calibrate the system, and also on several additional locations. The interpolation of transfer functions is used to increase the accuracy of the reconstruction.

KEYWORDS : *force reconstruction, convolution, inverse problem, Tikhonov regularization, experiment.*

INTRODUCTION

The safety or functionality of every structure can be significantly affected by defects. Therefore, they must be found prior to any catastrophic scenario. These defects can be undetectable by visual inspection. Currently, they are detected by non-destructive techniques like ultrasonic, X-ray, coin tapping or other methods [19], which are time and cost consuming and require the construction to be taken out of service. In contrary, the condition of construction can be evaluated during operation from measurements of sensors placed over the structure. This principle is so-called structural health monitoring. The identification of impact force and impact location is an important task of such systems and the ideal identification method should identify the impact force, or even the combination of impact forces, on complex structures in real time with low dependence of operating noise.

The hidden defects are very common especially in modern composite materials, such as carbon fiber reinforced epoxy laminates, that are widely used thanks to their high strength and stiffness to weight ratios. Not only is the design process of structures which contain parts from composite materials complicated due to effects such as non-linear behavior [3], specific damage behavior [9], and directional dependence of velocity of propagation of stress waves [15], but, furthermore, composites are highly susceptible to transverse loading, which can cause delamination and cracks in matrix and thus significantly reduce the stiffness or strength of the construction [21].

The impact identification problems have been studied by many researchers in recent years and several methods were proposed. The often used one is the inversion of forward problem, which can be performed in time, frequency or spectral domain. Direct deconvolution is a well-known ill-conditioned problem and its results are strongly influenced by quality of experimental data, appropriateness of the mechanical model and robustness of employed algorithm. Many researches define the problem rather as a minimization of the difference between measured and modeled responses of the impacted structure. Additional terms and constraints are added to minimization to regulate oscillations in results.

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Jacquelin et al. [6] analyzed the deconvolution in time domain. The influence of sensors location and different regularization methods were investigated. Similarly, Gunawan et al. [8] used the time domain. The impact force was approximated by cubic spline and the two-step B-spline regularization method was developed. On the other hand Yan and Zhou [13] used Chebyshev polynomials to represent the impact force and the modified genetic algorithm to solve the minimization problem. Park and Chang [7] determined the system experimentally and investigated several types of impacts. Martin and Doyle [1] used the Fast Fourier Transform to switch into frequency domain and solved the deconvolution directly. Furthermore, Doyle [2] employed the wavelet deconvolution and modeling with FEA. Other researches preferred to work in spectral domain. Hu et al. [12] formulated the minimization with regularization parameter and constraint, which was solved by quadratic programming method. Moreover, different types of sensors were compared and Chebyshev polynomials were employed to reduce the number of unknowns. Atobe et al. [14] used the gradient projection method to solve the minimization problem and compared the determination of the system by experiment or by FEA. Finally Sekine and Atobe [16] formulated the minimization where multiple impacts can be identified. Another possibility is to define the minimization in recursive form in time domain and to use filtering method to solve the investigated problem. Seydel and Chang [4, 5] used smoothing-filter method and investigated the influence of sensor locations and boundary conditions. Similarly, Zhang et al. [11] implemented smoothing-filter algorithm with the possibility of real-time computations.

The location of impact within these methods is often estimated from the minimization of the error between measured and modeled responses along the structure. This can be done by direct search methods [12] or by some other optimization techniques [14]. Another possibility is to use the techniques derived from methods used in acoustic emission (AE) [10, 4], where the difference in arrival time of signal is determined and the location of impact is estimated from velocity of waves. Unfortunately, the determination of exact time of arrival in composite material or complex structures is limited because of the dispersion and reflection of waves on boundaries. The alternative is calculation of distribution of energy in defined time step and the determination of its maximum [7].

Totally different approach is the determination of impact force and force location from models based on neural networks [17]. The model is composed of parallel elements connected by defined relations and trained by preliminary tests. The output of the model is then set by learned behavior. The weakness of such approach is the necessity of learning period and uncertain reaction of model to not learned impacts.

The above cited works differ in several features such as complexness of geometry, determination of the system model or the type and number of sensors. The impact force was investigated on metal beam [1], metal plate [2, 6, 8], composite plate [10, 12] or stiffened composite plate [5, 7, 11, 12, 13, 14, 16]. The model of the system is defined analytically [4, 11, 13] or determined by FEA [8, 12, 14, 16] or by experiment [7, 14]. Signal is mostly obtained from strain gauges [14, 16], accelerometers [1, 2, 12], simple piezoelectric sensors [12] or from sensor network [7, 13, 19, 20 and 22].

1 DISCRETE CONVOLUTION AND INVERSE PROBLEM

The methodology used in this work is based on the transfer function approach. For a linear system, its response h to an input f can be expressed by convolution

$$f * g = h \tag{1}$$

where g is so-called transfer function and it represents the characteristics of the system. In order to find the location of impact and to reconstruct the time dependence of the impact force, it is necessary to perform two consecutive steps; a) a calibration procedure, i.e., to

perform experimental measurements while recording the corresponding input and response, and to calculate the transfer functions for all combinations of impact (calibration) locations and sensors, and b) a reconstruction procedure, i.e. to reconstruct the force in each possible location for measured response for unknown impact and to seek the impact location by minimizing the error of response reconstruction.

Let us consider a system (a structure) with K impact locations and L sensors. First, we measure the force in location i and the corresponding response in sensor j. For discrete system the input and response signals, each consisting of N samples (assuming constant time increment Δt), can be written as

$$\mathbf{f}_i = [f_1, f_2, \ldots, f_N]^{\mathrm{T}} \quad \text{and} \quad \mathbf{h}_j = [h_1, h_2, \ldots, h_N]^{\mathrm{T}}, \tag{2}$$

respectively. The force vector can be rearranged to matrix $[N \times N]$ for each performed impact (or experiment) $m = 1 \ldots M$ and then a global matrix system can be assembled for up to M subsequent impacts as

$$\underbrace{\begin{bmatrix} 0 & \cdots & 0 & f_1 \\ \vdots & \iddots & f_1 & f_2 \\ 0 & \iddots & \iddots & \vdots \\ f_1 & f_2 & \cdots & f_N \end{bmatrix}}_{\mathbf{F}_i^m} \cdot \underbrace{\begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_N \end{bmatrix}}_{\mathbf{g}_{ij}} = \underbrace{\begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_N \end{bmatrix}}_{\mathbf{H}_j^m}, \quad \underbrace{\begin{bmatrix} \mathbf{F}_i^1 \\ \vdots \\ \mathbf{F}_i^M \end{bmatrix}}_{\mathbf{F}_i} \cdot \mathbf{g}_{ij} = \underbrace{\begin{bmatrix} \mathbf{H}_j^1 \\ \vdots \\ \mathbf{H}_j^M \end{bmatrix}}_{\mathbf{H}_j}. \tag{3}$$

The system is then represented by all solutions for each combination of i and j. However, each system of algebraic equations in (3) is overdetermined and ill-posed. If we rewrite (3) concisely as

$$\mathbf{Fg} \approx \mathbf{H} \tag{4}$$

the solution can be obtained by various methods, for example by simple pseudoinversion, by minimizing the residuum using least squares method, by quadratic programming techniques or others [19]. Nonetheless, to avoid unrealistic oscillations of the solution, it is advisable to use adequate regularization technique that imposes additional condition on the solution. Herein, the Tikhonov regularization [18]

$$\min\left\{\|\mathbf{Fg} - \mathbf{H}\|^2 + \lambda^2 \|\mathbf{g}\|^2\right\} \tag{10}$$

is used, where the additional term, compared to least square method, means that the norm of the solution will be minimized too. A proper choice of the parameter λ is needed to balance the ratio between the standard residuum and the oscillations.

When all transfer functions $\mathbf{g}_{ij}$ are known, we can attempt to reconstruct the unknown input signal from measured responses only. The response again with N samples as in (2) is obtained in all L sensors or only in a subset of sensors. Now, the transfer function for each combination of i and j must be rearranged to matrix $[N \times N]$ and then a global system for all selected sensors can be assembled as

$$\underbrace{\begin{bmatrix} 0 & \cdots & 0 & g_1 \\ \vdots & \iddots & g_1 & g_2 \\ 0 & \iddots & \iddots & \vdots \\ g_1 & g_2 & \cdots & g_N \end{bmatrix}}_{\mathbf{G}_{ij}} \cdot \underbrace{\begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_N \end{bmatrix}}_{\mathbf{f}_i} = \underbrace{\begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_N \end{bmatrix}}_{\mathbf{H}_j}, \qquad \underbrace{\begin{bmatrix} \mathbf{G}_{i1} \\ \vdots \\ \mathbf{G}_{iL} \end{bmatrix}}_{\mathbf{G}_i} \cdot \mathbf{f}_i = \underbrace{\begin{bmatrix} \mathbf{H}_1 \\ \vdots \\ \mathbf{H}_L \end{bmatrix}}_{\mathbf{H}}. \tag{5}$$

The solution can be performed for each possible (suspected) impact location i. Again, the problem (5), written concisely as

$$\mathbf{Gf} \approx \mathbf{H}, \tag{6}$$

is overdetermined and ill-posed. Moreover, as the impact force is always non-negative (assuming non-sticking impact), additional inequality constraint might be advantageous [20]. In this work, however, the Tikhonov regularization is used again without the inequality constraint. Hence, the solution $\mathbf{f}$ is found from

$$\min\left\{\|\mathbf{Gf} - \mathbf{H}\|^2 + \lambda^2\|\mathbf{f}\|^2\right\}. \tag{7}$$

To find the real location (or at least a good estimate) of the unknown impact, it is necessary to seek the location i which produces the smallest error δ_i between the measured response ($\mathbf{H}$) and the response ($\mathbf{H}_i$) reconstructed using the corresponding solution of (7) as

$$\mathbf{G}_i\mathbf{f}_i \approx \mathbf{H} \quad \rightarrow \quad \mathbf{H}_i = \mathbf{G}_i\mathbf{f}_i. \tag{8}$$

Therefore, the goal is to solve

$$\min_i\{\delta_i\}, \quad \delta_i = \|\mathbf{H}_i - \mathbf{H}\|. \tag{9}$$

The solution $\mathbf{f}$ which minimizes (9) can be sought by various methods, however, in this work, a brute-force search in all locations was conducted to ensure that the global minimum is found.

Further, an attempt was made to increase the accuracy of the reconstruction by interpolating the neighboring transfer functions. Each sector (four locations) between the calibration impact locations was subdivided into 5×5=25 subsectors. The transfer functions at locations q inside each sector are calculated using standard approximation functions for isoparametric quadrilaterals as

$$\mathbf{g}_{iq} = \sum_j \left(N_j\mathbf{g}_{ij}\right), \quad j = a,b,c,d \tag{10}$$

where the numbers a, b, c, and d correspond to locations defining the given sector and

$$N_a = \tfrac{1}{4}(1-\xi)(1-\eta), \quad N_b = \tfrac{1}{4}(1+\xi)(1-\eta),$$
$$N_c = \tfrac{1}{4}(1+\xi)(1+\eta), \quad N_d = \tfrac{1}{4}(1-\xi)(1+\eta). \tag{11}$$

2 EXPERIMENTAL TESTS

Composite airfoil segment was loaded using impact hammer B&K 8204 in 77 locations (one at a time) regularly covering rectangular area of dimensions 500×300 mm on the upper skin (see Figure 1 and 2). Three impacts (i.e. $M = 3$) were performed in each location in accordance with (3). The force was measured using embedded force sensor. The signals from the hammer and from the piezoelectric patches were recorded using NI CompactDAQ device with NI 9215 and NI 9234 modules. 2000 samples for each channel were recorded with sampling frequency of 51.2 kHz.

The segment was composed of an omega-shaped spar and two skins, all made of carbon textile using RTM (Resin Transfer Molding). The three parts were glued together and also patched along the leading and trailing edges. The segment was hanged using a clamp on the spar as shown in Figure 1. The sensors were piezoelectric foil patches DuraAct P-876.SP1 with applied shunt resistors (R = 1 MΩ). The sensors were attached using double sided adhesive tape.

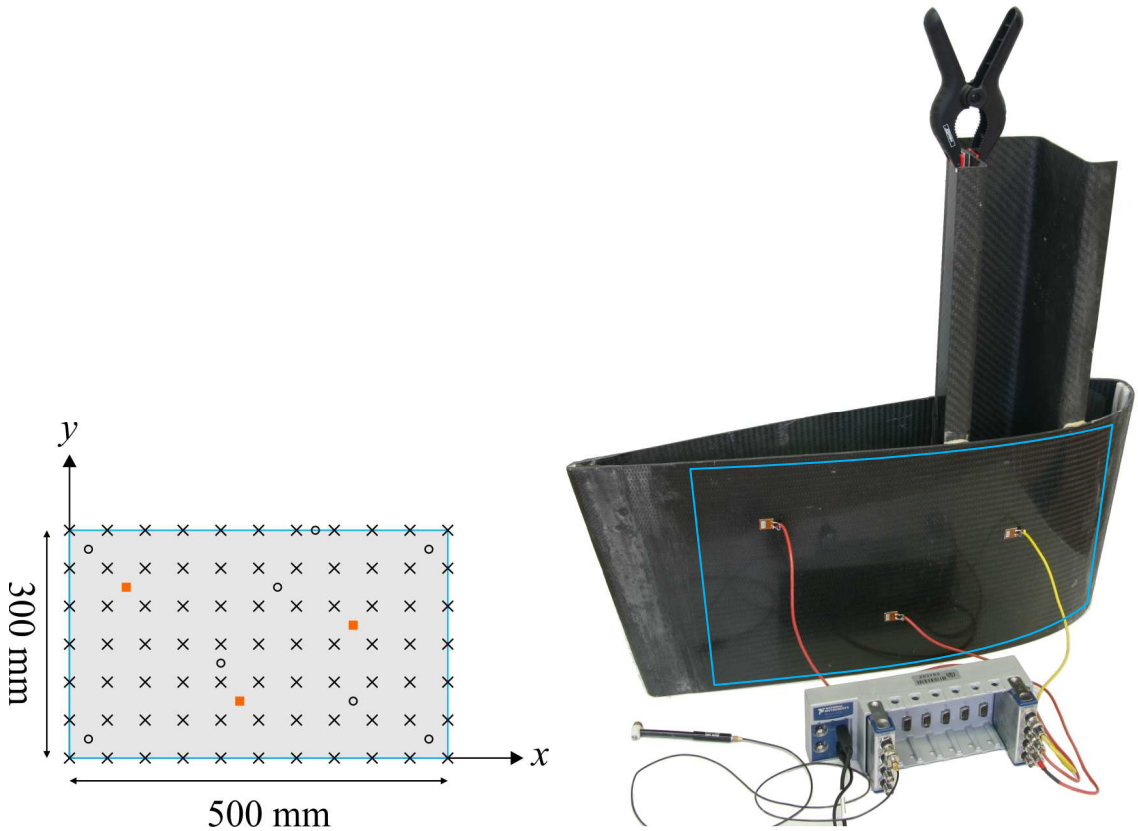

Figure 1: Schema of segment with sensors (■), calibration impact locations (×), additional impact locations (O), and photograph of segment with apparatus (right) including sensors with cables, acquisition modules, impact hammer and clamp for hanging. The blue lines denote the actual borders of the impacted area.

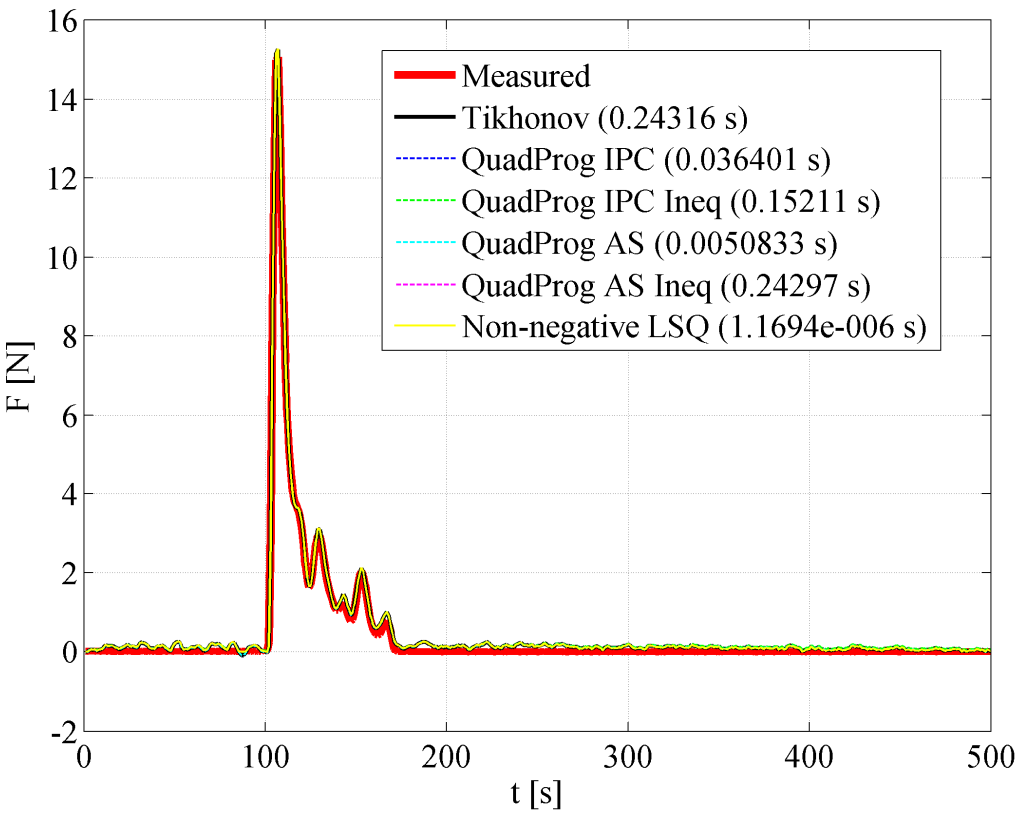

Figure 2: Measured and reconstructed force for impact for [x, y] = [0, 300] mm.

3 RESULTS

All 77 impact locations used for calibrating the system were identified exactly using (7). An example of measured and reconstructed forces is shown in Figure 2 for a selected location. Several methods were tested and compared also in terms of time needed for solution in Matlab.

The efficiency of the proposed approach is further shown on eight examples in Figure 3 when the impact occurred between the calibration positions (see additional impact locations in Figure 1). The values of error δ_i were calculated using (9). The corresponding impact locations are visually compared with the real locations in the graphs. The maximum difference between real and identified impact location was 25 mm (corresponding to the size of the interpolation grid). The position of the spar is visible in the contours of the graphs as it creates boundaries between areas with different elastic properties.

CONCLUSION

The proposed method for impact location identification and force reconstruction proved to provide results with sufficient accuracy on curved composite structure and also with only three sensors covering investigated rectangular area. The future work will focus on detailed optimization of placement of sensors and also on interpolation sector size with respect to specimen size and shape or material complexity. The interpolation used herein could be enhanced with general optimization algorithm within each sector instead of simple sector subdivision.

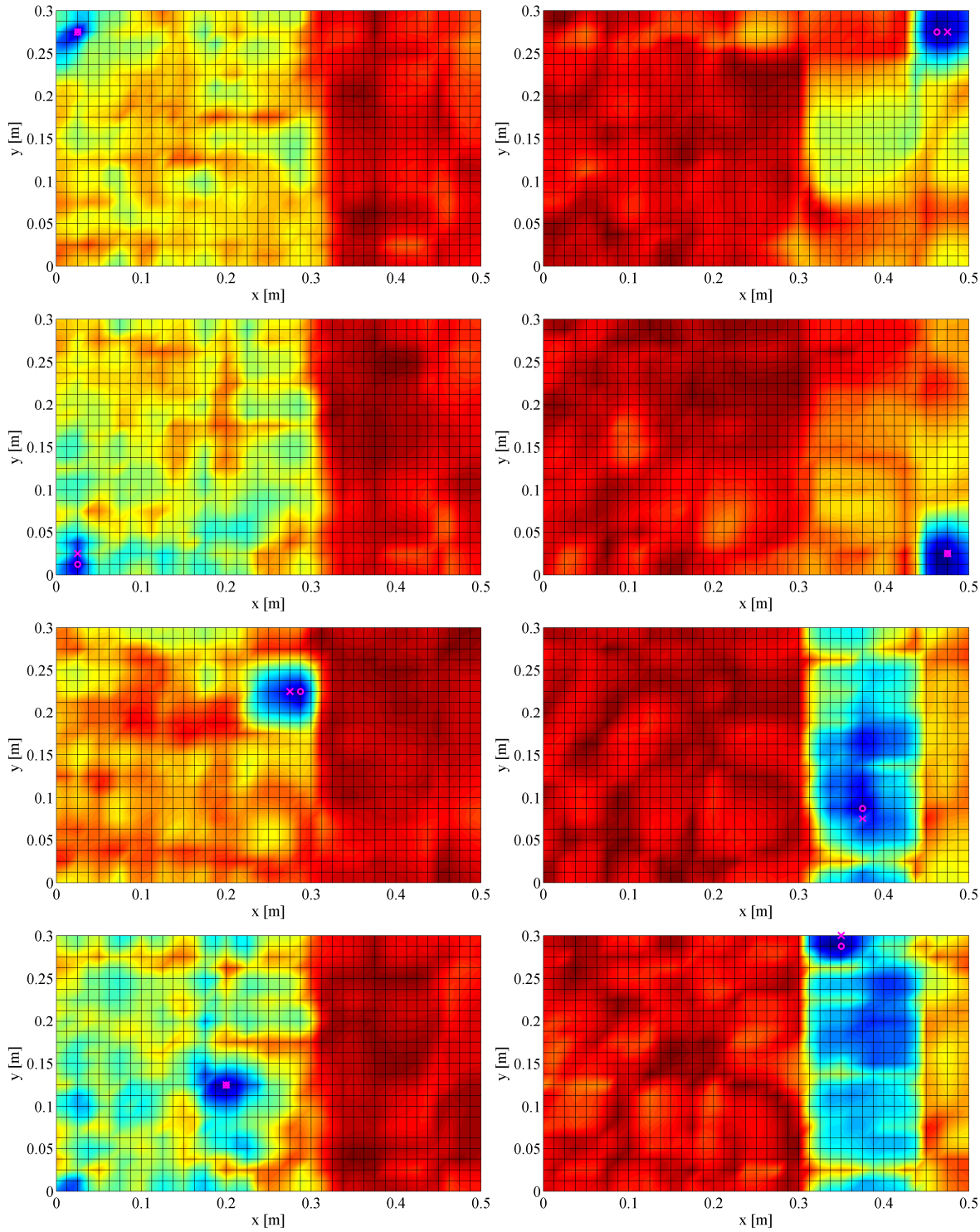

Figure 3: The contours of reconstruction error δ and comparison of location of real impact (×) and location identified using interpolated data (O) for all 8 tested impacts between calibrated data.

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