Mutual Coupling Compensation for Microwave Image Reconstruction

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1. Introduction

Confocal Microwave Imaging (CMI) method to detect the breast cancer in women at an early stage has attracted the interest of the research community recently [1]. CMI exploits the dielectric contrast between malignant and normal breast tissues and creates a map of scattered energy from the breast for ultra-wideband (UWB) microwave illumination. The presence of the tumour is reconstructed from the map of scattered fields from which the dielectric contrast is detected by employing signal processing methods. Recent measured data on breast tissues revealed that dielectric properties of malignant tumour could be very close to that of glandular tissues at UWB microwave frequencies [2]. This makes the identification of malignant tumour from benign breast tissues based on scattering response more difficult thus limiting the usefulness of the conventional beam forming based image reconstruction techniques. Therefore, there is a need for alternative approaches of breast cancer detection for CMI method. One important method that has emerged recently employs differentiation of malignant from healthy breast tissues by extracting the complex natural resonances (CNR) of these tissues [3]-[4]. For successful extraction of the CNRs from the scattered data, it is essential that pre-processing steps be employed which are vital to the calibration of the received signals and for removing the interference from clutter from other breast tissues as much as possible. In the literature, the reported calibration and pre-processing approaches for UWB breast cancer detection, use the signal averaging as the calibration template to remove the skin reflection and clutter responses [1]. After such a calibration, they then apply reconstruction methods based on beam forming to estimate and recover the scattered signal waveform from significant scatterers within the breast. Some of these beamforming techniques have bias due to steering vector uncertainties, finite number of snap shots etc. In addition, when many antennas are employed to receive the scattered signals at the receiver, mutual coupling can also affect the accuracy of the estimation of the scattering waveform.

In an attempt to reduce the steering vector bias, an imaging technique known as Multistatic Adaptive Microwave Imaging (MAMI) [5] was proposed which employs the Robust Capon Beamformer (RCB) to obtain an optimized waveform. While application of RCB overcame the bias due to the steering vector, however it cannot offset the estimation errors due to the mutual coupling between the receiving antenna elements. Since the microwave imaging techniques employ an array of antennas, and since the performance of beamformers are affected significantly by mutual coupling, it can not be neglected in practical situations. Recently, an experimental investigation on breast cancer detection was reported which employed MAMI technique using a hemispherical antenna array and the mutual coupling was reduced by simple array rotation [6]. In this paper, we present an auto-calibration method to compensate the mutual coupling effect [7] for microwave imaging to detect breast cancer. The auto-calibration method uses quadratic optimization method similar to that used in RCB to estimate the mutual coupling parameter. The optimized mutual coupling parameter coupled with RCB will give better calibration than the conventional pre-processing procedures. After compensating the mutual coupling, it is expected that better clutter rejection can be obtained and more accurate waveforms from regions of interest within the breast which may carry information on the malignancy can be accurately recovered.

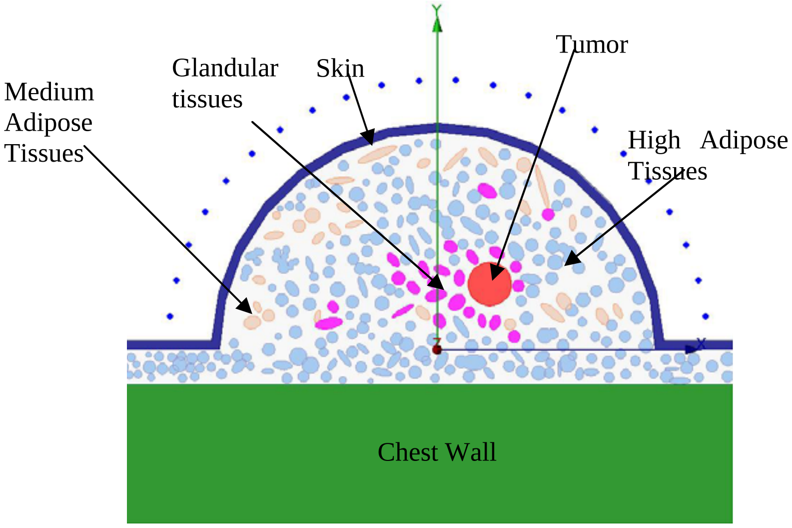

Fig. 1 Breast model with smooth benign tissue at (12, 16)mm.

In this paper, we employ a 2-Dimensional heterogeneous FDTD breast model as shown in Fig.1, in which the skin reflection and clutter interference is calibrated by using the tumor-free template. The tumor-free template is only useful for numerical breast models to remove the skin reflection and hence we employ in this paper to verify the proposed mutual coupling compensation method. However, the scattering responses from breast tissues that include tumor still get affected by the interference and clutter from surrounding tissues even after subtracting out the tumor-free template. The 2D FDTD breast model that is employed in this paper is simulated with 22 antenna elements as shown in Fig. 1.

2. Breast Phantom

The 2-D breast model is composed of the chest wall, the 2mm thick skin layer and breast tissues. A Circular antenna array with 22 antennas is located 10mm away from the skin. The tumor is surrounded by glandular tissues which have similar microwave dielectric properties as that of the tumor. Three main categories of breast tissues are included: high adipose (mostly fatty and little fibroconnective or glandular tissues), medium adipose, and low adipose (a small amount of fatty but mostly fibroconnective and glandular tissues). We use the accurate two-pole Debye models at frequency band from 0.5-20GHz to represent the dielectric properties as shown in Table I [2]. The dielectric properties of skin are ε_∞ =18.4, $\Delta\varepsilon$ =21.9, τ =17.5ps and σ_s =0.737 S/m. The chest wall follows: ε_∞ =6.75, $\Delta\varepsilon$ =47.91, τ =10.1ps and σ_s =0.85 S/m [2].

Table I: Dielectric Properties of Breast Tissues

	High Adipose	**Medium Adipose**	**Low Adipose**	**Malignant**
$\Delta\varepsilon_1$	0.58	19.64	20.81	25.61
$\Delta\varepsilon_2$	1.09	14.23	20.22	23.91
τ_1 ps	8.07	5.81	7.39	7.22
τ_2 ps	19.25	16.49	15.18	15.30
ε_∞	3.14	5.57	7.82	6.75
σ_s S/m	0.036	0.52	0.71	0.79

3. Mutual Coupling Compensation

The received signal is represented by:

$$x(n) = as(n) + e(n) \quad \text{n=1, 2 … N,} \tag{1}$$

where a is the steering vector, e is the noise plus clutter interference. And the estimated steering vector $\hat{a}$ is obtained by [5]:

$$\min_{\hat{a}} \hat{a}^H R^{-1} \hat{a} \ \text{ subject to} \left\| \hat{a} - a \right\| \le \varepsilon_a \tag{2}$$

where $R = \frac{1}{N}\sum_1^N x(n)x^H(n)$ is the covariance matrix of received signals, and ε is the empirical parameter. Then the RCB beamformer is then calculated by:

$$w_{RCB} = \frac{R^{-1}\hat{a}}{\hat{a}^H R^{-1}\hat{a}} \tag{3}$$

The waveform recovered by RCB is given by:

$$\hat{s} = w_{RCB}{}^H x \tag{4}$$

The estimation of mutual coupling parameter C is similar to (2), and it is alone estimated by [7]:

$$\min_{\hat{C}} \hat{C}^H S \hat{C} \ \text{ Subject to } \left\| \hat{C} - C \right\| \le \varepsilon_b \tag{5}$$

where $S = diag\{\hat{a}\}^H R^{-1} diag\{\hat{a}\}$.

When the steering vector from RCB is coupled with mutual coupling parameter, the beamformer is given by:

$$\hat{w}_{RCB} = \frac{R^{-1}\hat{\hat{a}}}{\hat{\hat{a}}^H R^{-1}\hat{\hat{a}}} \tag{6}$$

where $\hat{\hat{a}} = \hat{C}\hat{a}$. Using this, the recovered waveform of interest is calculated as:

$$\hat{\hat{s}} = \hat{w}_{RCB}{}^H x \tag{7}$$

4. Numerical Results

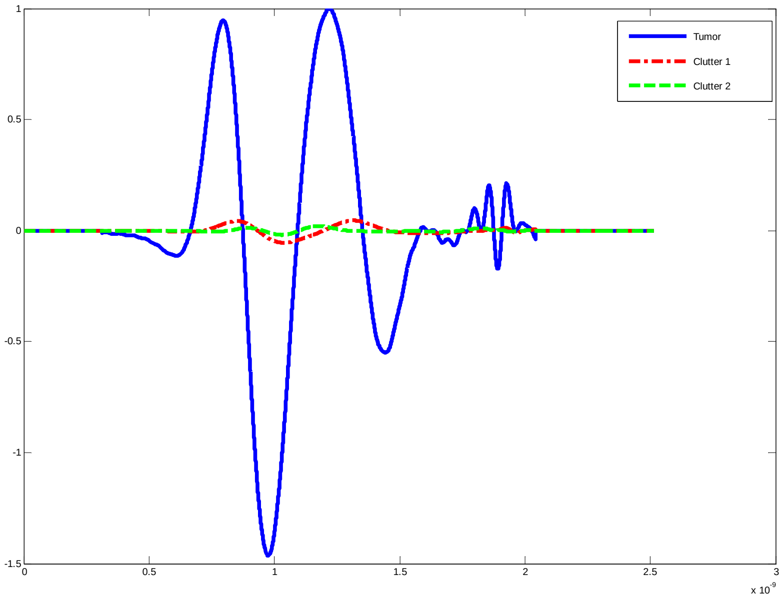

Fig. 2: Recovered waveforms by using RCB after mutual coupling compensation.

Fig. 2 shows recovered waveforms by using RCB after employing our proposed mutual coupling compensation. In this figure, the blue solid line represents the signal reconstructed from tumour and red dashed line represents the signal reconstructed from clutter due to clutter that is located at (5, 39) mm. The simulation included an incident modulated Gaussian UWB pulse impinging on the 2D breast model employing multi static imaging technique. The incident pulse has the bandwidth from 0.2 to 7.4 GHz. The antenna array recorded the received data. Then the beamformer scanned for the confocal points within the whole breast to reconstruct the waveforms from each confocal point. It is expected that the reconstructed waveforms due to the tumour are distinct from the recovered waveforms from other breast tissues. The simulated results indicate that the reconstructed waveforms due to scattering from healthy breast tissues are efficiently suppressed by our proposed mutual coupling compensation technique when coupled with RCB.

Fig. 2 also shows the reconstructed waveforms scattered from malignant tissues using RCB with proposed mutual compensation. From the figure, it can be concluded that the clutter response is well suppressed while the waveform of interest from tumour is reconstructed maximally. The same conclusion can also be observed on another clutter response (green dashed line) in Fig. 2 where the healthy tissue is located at (0, 18) mm.

5. Conclusions

This paper proposes a mutual coupling compensation method that can be coupled with RCB to recover the calibrated scattering waveform from regions of interest within the breast which carries malignancy information. Using a 2D breast model, we demonstrate that with the proposed mutual coupling compensation, the clutter responses are well suppressed. Thus, it helps to enhance the ability to differentiate the malignant tissues from healthy breast tissues.

Acknowledgments

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