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HIGH RESOLUTION RAPID MICROWAVE NDE OF METAL-COMPOSITE JOINTS USING METALLIC REFLECTORS

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ABSTRACT

With the ever increasing usage of composites in civil, automative and aerospace industries, there has been an emphasis on developing a high resolution nondestructive evaluation (NDE) system. Microwave NDE techniques are well suited for inspection of dielectric materials such as composites because of the ability of electromagnetic waves to interact with these materials. While a far field microwave system has the capability of rapid, large area inspection at large stand-off distances, their resolution is limited due to diffraction limits. This research leverages the benefits of super-resolution property of time reversal focusing in a metallic reflector environment for enhancing the resolution of microwave far field NDE. Numerical simulations involving detecting disbonds in metal-composite joints validate the concept and demonstrate the benefits of the proposed approach.

Keywords: time reversal, microwave NDE, super resolution

1. INTRODUCTION

Composites are being increasingly used in several industries to replace metals, fully or partially due to their unique properties such as high strength, durability and light-weight [1]. Critical defects while manufacturing or in-service that affect the structural integrity of composites need to be identified and monitored by a reliable NDE system [2]. Microwave NDE is particularly suited for inspection of Glass Fiber Reinforced Polymer (GFRP) composites due to their high sensitivity to low loss dielectric materials in comparison to other conventional NDE techniques [3]. Some of the recent applications of Microwave NDE involve corrosion detection in painted aluminum and steel substrates and flaw detection in Sprayed on Foam Insulation of space shuttles [4, 5].

Microwave far field imaging techniques are non-contact in nature and quite useful in rapid inspection of large areas at large stand-off distances. However, the diffraction limits constrain the resolution of microwaves to the order of the operating wavelength (~ 100 cm - 1 cm) [6]. While microwave near field imaging systems can provide much finer resolution (order of mm), it results in exceptionally high scanning time which may be unacceptable for a rapid inspection system [7]. This research focuses on enhancing the resolution of far field microwave imaging by exploiting the super-resolution properties of time reversal focusing in a metal-reflector environment.

Time reversal is a source focusing method which can be utilized to image defects that act as secondary sources in composite materials [8, 9]. Metal reflectors placed in the imaging environment serve to reflect the outgoing electromagnetic fields and direct them towards the receiving antenna array. The increase in the aperture size of the receiving antenna array due to the reflected energy results in an increase in the spatial resolution, leading to super resolution. Simulation studies demonstrate the capability and robustness of the approach for imaging disbonds in metal-composite joints.

2. TIME REVERSAL WITH METAL REFLECTORS

The time reversal property is a consequence of the time-symmetric nature of the electromagnetic wave equation [10]. Due to this property, the scattered fields from a point source collected by the receiver antenna array can be time reversed and back propagated using a numerical model to focus back at the source location. Spatio-temporal localization techniques such as the time integrated energy method can be utilized for imaging applications [11]. Since defects behave as secondary sources, scattered fields from defects can be time reversed and back-propagated to perform imaging using the same algorithm.

The presence of the metal reflectors in effect extends the aperture of the receiver array. This can be physically understood from the following argument. The metal reflectors behave like additional receivers that trap electromagnetic waves that would have otherwise diverged away from the receiver array, thereby virtually extending the effective aperture size.

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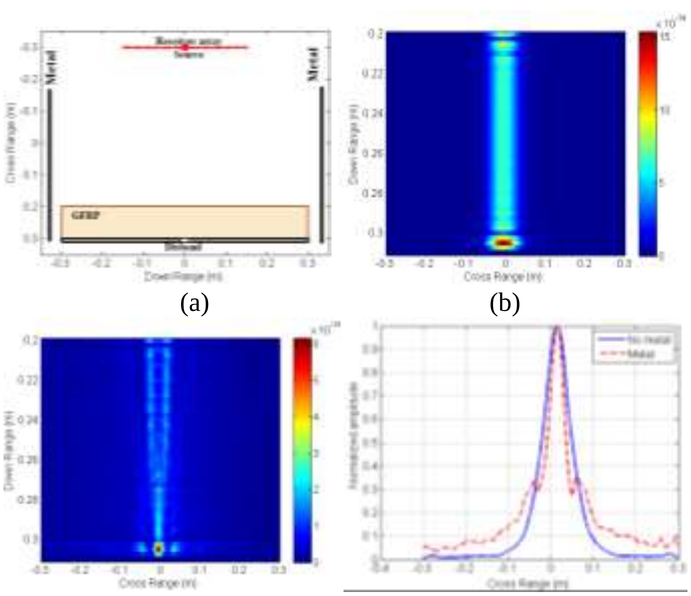
3. NUMERICAL STUDIES

Numerical studies were conducted with and without the metal reflectors in order to study the effects of the reflectors on imaging resolution. The wave propagation phenomenon is numerically modeled for a two-dimensional TMz mode excitation using the finite difference time domain technique, with perfectly matched layer (PML) boundary conditions to truncate the computational domain. The spatial and temporal parameters satisfy Courant's stability criterion. The transmitter is modeled as a point source, and a circular array of sensors is used to collect the back-scattered fields. A modulated Gaussian pulse with a center frequency of 2 GHz and a wide bandwidth of 2 GHz is chosen as the excitation source. The fields are time reversed and back propagated in the same model. A time integrated energy localization method is utilized to detect presence of defects in the dielectric material.

A test sample comprising metal-composite joint is introduced in the inspection geometry, as shown in Figure 1 (a). The geometry of the problem consists of a GFRP composite material adhesively bonded to a metal layer (conductor) via an epoxy layer. Defects in the form of disbonds are introduced as air gaps in the epoxy layer. The material properties of the sample are as follows: ε_r=4.6 and tan δ=0.012 for GFRP, ε_r=2.8 and tan δ=0.017 for the epoxy and ε_r=1 and tan δ=0 for the disbond [12]. The spatial dimensions of the sample are as follows: 0.6 m × 0.1 m for GFRP, 0.6 m × 0.02 m for the epoxy and 0.03 m × 0.02 m for the disbond. The scattered signals are subtracted from a baseline measurement to obtain the defect contribution. The defect signals without the metal reflector environment are time reversed and back-propagated in accordance with the time reversal algorithm. The back-propagated time reversed energy



(a) (b) (c) (d)

FIGURE 1: DETECTION OF DISBONDS: (A) SCHEMATIC OF TEST GEOMETRY, (B) TR ENERGY WITHOUT METAL REFLECTORS, (C) TR ENERGY WITH METAL REFLECTORS, (D) COMPARISON OF CROSS RANGE SIGNALS

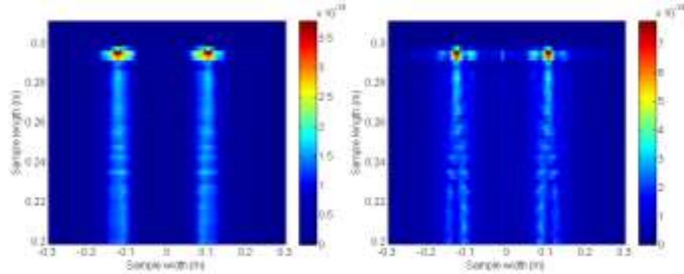


FIGURE 2: TR ENERGY FOR VARYING METAL LENGTHS, (LEFT) LENGTH: 5 CM, (RIGHT) LENGTH: 40 CM

highlights the location and spatial extents of the disbond, as seen in Figure 1 (b). However, there is a spreading effect observed along the down range direction resulting in a smeared image of the defect, due to limited aperture size of the receiver array along the down range direction. Similar simulations are carried out with 2 metal reflectors with spacing and length of 20 cm and 17 cm respectively. The TR energy is more accurately focused near the disbond location when the metal reflectors are introduced, as seen in Figure 1 (c). The down range spreading effect is diminished to a large extent with the metal reflectors, leading to an enhancement in imaging resolution. The cross range signal is defined by a line scan across the energy image corresponding to the source location. There is also improvement in the cross range resolution as can be seen from the comparison of the cross range signals with and without the metal reflectors (Figure 1 (d)). The full width at half maxima (FWHM) of the signals is used to estimate the length of the disbond. The true disbond length is 3 cm; the estimated length without the metal reflectors is 7.5 cm and in the presence of the metal reflectors, the estimate is 4cm. This example quantitatively validates the hypothesis of enhancing imaging resolution via increased aperture size by introducing appropriate metal reflectors.

Next simulations are conducted with two disbonds separated by 20 cm, with a fixed metal spacing of 80 cm. Two cases with the length of the metal reflectors as 5 cm and 40 cm are studied. As shown in Figure 2, the imaging resolution improves with increase in the length of the metal reflectors. This is because as the length of the metallic reflectors increase, the incident field at larger angles get reflected towards the receiver array, leading to an improvement in resolution. The estimation of the disbond size becomes more accurate with increase in the length of the reflectors, the estimated value nearing its actual value when the metal length is 40 cm.

Finally, simulations are conducted with two disbonds separated by 20 cm, with a fixed metal length of 50 cm. Two cases with the spacing between the metal reflectors as 6 cm and 8 cm are studied. As shown in Figure 3, the imaging resolution improves with increase in the spacing between the metal reflectors. This is because as the spacing between the metallic reflectors increase, the incident field at larger angles get reflected towards the receiver array, leading to an improvement in resolution. The estimation of the disbond size becomes more accurate with increase in the length of the reflectors, the

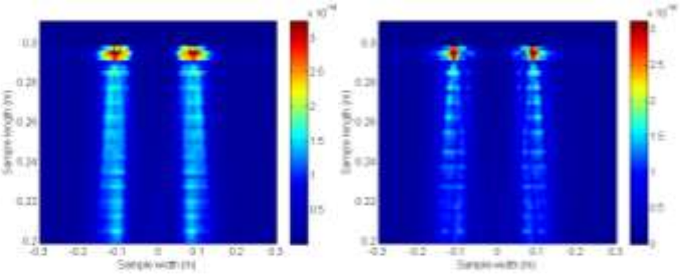


FIGURE 3: TR ENERGY FOR VARYING METAL SEPARATION, (LEFT) GAP: 6 CM, (RIGHT) GAP: 8 CM

estimated value nearing its actual value when the metal spacing is 8 cm.

4. CONCLUSION

This research investigates the feasibility of implementing time reversal imaging to data collected in the presence of metal reflectors in order to enhance the resolution of microwave far field imaging. Numerical simulations based on FDTD are conducted to show the efficiency of the proposed approach for detection of disbonds in metal-composite joints. The effect of the length of the reflectors and the gap between them are studied numerically in order to understand some guidelines for choosing geometrical parameters of the test setup with metal reflectors. The results presented in this paper lays the foundation for building a robust, high resolution microwave experimental imaging system for NDE of composites. More extensive validation of the method for detecting different damage mechanisms such as impact damages is in progress.

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