MICROVAWE IMAGING FOR NONDESTRUCTIVE EVALUATION OF CIVIL STRUCTURES

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Abstract: Subsurface imaging of civil structures is a subject of growing interest because of the need check the integrity of buildings, roads, and bridges in a non-invasive (and certainly nondestructive way). In this framework, this study is aimed at presenting a microwave imaging technique for crack or failure detection. The proposed approach is based on a numerically computed Green's function and on an effective evolutionary optimization technique. In order to evaluate the achieved results and to assess the effectiveness and current limitations of the proposed approach, a set of selected numerical simulation is presented.

Introduction: Non-invasive diagnostics methods based on microwaves are currently used in various applications ranging from industrial and civil engineering to geophysical monitoring and biomedical analysis [1]-[4]. In this framework, microwave tomographic approaches have been recently proposed. [5]-[7]. Starting from the knowledge of the fields scattered from an unknown sample under test illuminated by means of a known probing electromagnetic source, these techniques are aimed at determining the distribution of the dielectric characteristics of the whole investigation domain.

However, such a redundant information is not needed in non-destructive evaluation (NDE) and non-destructive testing (NDT) applications. Generally, only the reconstruction of a small defect buried in a completely known host medium is required. Consequently, customized approaches have been developed [8]-[10]. More in detail, these approaches resort to a parameterization of the unknown defect, assumed of rectangular shape, by defining some key features as the position, the dimensions and the orientation. Then, the inverse problem to be handled turns out to be notably simplified with a reduction of the overall computational burden for the optimization procedure.

In this paper, an effective method called Inhomogeneous Green's based Approach (IGA), belonging to the class of NDE/NDT customized strategies, is applied to the civil engineering scenarios.

The paper is organized as follows. After a brief presentation of the mathematical formulation (Sect. "Mathematical Formulation"), a numerical validation will be presented by considering selected experiments (Sect. "Numerical Validation"). Finally, some conclusion will be reported (Sect. "Conclusions").

Mathematical Formulation: Let us consider a standard inverse scattering problem (Fig. 1), where a two-dimensional scenario is illuminated by a set of V known electromagnetic sources radiating electric fields $E_{inc}^{v}(x, y)$, $v = 1,...,V$.

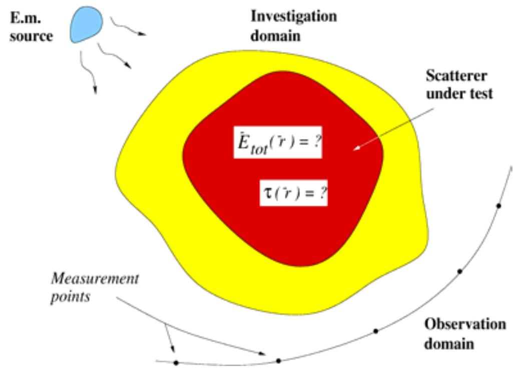


Fig. 1. Inverse scattering reference scenario

Starting from the knowledge of the scattered electric field collected at M measurement points $E^{v}_{scatt}(x_m, y_m)$, $m = 1,...,M$, the inversion procedure is aimed at determining the object function $\tau(x, y)$ and the electric field distribution in the investigation domain $(x, y) \in D_I$.
On the other hand, the aim of a NDT/NDE inversion process is to retrieve the descriptive parameters of an unknown object (called in the following "defect" or "crack") buried into a known host medium (Fig. 2).

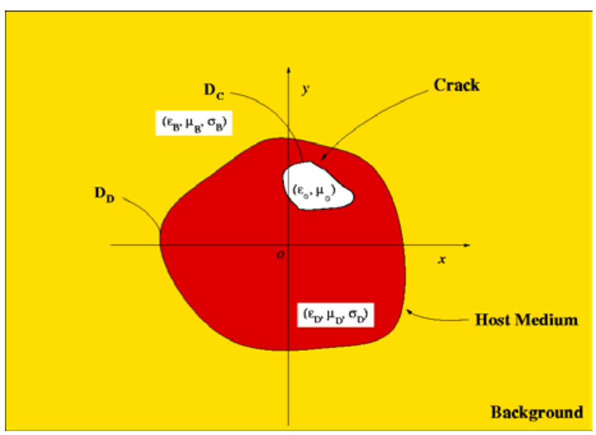


Fig. 2. NDE/NDE reference geometry

Neither an image of the dielectric distribution of the investigation domain nor an accurate description of the defect is required. A large amount of *a-priori* information is available. Then effective numerical techniques, able to fully exploit this knowledge and to determine a limited set of parameters, could be efficiently used. Towards this end, several numerical strategies have been proposed based on optimization procedure (see [8] and the references cited therein), which define a two-step process. Firstly, the existence of the defect is verified. Then, the unknown defect is reconstructed by determining its descriptive parameters.

More in detail, the first step verifies the presence of a defect by defining a detection cost function ϕ_d

$$\phi_d = \frac{1}{V}\sum_{v=1}^{V}\left\{\frac{\int_S \left|E^v_{scatt\,(cf)}(x,y) - E^v_{scatt\,(c)}(x,y)\right|^2 dxdy}{\int_S \left|E^v_{scatt\,(cf)}(x,y)\right|^2 dxdy} - \Omega_{noise}\right\} \leq\geq \xi \qquad (1)$$

where $E^v_{scatt(cf)}$ is the scattered electric field of the known crack-free configuration, $E^v_{scatt(c)}$ is the actual measure, and

$$\Omega_{noise} = \frac{\int\int_S \left|E^v_{scatt\,(cf)}(x,y) - E^{v(noiseless)}_{scatt\,(c)}(x,y)\right|^2 dxdy}{\int_S \left|E^{v(noiseless)}_{scatt\,(cf)}(x,y)\right|^2 dxdy}$$

is a known measure of the environmental noise. If the value of the detection function is greater than a fixed threshold (heuristically defined) the algorithm assumes the "presence of a defect". Otherwise the structure is assumed crack-free and the inversion process stops.
If the presence of a defect has been assumed, the retrieval procedure starts. Under the hypothesis of a buried defect with a rectangular shape (Fig. 3), the process is aimed at defining the defect descriptors (i.e., the coordinates of the defect center, the dimension and the orientation):

$$\overline{p}_{crack} = \{x_0, y_0, L_{crack}, W_{crack}, \alpha_{crack}\} \qquad (2)$$

Moreover, the electric field distribution in the investigation domain has to be determined as well

$$\overline{p}_{field} = \{E^v_{tot}(x_n, y_n); v = 1,\ldots,V; n = 1,\ldots,N\} \qquad (3)$$

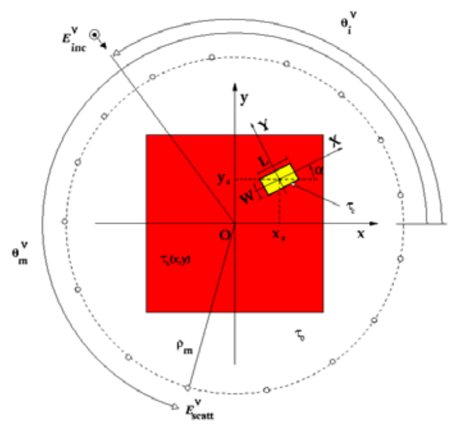


Fig. 3. Crack Parametrization

The problem solution is then recast into an optimization one. A suitable cost function Θ is defined [9][10] according to inverse scattering equations

$$\Theta(\overline{p}) = \Theta_{Data}(\overline{p}) + \Theta_{State}(\overline{p}) \tag{4}$$

where

$$\Theta_{Data}(\overline{p}) = \frac{\sum_{v=1}^{V}\sum_{m=1}^{M}\left|E_{scatt}^{v}(x_m, y_m) - \Omega_{Data}^{m}\{\overline{p}\}\right|^2}{\sum_{v=1}^{V}\sum_{m=1}^{M}\left|E_{scatt}^{v}(x_m, y_m)\right|^2}$$

and

$$\Theta_{State}(\overline{p}) = \frac{\sum_{v=1}^{V}\sum_{n=1}^{N}\left|E_{inc}^{v}(x_n, y_n) - \Omega_{State}^{n}\{\overline{g}\}\right|^2}{\sum_{v=1}^{V}\sum_{n=1}^{N}\left|E_{inc}^{v}(x_n, y_n)\right|^2}$$

where $\overline{p} = \{\overline{p}_{crack}, \overline{p}_{field}\}$. Since such a cost function presents a high nonlinearity degree, the minimization needs the use of a global optimization technique in order to avoid the convergence solution be trapped in a local minima (which represents a wrong reconstruction) [9].
However, if the use of a hill-climbing technique strongly limits the occurrence of false solution, it does not allow a real-time processing. Towards this end, a formulation based on the numerical computation of the inhomogeneous Green's function (IGA) [10] heavily improves the effectiveness of the iterative optimization process by limiting the searching space. In such a framework, the standard Fredholm [11] equation is rewritten in the alternative form

$$E_{tot}^{v}(x,y) = E_{inc}^{v}(x,y) + \iint_S \tau_{S_D}(x',y')E_{tot(cf)}^{v}(x',y')G_0(k_0 r)dx'dy' + \iint_D \tau_D(x',y')E_{tot}^{v}(x',y')G_I(x,y/x',y')dx'dy' \tag{5}$$

where S refers to the unperturbed configuration, τ_D is the differential object function (defined as the difference between the object function of the host medium and that of the defect), $E_{tot(cf)}^{v}$ is the electric field induced in the crack-free investigation domain by the incident field and G_I satisfies the following equation

$$G_I(x,y/x',y') = G_0(x,y/x',y') + \iint_S \tau_{S_D}(x'',y'')G_I(x'',y''/x',y')G_0(x,y/x'',y'')dx''dy''. \tag{6}$$

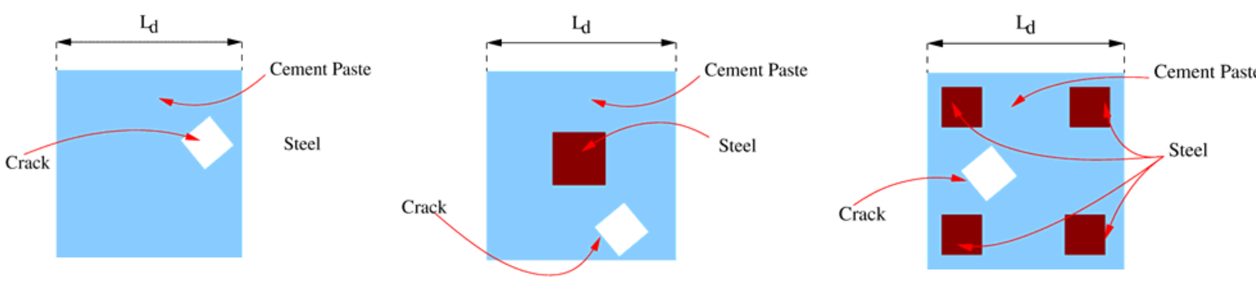
Since the first two terms of equation (5) can be considered as a known equivalent "incident field", once G_I has been numerically computed, the problem is limited to the estimate of the descriptors of the "differential object function" which occupies the defect area [10].
Numerical Validation: In order to assess the effectiveness of the proposed approach, a set of selected numerical results has been considered. Figure 4 shows the geometrical configurations of the reference test cases used for the validation. The investigation domain is supposed to be a squared cylinder $L_d = 4.167\,\lambda_0$-sided. $M = 50$ measurement points have been placed in a circular

observation domain $2.83\lambda_0$ in radius. The scenario under test has been illuminated from $V = 4$ orthogonal directions.

More in detail, the test case called "Structure Type 1" (Fig. 4(*a*)) is composed by an host medium modeling a homogeneous cement paste and characterized by $\varepsilon_R^{host} = 2.37$ and $\sigma^{host} = 5.7\times10^{-4}\ S/m$ [12]. This situation can represent the section of a decorative column in a room.

As far as the second test case is concerned ("Structure Type 2" – Fig. 4(*b*)), it considers the presence of a squared load bearing ($0.42\lambda_0$-sided) in the center of the structure ($\varepsilon_R^{steel} = 1.0$, $\sigma^{steel} = 1.1\times10^{6}\ S/m$) [12].

The last scenario ("Structure Type 3", Fig 4(*c*)) is composed by a load bearing beam with 4 steel bars inserted representing a "reinforced concrete" structure. The side of the squared bars is $0.31\lambda_0$ in side and the distance from the border of the pillar is equal to $0.52\lambda_0$.



(*a*) (*b*) (*c*)

Fig. 4. Test cases: (*a*) Structure "Type 1", (*b*) Structure "Type 2", and (*c*) Structure "Type 3".

Firstly, the dependence of the reconstruction accuracy of the IGA-based approach from the dimensions of the defect has been evaluated. The ratio $\left(A_C/\lambda_0^2\right)$ has been varied from 1.1×10^{-4} to 2.7×10^{-3}, A_C being the area of the unknown defect in the actual configuration. In order to quantitatively estimate the reconstruction accuracy, the following error figures are then defined. The *localization error* δ_C

$$\delta_C = \frac{\sqrt{(x_c-\hat{x}_c)^2+(y_c-\hat{y}_c)^2}}{d_{\max}}\times100 \tag{7}$$

where $d_{\max}$ is the maximum error equal to the diagonal of the investigation domain, and the *area estimation error* δ_A

$$\delta_A = \frac{A_c-\hat{A}_c}{A_c}\times100 \tag{8}$$

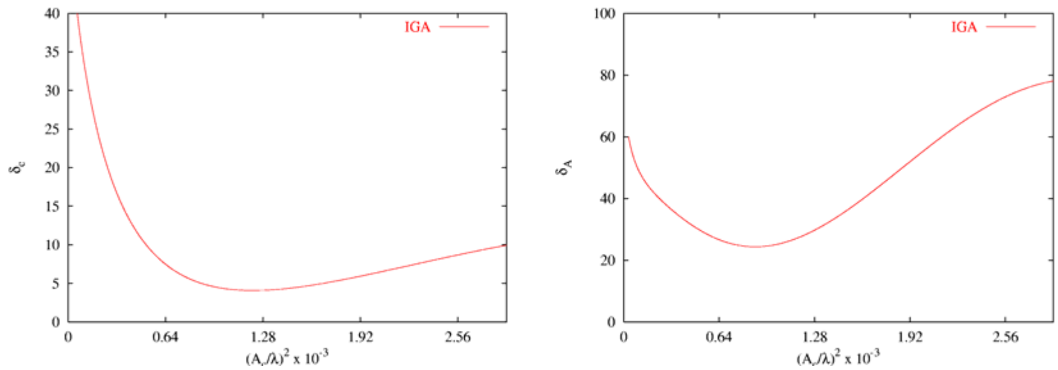
where the superscript ^ differentiates estimated from actual quantities, respectively.

Moreover, because of the stochastic nature of the optimization method, $P = 10$ independent simulations have been carried out for each configuration under test (in terms of the area of the unknown crack in the actual geometry) and the average values of the error figures will be reported in the following.

As far as the first case is concerned (Fig. 4(*a*)), the localization of a crack with area $A_c > 0.11\,\lambda_0^2$ is obtained with a maximum error of about $av_{p=1,\dots,P}\{\delta_C\} = 15\%$ (Fig. 5(*a*)) and the error in estimating the crack area is on average equal to $av_{A_c}\{av_{p=1,\dots,P}(\delta_A)\} = 45\%$.

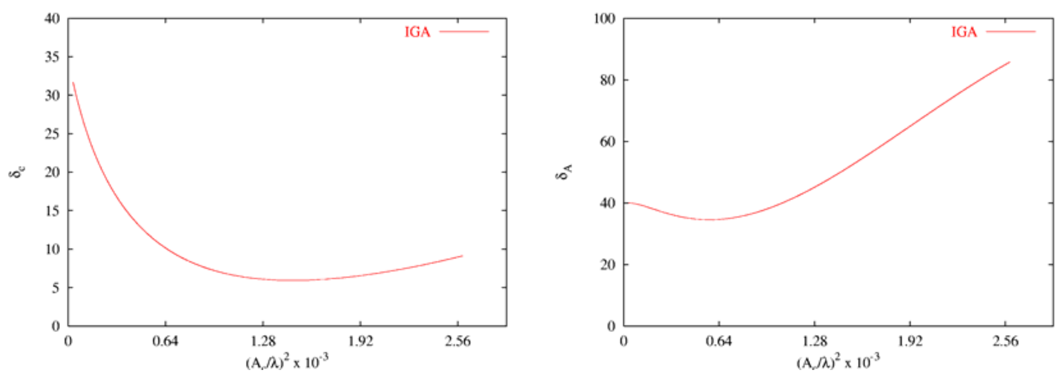
The reconstruction results related to the "Structure Type 2" are reported in Fig. 6. In this environment, the crack is localized with a great accuracy when $A_c > 0.22\,\lambda_0^2$ ($av_{p=1,\dots,P}\{\delta_C\} < 10\%$ being the localization error figure) (Fig. 6(*a*)). On the other hand, the mean error in estimating the defect dimensions slightly increases with respect to the structure 1 ($av_{A_c}\{av_{p=1,\dots,P}(\delta_A)\} = 47\%$).

As can be observed from Fig. 7, the presence of a set of four steal bars significantly affects the performances of the proposed approach. On average, the localization error as well as the estimation of the defect area increases ($av_{A_c}\{av_{p=1,\dots,P}(\delta_c)\} = 17\%$ and $av_{A_c}\{av_{p=1,\dots,P}(\delta_A)\} = 58\%$).



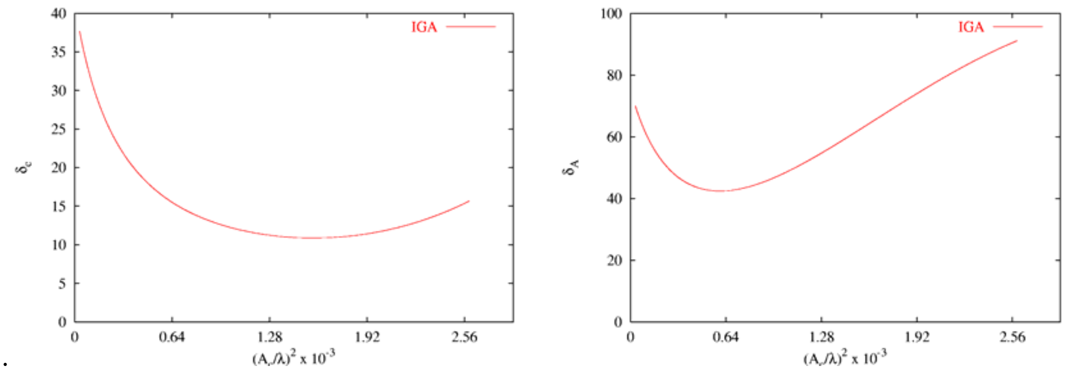
(*a*) (*b*)

Fig. 5. Structure "Type 1" - Error Figures: (*a*) Localization Error and (*b*) Area Estimation Error.



(*a*) (*b*)

Fig. 6. Structure "Type 2" - Error Figures: (*a*) Localization Error and (*b*) Area Estimation Error.



(*a*) (*b*)

Fig. 7. Structure "Type 3" - Error Figures: (*a*) Localization Error and (*b*) Area Estimation Error.

Conclusions: In this paper, a microwave imaging technique for non-destructive evaluation of civil structures has been presented. By considering a numerically-computed Green's function related to the inhomogeneous host medium, the method is able to improve the effectiveness of the optimization procedure avoiding at the same time that the solution be trapped in false solutions corresponding to wrong reconstructions. Selected simulation results, related to realistic structures, have demonstrated a significant accuracy in the defect retrieval in terms of localization as well as estimation of the occupation area. Future developments will be aimed at further exploit the *a-priori* information on the scenario under test as well as at extending the approach to three-dimensional geometries.

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