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FINITE FREQUENCY SENSITIVITY KERNELS FOR MICROWAVE NDE OF METAL-COMPOSITE JOINTS

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ABSTRACT

Composites are being increasingly used in civil, military and aerospace applications due to their unique properties such as high strength, low weight, durability and corrosion resistance. The high sensitivity of microwaves towards dielectric composites can be utilized for nondestructive evaluation and structural health monitoring. We investigate the capability of the adjoint inversion method for microwave imaging of composites. The computed electromagnetic finite frequency sensitivity kernels derived from the adjoint technique are utilized for imaging disbonds and for providing structural integrity information of metal-composite interfaces.

Keywords: microwave NDE, composites, adjoint, disbond

1. INTRODUCTION

Composites are replacing metals, either partially or fully in the aerospace, civil and automotive industries over the past few decades [1]. In structures involving both metals and composites, adhesively bonded joints are preferred in contrast to conventional fasteners, since they provide low weight designs, reducing potential stress concentrations. The quality and performance of these materials can be severely compromised due to manufacturing or in-service faults. Defects in the form of disbonds, voids and delaminations may appear in these materials, affecting their overall strength and performance [2]. Thus, there is a need for a reliable nondestructive evaluation technique for determining the structural integrity of such materials.

Microwaves have the ability to propagate through composite materials, without suffering much attenuation [3]. The scattered fields depend on the dielectric properties, and hence provide information about the structural integrity of these materials. Microwave NDE techniques offer significant advantages over existing NDE techniques such as rapid, large area inspection at large stand-off distance, high resolution and deep penetration, single side access and no requirement for a coupling medium [4].

In this contribution, we introduce the finite-frequency sensitivity kernels for microwave NDE of metal-composite joints. These kernels are derived based on the interaction of a forward wavefield and a back propagated wavefield, called an adjoint field. Numerical simulations are performed using a highly efficient spectral-element code, that is capable of handling complex geometries, while maintaining exponential convergence and high accuracy. The kernels highlight the sensitivity of the recorded electromagnetic field to different parameters such as permittivity and conductivity of the composite material. The overall approach is applied towards detection of disbonds in a metal-composite joint sample in order to demonstrate the efficiency of the proposed approach.

2. ADJOINT INVERSION

The adjoint method is used to solve an inverse problem by performing two numerical simulations. The first simulation computes a forward field from a source to receiver electrodes, while the second simulation calculates an adjoint field, which consists in backpropagating time reversed signals from the receiver electrodes (similar to what has been done successfully for seismic adjoint tomography, see e.g., [5]). The adjoint simulation uses the same numerical solver and framework as the forward simulation, with the exception of the source term, which can be defined as, for example, the difference between simulated and observed data. The overall imaging method can be briefly explained by the following steps:

- Forward wave propagation: One by one, each source transmits electromagnetic waves sequentially, which is back-scattered from the defective metal-composite sample and received by the receiver array.
- A baseline signal is measured for each configuration in a defect free sample in order to obtain the scattering contribution from the sample and metal boundaries.
- The perturbation field due to the defect is achieved by subtracting the baseline signal from the forward field signal for each configuration.

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- The adjoint source corresponding to the perturbation field is back-propagated from the receiver array in a defect free sample model, which is able to provide sensitivity kernels for imaging defects.

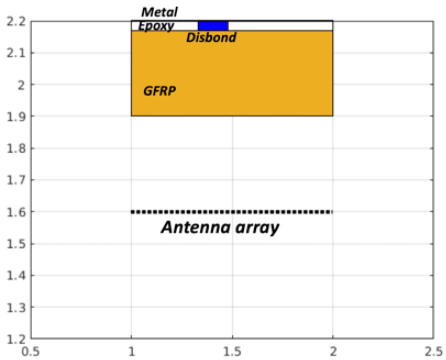

FIGURE 1: SCHEMATIC OF SIMULATION.

2.1 Finite frequency sensitivity kernels

Numerical simulations are performed using the spectral-element software SPECFEM [6], which has been modified to solve for Maxwell's EM equations [7]. The EM adjoint equations and the finite frequency sensitivity kernels for the dielectric permittivity, magnetic permeability and electrical conductivity, are derived by minimizing a misfit function subject to the constraint that the electric field satisfies the EM wave equations, using a Lagrange multiplier method [8]. The resulting expressions for the dielectric permittivity (K_{ε}), magnetic permeability (K_{μ}) and electrical conductivity (K_{σ}) kernels are given by:

$$K_{\varepsilon} = -\int_{0}^{T} \varepsilon^{e} \boldsymbol{E}^{\dagger}(T-t) \,.\, \partial_t^2 \boldsymbol{E}(t)\ dt$$
$$K_{\mu} = -\int_{0}^{T} 2\, \mu^{-1}\, \boldsymbol{\tau}(t) :\, \boldsymbol{\varphi}^{\dagger}(T-t)\, dt \qquad (1)$$
$$K_{\sigma} = -\int_{0}^{T} \sigma^{e} \boldsymbol{E}^{\dagger}(T-t) \,.\, \partial_t \boldsymbol{E}(t)\ dt$$

where $\boldsymbol{E}$ is the forward electric field, $\boldsymbol{E}^{\dagger}$ is the adjoint electric field, $\boldsymbol{\tau} = \frac{1}{2}[\nabla \boldsymbol{E} - (\nabla \boldsymbol{E})^{T}]$, $\boldsymbol{\varphi}^{\dagger} = \frac{1}{2}[\nabla \boldsymbol{E}^{\dagger} - (\nabla \boldsymbol{E}^{\dagger})^{T}]$, ε^{e}, μ and σ^{e} are the dielectric permittivity, magnetic permeability and electrical conductivity respectively.

3. SIMULATION RESULTS

In the following, we synthetically test the capability of adjoint inversion for defect detection. The computational domain is truncated using absorbing boundary conditions. The excitation source is a Ricker wavelet pulse with a dominant frequency of 1 GHz (λ=0.3 m) and a pulse width of 400 ps, corresponding to a wide bandwidth of 4 GHz. The sample to be inspected is a composite bonded to a metal by an epoxy layer. The composite is chosen to be Glass Fiber Reinforced Polymer (GFRP), which is predominantly used in the aerospace industries and are quite sensitive to microwaves. Disbonds are defects in the epoxy layer modeled as air gaps. The schematic of the geometry along with the dimensions are shown in Figure 1. The dielectric properties of the sample are used as follows: ε_r=4.6, tan δ=0.012 for GFRP

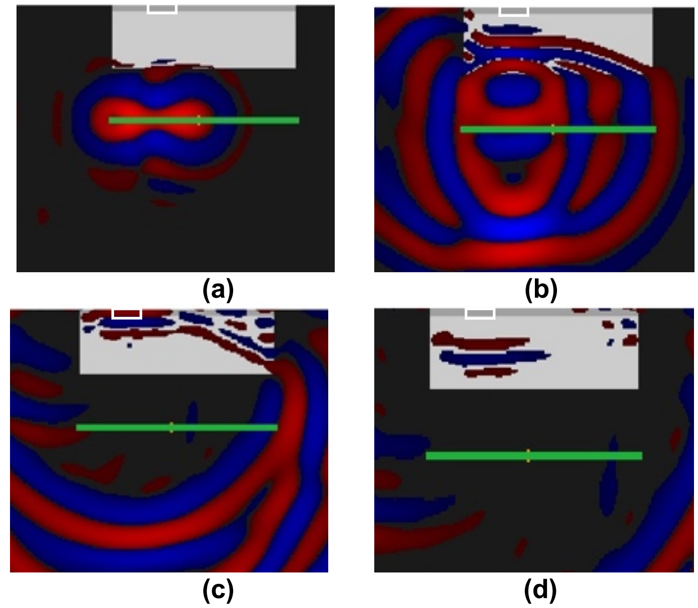

FIGURE 2: VISUALIZATION OF BACK-PROPAGATING ADJOINT EM FIELDS CORRESPONDING TO A SINGLE SOURCE SHOWS THE TRIGGERED WAVE: (a) INITIATING FROM RECEIVER ARRAY, (b) STARTING TO CONVERGE, (c) FOCUSED AT THE DISBOND LOCATION AND (d) DIVERGES AWAY FROM THE DISBOND.

and ε_r=2.8, tan δ=0.012 for the epoxy layer [9]. The spatial dimensions of the sample are as follows: 1 m (3.3 λ) × 0.3 m (λ) for GFRP, 1 m (3.3 λ) × 0.03 m (λ/10) for the epoxy layer and 0.3 m (λ) × 0.03 m (λ/10) for the disbond. The scattered signals from the defect sample are subtracted from scattered signals from a defect free sample in order to obtain the disbond contribution.

A radar array survey setup with 20 evenly distributed sources and 50 evenly spaced receivers located at the surface between 1 m and 2 m is used to collect the backscattered EM fields. Forward and adjoint simulations are conducted for all the sources individually, in accordance with the imaging method. Visualization of the back-propagated adjoint EM fields for each source location shows the waves radiating out from the receiver array, starting to converge, focused at the disbond and diverging away from the disbond location, as shown in Figure 2. The kernels for each source configuration are computed and stacked together by simply summing up them all in order to produce a complete image for the entire domain. The kernels are displayed in Figure 3. The presence of the disbond in the epoxy layer can be clearly detected in all the kernels. The permittivity kernel shows the maximum sensitivity towards the defect due to the high dielectric contrast between the GFRP composite and air. Although the permeability and conductivity kernels can detect the disbond, their sensitivity towards down range is poor since there is no contrast of permeability and very less contrast of conductivity. Additionally, the down range resolution is limited due to diffraction limits, which states that the maximum achievable resolution in the far field is of the order of (λ/2). As the thickness of the disbond is 10 times less than the operating wavelength, the focusing spot around the disbond is stretched along the down range direction. The comparison of the normalized kernels shows that the full width at half maxima of the kernels (0.4 m) is almost equal to the length of the disbond.

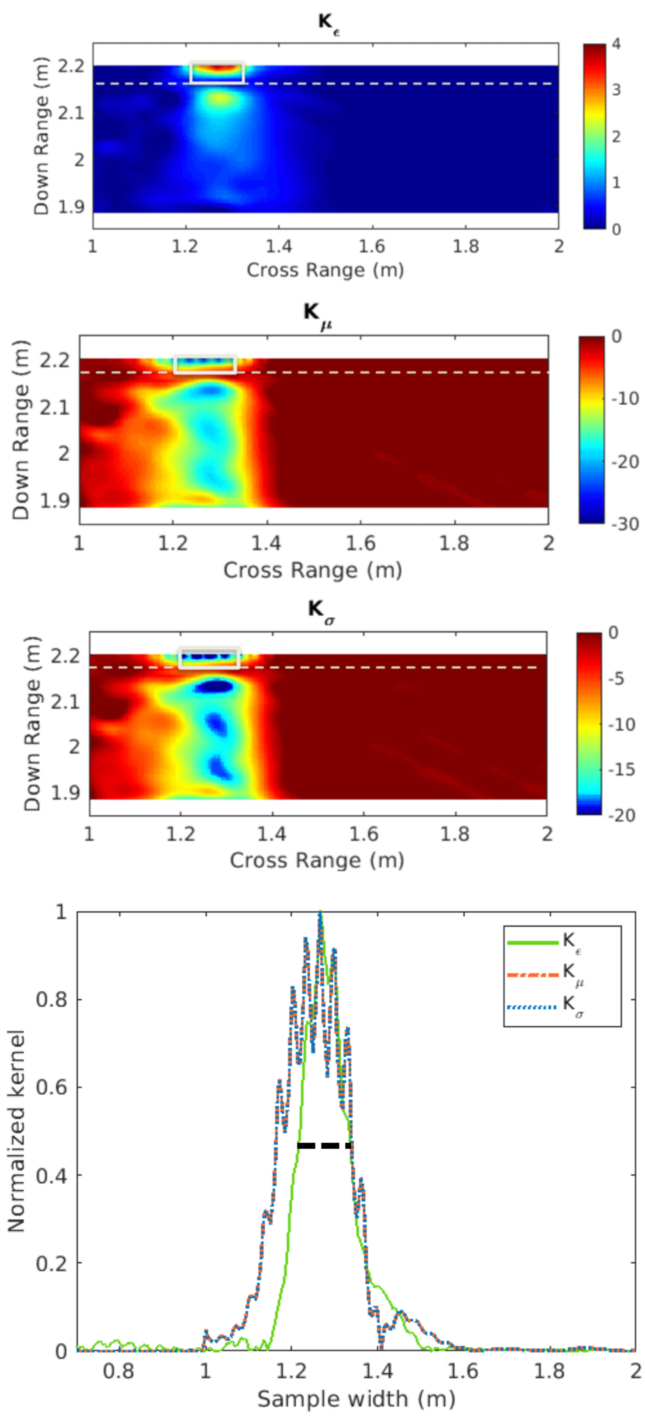

FIGURE 3: EM KERNELS (FROM TOP TO BOTTOM): K_ε, K_μ, K_σ, AND COMPARISON OF DIFFERENT KERNELS (DASHED LINE INDICATES ACTUAL DISBOND SIZE).

4. CONCLUSION

In this contribution, the capability of using finite frequency EM sensitivity kernels was studied for NDE of metal composite joints. The back-scattered electromagnetic fields are subtracted from a healthy sample in order to obtain the disbond perturbation. The perturbation field is converted into corresponding adjoint sources and back-propagated in a healthy sample model. The fields start converging from the receiver array, are focused at the disbond and diverge away from the defect location. The EM sensitivity kernels obtained from the adjoint method highlight the sensitivity of the recorded EM fields to dielectric and conductive discontinuities. The kernels are capable of imaging and accurately sizing sub-wavelength sized disbond in the metal-composite interface.

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