MICROWAVE IMAGING OF DEFECTS IN SOLIDS

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INTRODUCTION

As higher and higher frequencies of microwaves become available, electromagnetic *waves*, and not only electromagnetic eddy currents are about to develop as a powerful tool for NDE. Particularly, existing ultrasonic imaging methods which rely on the typical physical behavior of waves might be checked against their utilization in microwave equipments. It is the aim of this paper to investigate the performance of SAFT type algorithms when applied to a simple microwave scattering experiment. In addition, it is pointed out how the polarimetric information of electromagnetic waves could be exploited for better quantitative imaging.

SYNTHETIC APERTURE FOCUSING

Let us give a brief explanation what the ultrasonic imaging scheme "SAFT" — Synthetic Aperture Focusing Technique — is all about. Suppose, the vector of position $\underline{\mathbf{R}}'$ varies on a twodimensional, not necessarily planar, measurement surface S_M, and ultrasonic rf-scattering data $\Phi(\underline{\mathbf{R}}', t)$, where t is the time, are recorded on that surface in a pulse-echo mode of operation. Then, a SAFT image $o(\underline{\mathbf{R}})$ — $\underline{\mathbf{R}}$ varies in imaging space — is *defined* via backpropagation of these data in terms of

$$o(\underline{\mathbf{R}}) = \int\int_{S_M} \Phi\left(\underline{\mathbf{R}}', t = \frac{2|\underline{\mathbf{R}} - \underline{\mathbf{R}}'|}{c}\right) \mathrm{d}S' \quad . \tag{1}$$

Here, c denotes the wave speed of the waves under concern in the *unbounded, homogeneous,* and *isotropic* host medium of the scattering defect. Since $\Phi(\underline{\mathbf{R}}', t)$ is processed as a strictly scalar quantity, the vector character and the polarization of the waves is not accounted for, neither is the particular wave mode — pressure or shear — except for the proper wave speed.

Of course, the question arises in what sense $o(\underline{\mathbf{R}})$ is a useful image or even a *reconstruction* of the defect geometry, location and material composition. This question has been answered with the help of inverse scattering theory [1,2], and all assumptions and approximations have been identified, which make (1) a useful imaging scheme. In addition, algorithmic alternatives like FT-SAFT — Fourier Transform SAFT — have been derived [3], which are particularly fast and effective in 3D. The various algorithms were thoroughly compared against experiments and synthetic data [4].

MICROWAVE REMOTE SENSING

Microwave imaging is not only an issue in NDE; it has been, and is, extensively applied in remote sensing as the most general radar problem. In particular, the EMSL — the European Microwave Signature Laboratory — in Ispra/Italy as a research institution of the European Union has been established in order to investigate the potential use of microwaves for *quantitative* determination of, say, parameters of vegetation, soil, ice and so on [5]. We have been able to process some preliminary data obtained in this laboratory with several versions of the SAFT algorithm [6].

MICROWAVE SYNTHETIC APERTURE FOCUSING

The geometry under concern is diplayed in Fig. 1: An acrylic test specimen of size $35\times15\times7$ cm^3 contains a series of circular cylindrical side drilled holes with equal

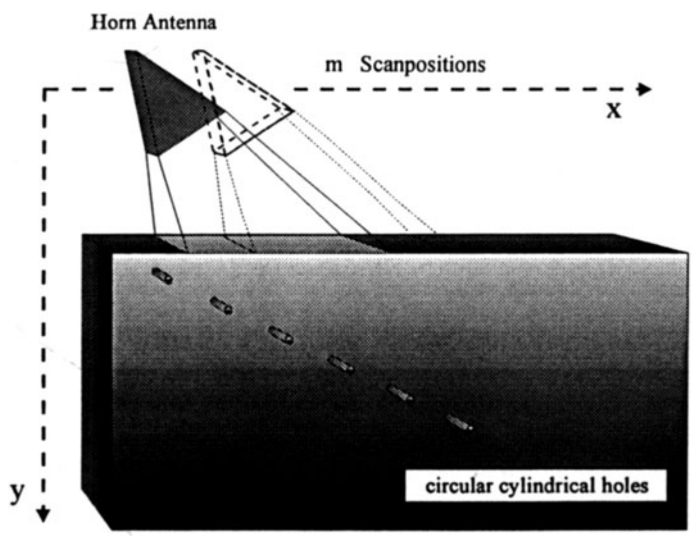

Figure 1. Geometry of microwave experiment.

diameters of 0.3 cm in different depths; its surface is scanned by a horn antenna in a pulse-echo mode, i.e. the antenna is simultaneously used as transmitter and receiver at 513 scan positions, the swept frequency range being 75-100 GHz. The microwave device is an HP network analyzer. Notice, the horn antenna is tilted with regard to the surface normal in order to avoid the reception of the surface reflected signal. Fourier transforming the received complex frequency data into the time domain results in xt-rf-data, which are displayed in Fig. 3. Feeding these data into the algorithm (1), an appropriate wave speed of a *homogeneous* medium has to be chosen. We have tried two alternatives, concentrating either on the air (vacuum) or on the acrylic wave speed, and, obviously, both microwave SAFT results are more or less garbage: Figure 3 exhibits "scattering centres" for both cases, but at the wrong locations. It seems necessary to formulate a two-media SAFT, which accounts for the wave propagation in air (vacuum) *and* acrylic. Since the surface of the specimen is known, a pixel-driven SAFT version based on Fermat's principle, thus accounting for the diffraction at the surface, could be implemented (Figure 2).

The pertinent two-media microwave SAFT result is also given in Figure 3 together with the — known — geometry of the holes: Obviously, the defect location is correct now.

The next example comprises one large — with regard to the wavelength — circular cylindrical side drilled hole with a diameter of 4 cm. The front wall imaging problem is obviously a two-media problem, whereas the backwall imaging problem would be a three-media one — because of the air-filled hole. Indeed, Figure 4, which is similarly composed as Figure 3, perfectly confirms this: Two-media microwave SAFT is not yet able to locate the backwall correctly. By the way, in terms of inverse scattering theory, this drawback is inherent in the linearization of the SAFT "solution" to the inverse scattering problem, i.e. the circular cylindrical hole as a penetrable object for electromagnetic waves is not a weak scatterer as it should be in order to make the SAFT image a reconstruction [1,2,6].

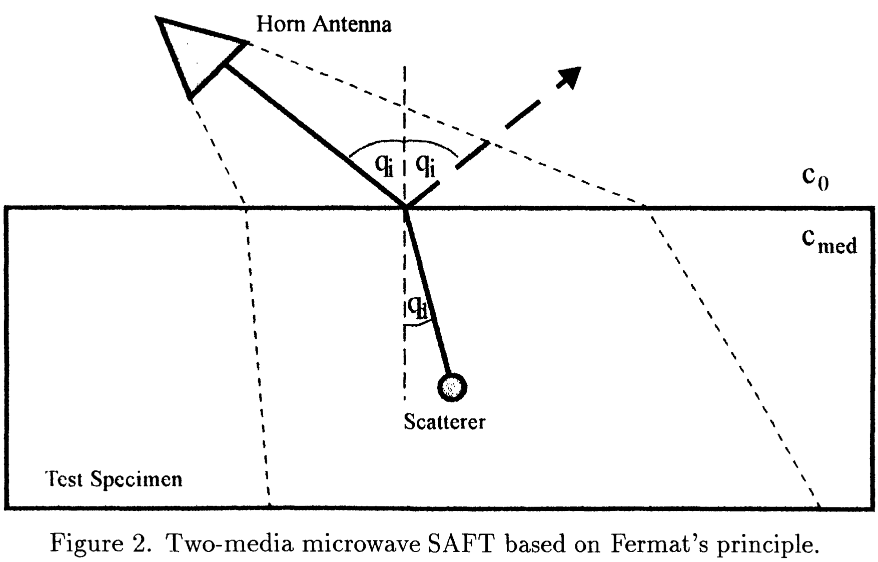

Figure 2. Two-media microwave SAFT based on Fermat's principle.

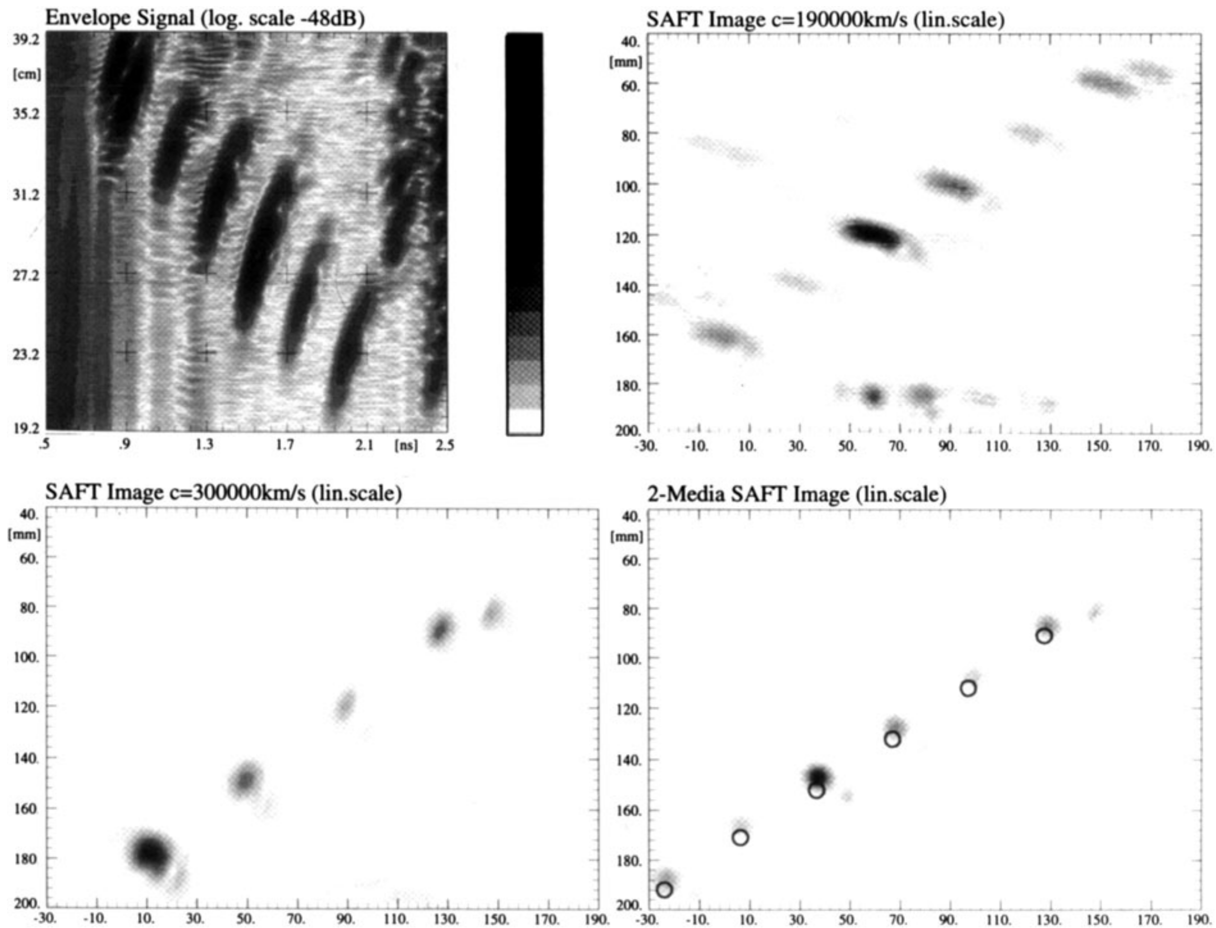

Figure 3. Microwave SAFT: envelope of xt-rf-data (top left); SAFT-image with vacuum wave speed (bottom left); SAFT-image with acrylic wave speed (top right); SAFT- image with two wave speeds (bottom right).

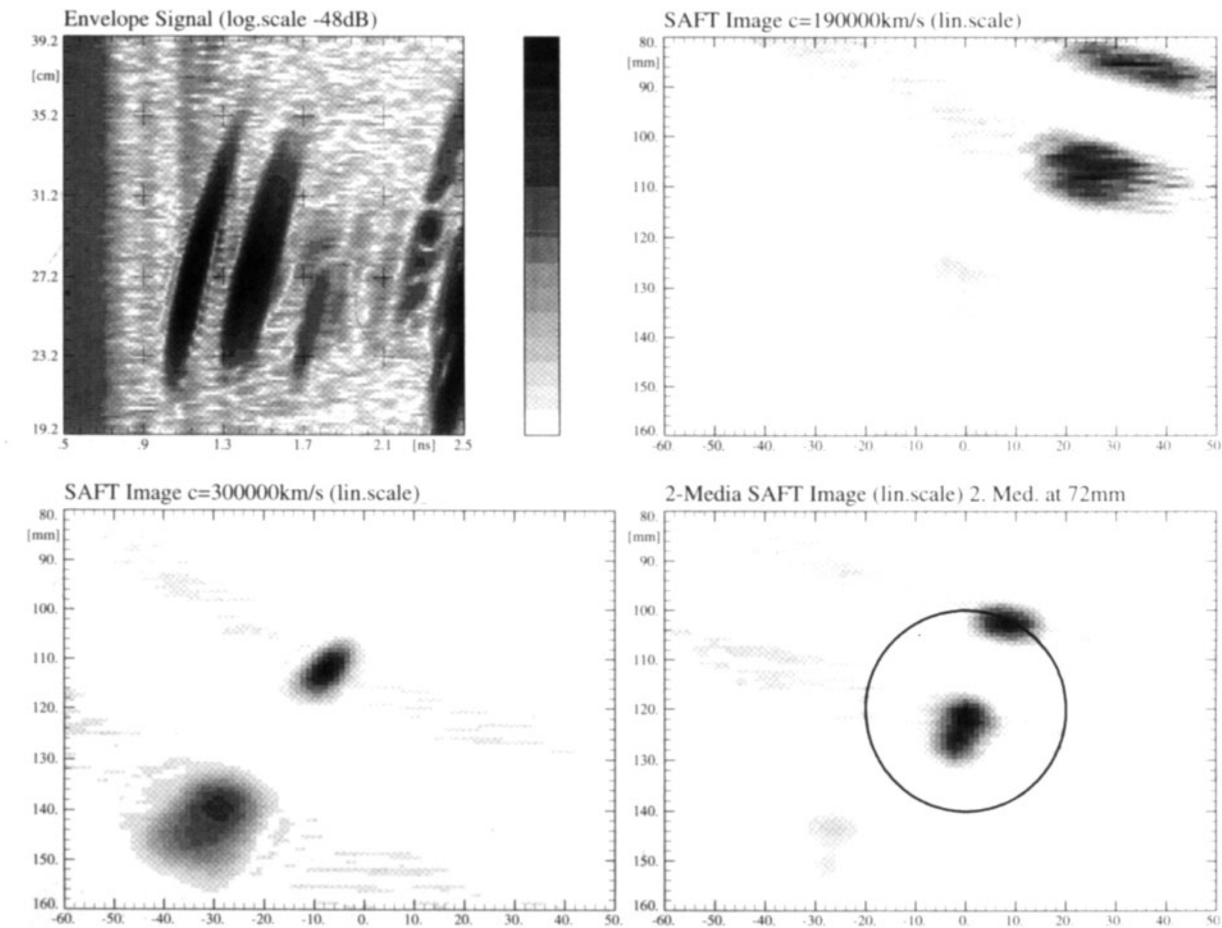

Figure 4. Microwave SAFT: envelope of xt-rf-data (top left); SAFT-image with vacuum wave speed (bottom left); SAFT-image with acrylic wave speed (top right); SAFT- image with two wave speeds (bottom right)

POLARIMETRIC MICROWAVE IMAGING

Electromagnetic waves are vector waves, and as such, their polarization is an important carrier of information; particularly, the depolarization through scattering is in some sense a measure for the complexity of the scatterer. Hence, a scalar imaging algorithm applied to one component of the field vector, or to the output voltage of a receiver might not be the best and most appropriate imaging scheme. As a matter of fact, we have been able to derive an electromagnetic "polarimetric SAFT" [7], which, when applied to synthetic scattering data of an airplane, was far superior to the scalar one [8]. This algorithm is waiting for its application in NDE.

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