# Detection of Impact Damage for Composite Structure by Electrical Impedance Tomography

**Z. J. Yang and G. Yan**

**Abstract** This paper presents an experimental work on detection of impact damage for composite structure by using electrical impedance tomography (EIT). A piece of carbon nanotube (CNT) film is attached on the surface of the composite structure as a sensing skin to detect impact damage through its conductivity change. Electrodes are equally spaced along the film's boundary, and a constant DC current is injected into the film between the adjacent electrode pair sequentially while voltage measurements are acquired from the rest of electrode pairs. EIT is then used to reconstruct the change of internal conductivity of the CNT film caused by impact damage with these measurements. It is formulated as a linear inverse problem, and an inverse analysis with L1-norm regularization is used to perform the reconstruction. Experimental results have demonstrated that EIT can successfully reconstruct the localized areas with reduced conductivity, thus quantitatively identifying the impact damages.

**Keywords** Damage detection · Composite structure · Electrical impedance tomography · Carbon nanotube film · L1-norm regularization

## 1 Introduction

Along with the growing use of composites in aerospace industry, more and more attention has been paid to the safety of composite structures because they are vulnerable to damage, especially the invisible low-impact damage. Thus it is very important to develop structural health monitoring (SHM) technology to detect the occurrence and development of damage. In recent years, carbon nanotubes (CNTs) have been introduced into SHM with their excellent self-sensing ability [2]. For instance, Mactabi et al. fabricated aluminum single lap joints using CNT reinforced epoxy

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adhesive, and monitored the electrical resistance perturbation of the joints during fatigue loading [7]. Thostenson and Chou processed the glass fiber–epoxy composites with multi-walled CNTs dispersed in the epoxy phase as distributed sensors to evaluate the onset and evolution of damage [9]. However, the inadequacy of these studies is that they only handle with simple one-dimensional structures.

Recently electrical impedance tomography (EIT) has been used in the field of SHM for two-dimensional structures [4, 5]. Originally, EIT is developed from medical and geological applications and it is a soft-field tomographic imaging method that uses boundary voltage measurements from flowing electric current to reconstruct internal electrical property (usually conductivity or resistivity) distribution of an object. For example, Tallman et al. proposed a method by combining imaging capabilities of EIT with conductive networks of nanofillers in composite matrix to locate impact damage [8]. Baltopoulos et al. exploited electrically conductive CNT networks with EIT for damage assessment for a glass fiber reinforced polymer (GFRP) plate by using the least-squares method with Tikhonov regularization [3].

In this study EIT is employed to quantitatively identify the damage in a composite unmanned aerial vehicle (UAV) wing with a CNT film as a smart sensing skin. An EIT system is established to measure boundary voltage change of the CNT film efficiently and L1-norm regularization is used to solve the inverse problem of reconstructing the conductivity change caused by damage. The validity of this method is well confirmed by the experimental results.

## 2 Experimental Set-up

As illustrated in Fig. 1, a composite UAV wing with a CNT film (JCNTF-20C, JCNANO Tech Co., Ltd) is considered. The CNT film is fabricated by floating catalyst chemical vapor deposition (FCCVD) method with thickness of about 6–10 $\mu$m and conductivity of about 0.8–3.0 $\times$ $10^5$ S/m. The shape of the film is a right-angled trapezoid, and it is attached on the surface of the UAV wing by epoxy. When the UAV wing is damaged, it can cause damage to the CNT film at the same locations. Therefore, after using EIT to reconstruct the conductive change of the CNT film caused by damage, the damage in the UAV wing can be detected and identified. Comparing with other methods, this approach is simple to setup and operate.

In total, 20 electrodes coated with a conductive silver paint (SCP03B, A Division of HK Wentworth, Ltd) are equally spaced along the boundary of the film. Thin wires are then attached to electrodes using a conductive glue (Type3703, Shenzhen Sinwe New Material Co., Ltd) and the other ends are connected to the EIT system.

In order to perform the experiments, an EIT system is developed. It mainly consists of a high precision DC current source (Keithley 6221), a nanovoltmeter (Keithley 2182A), a system switch (Keithley 3706A-S) and a controller (Lenovo WorkStation P510). Besides, a LabVIEW-based software is designed to control the data acquisition unit. The adjacent current injection protocol for measuring voltages is adopted in this experiment. As shown in Fig. 2, in detail, a constant DC current of 100 mA

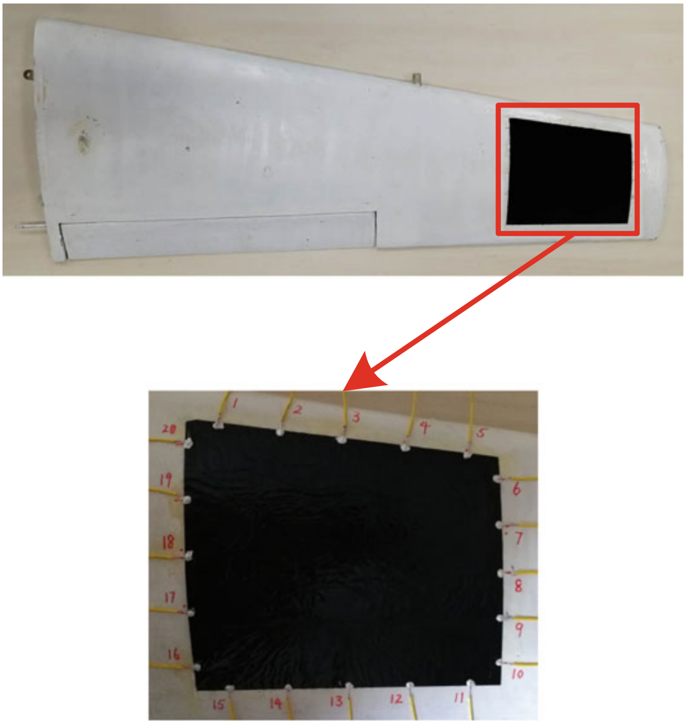
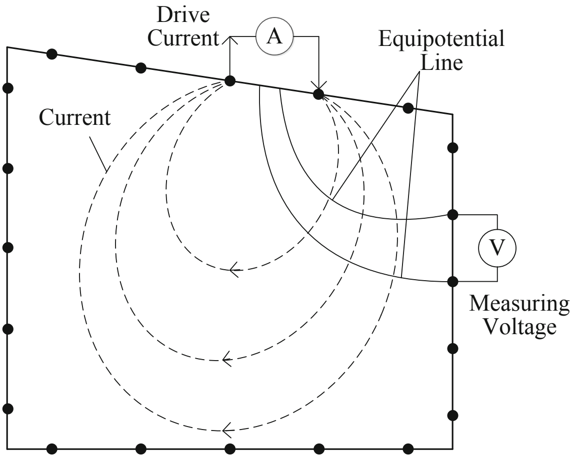


**Fig. 1** The UAV wing with CNT sensing skin

**Fig. 2** Illustration of EIT adapted for the CNT film



generated by current source is applied to the film between the adjacent electrode pair sequentially and corresponding voltage measurements are acquired from the rest of the adjacent electrode pairs by nanovoltmeter. The system switch is used to automatically switch over the current source and voltage measurements between electrodes. The test procedure is first performed under the pristine state, i.e., the CNT film and the UAV wing are undamaged, to obtain a set of reference voltage measurements. Then, damage is introduced and the same test procedure is performed to obtain voltage measurements under the damaged state. So two sets of the boundary voltages (before and after the damages) are obtained for subsequent damage detection and imaging.

## 3 Image Reconstruction Algorithm of EIT

EIT aims to obtain the conductivity distribution supplied to the forward operator until the difference between the experimentally measured voltages and the computationally predicted voltages is minimized in the least-squares sense. That is,

$$\sigma^{*} = \min_{\sigma}\left(\| V_m - F(\sigma) \|_2^2\right) \tag{1}$$

where $V_m$ is the vector of experimentally measured voltages, and $F$ the forward operator which is usually performed by finite element method (FEM). When the background conductivity distribution $\sigma_0$ is known, $F(\sigma)$ can be approximated by a Taylor series expansion centered about $\sigma_0$, and then Eq. (1) which is a nonlinear inverse problem can be transformed to a linear inverse problem to obtain the conductivity change as

$$\Delta\sigma^{*} = \min_{\Delta\sigma}\left(\| \Delta V - J\Delta\sigma \|_2^2\right) \tag{2}$$

where $\Delta V = V_m - F(\sigma_0)$, $\Delta\sigma = \sigma - \sigma_0$, and $J = \partial F(\sigma_0)/\partial\sigma$, known as the sensitivity matrix, is formed by enforcing the conservation of power through the electrodes and in the domain thereby relating the electrode voltage perturbations to conductivity perturbations.

In general, it is not straightforward to reconstruct the conductivity change by a direct matrix inversion from Eq. (2), since the least-squares problem may be ill-posed (e.g., $J$ is singular) when measurement noise and modeling error are present. To provide a bounded solution, a regularization term should be added to Eq. (2). With regard to the damage detection for composite structures, the media in the measured region are often discontinuous. In order to reflect the sparsity of the problem and improve the quality of the reconstruction, L1-norm regularization is adopted. In L1-norm regularization, a sum of absolute values is used as the regularization term as

$$\Delta\sigma^* = \arg\min_{\Delta\sigma}\left(\|\Delta V - J\Delta\sigma\|_2^2 + \lambda\|\Delta\sigma\|_1\right) \tag{3}$$

where $\|\Delta\sigma\|_1 = \sum_i |\Delta\sigma_i|$ denotes the L1 norm of $\Delta\sigma$.

Equation (3) can be transformed to a convex quadratic problem, with linear inequality constraints

$$\begin{aligned} &\Delta\sigma^* = \arg\min_{\Delta\sigma}\left(\|\Delta V - J\Delta\sigma\|_2^2 + \lambda\sum\nolimits_i v_i\right) \\ &\text{subject to } -v_i \le \Delta\sigma_i \le v_i \end{aligned} \tag{4}$$

A primal interior-point method is introduced to solve the problem [6]. In the primal interior-point method, the logarithmic barrier for the bound constraints in Eq. (4) is defined as

$$\Phi(\Delta\sigma, v) = -\sum\nolimits_i \lg(v_i + \Delta\sigma_i) - \sum\nolimits_i \lg(v_i - \Delta\sigma) \tag{5}$$

The central path consists of the unique minimizer of the convex function

$$\phi_t(\Delta\sigma, v) = t\|\Delta V - J\Delta\sigma\|_2^2 + \lambda t\sum\nolimits_i v_i + \Phi(\Delta\sigma, v) \tag{6}$$

We compute a sequence of points on the central path, for an increasing sequence of values of $t$, starting from the previously computed central point. A typical method uses the sequence $t = t_0, \beta t_0, \beta^2 t_0 \ldots (\beta > 1)$. Then, Newton's method is used to minimize $\phi_t$, i.e., the search direction is computed as the exact solution to the Newton system

$$H\begin{bmatrix} \Delta(\Delta\sigma) \\ \Delta v \end{bmatrix} = -\nabla\phi_t(\Delta\sigma, v) \tag{7}$$

where $H = \nabla^2\phi_t(\Delta\sigma, v)$ is the Hessian matrix.

For Eq. (3), the range of L1-norm regularization parameter $\lambda$ is $0 < \lambda < ||2J^{\mathrm{T}}\Delta V||_\infty$ ($|| \bullet ||_\infty$ shows the infinite norm of a vector). In general, we choose parameter $\lambda = 0.01||2J^{\mathrm{T}}\Delta V||_\infty$, and if the sparsity of the matrix is poor, we can choose parameter $\lambda = 0.001||2J^{\mathrm{T}}\Delta V||_\infty$ to get better results.

## 4 Results and Discussion

In the experimental study, impact damage is introduced to the UAV wing by impact hammer. First, single damage case is considered, and the location of the impact damage is illustrated in Fig. 3. After the boundary voltage measurement before and after impacts are obtained by the data acquisition system, based on the image

**Fig. 3** Single impact on the UAV wing

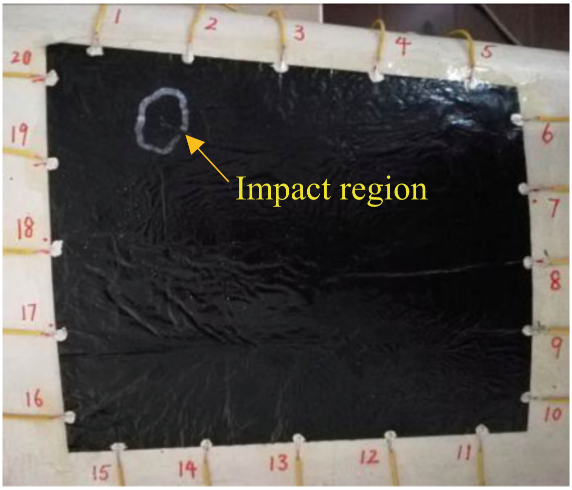
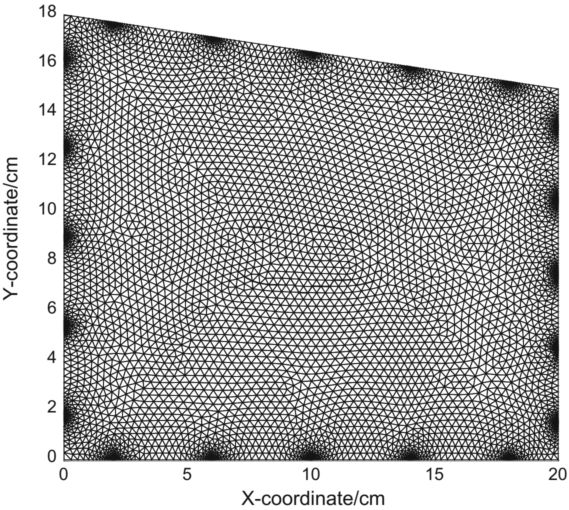


**Fig. 4** Inverse finite element model for reconstruction of the conductivity change using EIT



reconstruction algorithm of EIT, experimental data is processed through MATLAB along with an open software EIDORS [1].

In detail, the inverse finite element model for reconstruction of the conductivity change is illustrated in Fig. 4. Considering a certain error in the measurement data, we choose parameter $\lambda = 0.001||2J^{\mathrm{T}}\Delta V||_{\infty}$ for L1-norm regularization. EIT based on L1-norm regularization with the selected regularization parameter is then used to reconstruct conductivity change of the CNT film caused by damage with the boundary voltage measurements. Figure 5 shows the tomographic image of the conductivity change corresponding to Fig. 3 constructed by a normalized version of the proposed algorithm. It can be seen that the damage is well indicated by the localized area with

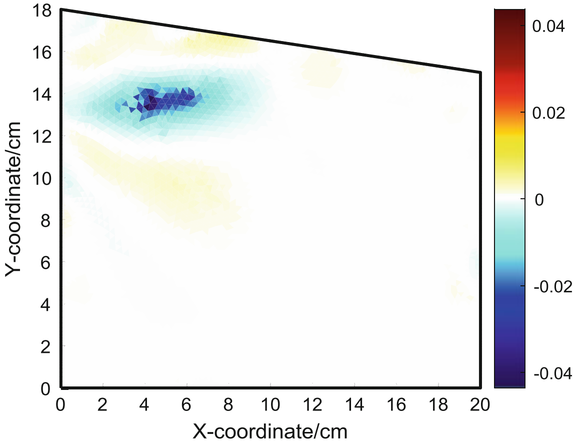


**Fig. 5** Reconstructed conductivity change of the CNT film with single impact damage

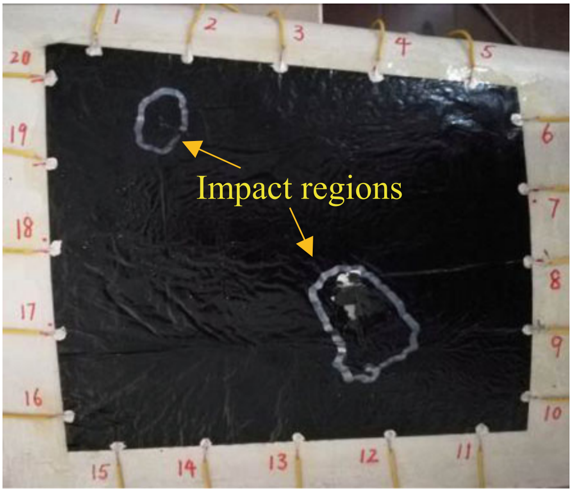


**Fig. 6** Double impacts on the UAV wing

a significant conductivity reduction, demonstrating the effectiveness of the L1-norm regularization EIT algorithm for detecting the damage.

By applying the same procedure, a further exploration is conducted. As Fig. 6 shows, when the UAV wing is impacted at another point, voltage measurements are obtained by the EIT system in the same way. Figure 7 shows the tomographic image of the conductivity change corresponding to Fig. 6. It can be seen that the damage in two sites are well indicated by the localized areas with significant conductivity reduction.

In order to reflect the actual damage of the UAV wing, non-destructive testing (NDT) is used to detect damage for the purpose of comparison. The damage of the UAV wing are detected by infrared thermography, and as Fig. 8 shows, the results show the damage regions and the wing spars. It can be seen that the damage detected

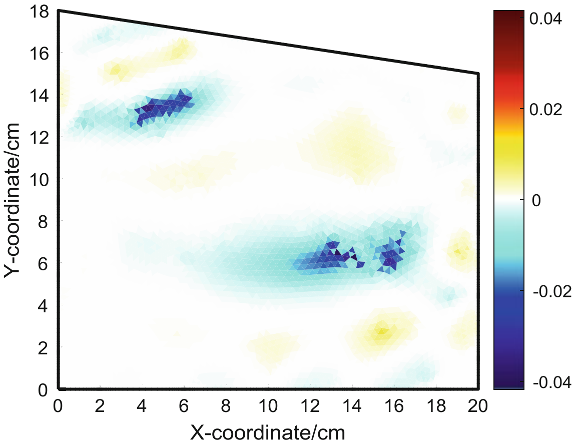


**Fig. 7** Reconstructed conductivity change of the CNT film with double impact damage

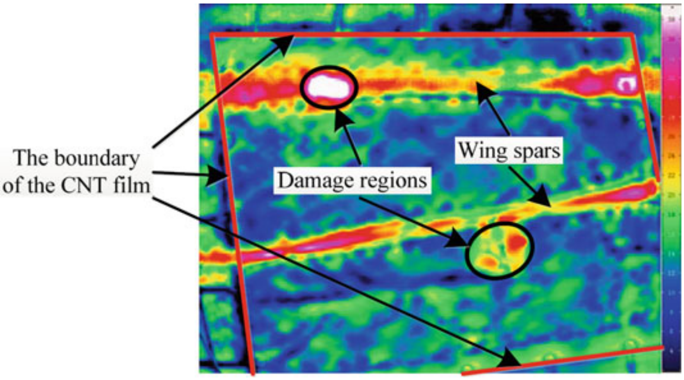


**Fig. 8** Infrared thermal images of the UAV wing with impact damage

by L1-norm regularization algorithm are close to those detected by infrared thermography, thus further demonstrating the effectiveness of the L1-norm regularization EIT algorithm for detecting the damage.

## 5 Conclusion

In conclusion, this study describes an experimental methodology for SHM of composites by EIT. Specifically, a CNT film is used to damage detection and imaging for a composite UAV wing by providing the structure with self-sensing capability. An EIT system is established to inject current and efficiently measures the change of boundary voltages caused by damage. In order to solve the ill-posed EIT inverse problem, L1-norm regularization is used to perform the reconstruction. Experimental results have demonstrated that L1-norm regularization can well reconstruct the conductivity change caused by impact damage, thus enabling EIT to detect and localize of the impact damage in the UAV wing.

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