DUAL-USE SPACE TECHNOLOGY TRANSFER CONFERENCE
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MICROWAVE IMAGING OF METAL OBJECTS

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ABSTRACT

The procedure of microwave imaging by maximum entropy method is discussed. First, the relationship between the induced current on the metal object surface and the scattered field is introduced. Our imaging concept is to reconstruct the induced current on the object surface from the measured scattered field. The object configuration will be provided by the induced current which is zero everywhere except on the object surface. Future work is also included with focus on the application of microwave imaging to both NASA and industry.

I INTRODUCTION

To achieve the highest resolution in microwave imaging has been a goal for a long time for scientist and engineers attributed largely to its academic significant and the understandable commercial and military values. The quality of microwave imaging is judged by how faithfully the microwave image represents the spatial distribution of the object of interest.

In the most direct form, imaging a three-dimensional object can be accomplished by using a range-gated, short-pulse radar with a pencil-beam antenna. The antenna beam and the range gate are systematically scanned throughout the three-dimensional volume, and the intensity of the signals received is displayed as a function of the spatial coordinates being interrogated. Because the spatial resolution is established by the angular and range resolution of the sensor, the image is obtained directly, without subsequent processing.[1]

The relative simplicity of forming the image, which requires minimal data processing, and the fact that the image can be obtained while the object is stationary constitute the advantages of the direct imaging method. The principal disadvantages of the direct method are:

• A high degree of spatial resolution requires subnanosecond pulses and large apertures, posing practical limitations.

• The cross-range resolution, obtained from the antenna beamwidth, degrades as the range increases.

• The spatially limited irradiation of the object omits interactions and coupling that may occur when the entire object is simultaneously irradiated.

Synthetic imaging means the imaging is obtained by synthetic means when results of many observations of the object at different frequencies and angles are coherently combined, and the short-pulse, and large aperture antenna are still very important to produce a faithful imaging of the objects.

In this paper, we will investigate the imaging of a metal object by single frequency microwaves. First we will introduce our imaging concept. The relationship of the induced current on a metal object surface and scattered field is introduced, and then maximum entropy method will be used to reconstruct the induced current on the object surface, thus reveal the object configuration.

II. THE MAXIMUM ENTROPY METHOD FOR MICROWAVE IMAGING

From electromagnetic theory we know that once the radiated field is known, the induced current (tangential electric field) on the surface of a metal object can be found by the boundary conditions. The induced current is therefore known at every point. According to the Huygens' principle, each point can then be treated as a radiating element, and the total scattered field can be obtained by integrating over the entire object surface.

For microwave imaging, this means that if we are able to determine the induced current which is

$$\mathbf{J} = 0 \quad \text{inside the object}$$
$$\mathbf{J} \neq 0 \quad \text{outside the object}$$

we will be able to reconstruct the image of the object. The general relationship between the induced current on the metal object surface and the scattered field can be expressed as surface integration of the Green's function. For example, if the induced current on the object surface is in the x-direction, we will have[2]

$$E_x(\mathbf{r}, \mathbf{r}') = \iint_{s'} U(\mathbf{r}, \mathbf{r}') J_x(\mathbf{r}') ds'$$

where

$$U(\mathbf{r}, \mathbf{r}') = \frac{\exp(-ik|\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|} - \frac{1}{k^2} \frac{\partial^2}{\partial r \partial r'} \left(\frac{\exp(-ik|\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|} \right)$$

the numerical model of the above imaging problem with the random error added is

$$\mathbf{E} = \mathbf{UJ} + \boldsymbol{\mathcal{E}}$$

where $\mathbf{J} = [J_1, J_2, \ldots\ldots, J_N]$ is the vector which contains the data of the image to be reconstructed, N is the number of current elements on the metal object surface, $\mathbf{E} = [E_1, E_2, \ldots\ldots, E_M]$ is the vector which contains the measured data for the scattered field from which the induced current is to be reconstructed, and $\boldsymbol{\mathcal{E}} = [\varepsilon_1, \varepsilon_2, \ldots\ldots, \varepsilon_M]$ is the vector representing the error, M is the number of measurement points and U is a matrix of size $M \times N$.

The concept of maximum entropy is related to that of probability density and it determines an image $\mathbf{J} = [J_1, J_2, \ldots\ldots, J_N]$ which maximizes the function

$$S(\mathbf{J}) = \sum_{k=1,}^{N} \ln J_k - \lambda \sum_{i=1}^{M} \frac{1}{\sigma_i^2} \left(\sum_{k=1,}^{N} U_{ik} J_k - E_i \right)$$

where the first term is the entropy of the image, and the second term is a quadratic term which represents noise. This maximum problem can be solved iteratively.

The maximum entropy criterion is as follows. First, the difference between the computed fields and the measured fields is to be minimized at the same time the entropy of the scattering current is also to be minimized. The entropy is an indication of the fluctuation of the scattering current from cell to cell. The global maximum entropy is the case where the scattering current is a constant, but constant scattering current may produce a large discrepancy between the computed fields and the measured fields. By minimizing the difference, together with maximizing the entropy, a compromise is reached where the variation of scattering current from cell to cell is smooth but at the same time the resulting computed field is different from the measured field by a tolerable amount.

III. THE SCATTERED FIELD BY A FLAT METAL OBJECT

Consider a planar radiating aperture A, defined as the area on the aperture plane $z = 0$ over which the tangential field is non-zero. The electric field in the aperture plane is entirely x-directed

$$E_{ax}(x,y) = E_x(x,y,0)$$

the radiated field exits in the half-space $z \geq 0$. In the far field region, the electric field at point $P(x,y,z)$ or $P(r,\theta,\phi)$ with direction cosines (α,β,γ) can be expressed as[3]

$$\mathbf{E}(r,\theta,\phi) = j\frac{2\pi}{kr}\exp(-jkr)F_x(\alpha,\beta)\left[\mathbf{u}_x\gamma - \mathbf{u}_z\alpha\right]$$

and the corresponding magnetic field is

$$\mathbf{H}(r,\theta,\phi) = j\frac{2\pi}{Zkr}\exp(-jkr)F_x(\alpha,\beta)\left[-\mathbf{u}_x\alpha\beta + \mathbf{u}_y\left(1-\beta^2\right) - \mathbf{u}_z\beta\gamma\right]$$

where Z is the plane-wave impedance of the medium and

$$F_x(\alpha,\beta) = \frac{1}{\lambda^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E_{ax}(x,y)\exp\left[jk(\alpha x + \beta y)\right]dxdy$$

is the angular spectrum which is Fourier transformation of the radiation aperture field.

Suppose that we have a flat metal object which is parallel to the incident aperture of which the radiating field is expressed by their angular spectra and the distance between the object and the incident aperture is z.

Over the surface of the conducting plate, the total tangential electric field must be zero to satisfy the boundary condition. When dimension of the object is large in comparison to the wavelength, the local diffraction effects are negligible. By the tangent-plane approximation of physical optics, the aperture field assumes that the field on reflection is the same over the conducting plate as if it were part of an infinite plane. This is the simplest the aperture field corresponding to the scattered field can be taken to be the negative of the tangential component, therefore the induced current, of the incident field over the conducting plate, and zero elsewhere in the x-y aperture plane. From the above discussion we can see that when the incident aperture field is entirely x-directed, the induced current on the object surface will be also x-directed. Therefore the same angular spectrum method can be used to find the scattered field.

One example of the plane radiating aperture is horn antenna. The aperture field distribution of a horn antenna can be expressed as

$$E_{ax}(x,y) = E_o\cos\left(\frac{\pi y}{b}\right)\exp\left[-\frac{jk}{2}\left(\frac{x^2}{l_E} + \frac{y^2}{l_H}\right)\right]$$

The angular spectrum describing the radiating field is

$$F_x(\alpha,\beta) = \frac{E_0}{2\lambda^2} X_f \left(Y_f^+ + Y_f^- \right)$$

where

$$X_f = \sqrt{\frac{\lambda l_E}{2}} \exp\left(\frac{j\alpha^2 l_E \pi}{\lambda} \right) \left[F\left(\sqrt{\frac{2}{\lambda l_E}} \frac{a}{2} - \sqrt{\frac{\lambda l_E}{2}} \frac{2\alpha}{\lambda} \right) + F\left(\sqrt{\frac{2}{\lambda l_E}} \frac{a}{2} + \sqrt{\frac{\lambda l_E}{2}} \frac{2\alpha}{\lambda} \right) \right]$$

$$Y_f^+ = \sqrt{\frac{\lambda l_H}{2}} \exp\left(\frac{j\beta_+^2 l_H \pi}{\lambda} \right) \left[F\left(\sqrt{\frac{2}{\lambda l_H}} \frac{b}{2} - \sqrt{\frac{\lambda l_H}{2}} \frac{2\beta_+}{\lambda} \right) + F\left(\sqrt{\frac{2}{\lambda l_H}} \frac{b}{2} + \sqrt{\frac{\lambda l_E}{2}} \frac{2\beta_+}{\lambda} \right) \right]$$

$$Y_f^- = \sqrt{\frac{\lambda l_H}{2}} \exp\left(\frac{j\beta_-^2 l_H \pi}{\lambda} \right) \left[F\left(\sqrt{\frac{2}{\lambda l_H}} \frac{b}{2} - \sqrt{\frac{\lambda l_H}{2}} \frac{2\beta_-}{\lambda} \right) + F\left(\sqrt{\frac{2}{\lambda l_H}} \frac{b}{2} + \sqrt{\frac{\lambda l_E}{2}} \frac{2\beta_-}{\lambda} \right) \right]$$

and

$$\beta_+ = \beta + \frac{\pi}{bk}$$

$$\beta_- = \beta - \frac{\pi}{bk}$$

and F(x) is the Fresnel Integral

$$F(x) = \int_0^x \exp\left(-j\frac{\pi u^2}{2} \right) du$$

The advantage to use the angular spectrum method to find the radiating field is that we can assume the aperture field incidence instead of assuming the plane wave incident. From the above example we can see that the incident wave can be expressed analytically.

In the process of imaging reconstruction, to find the scattered field from the known source is called the forward modeling and to find the imaging from the measured (or simulated) scattered field is call the inversion. Because the inversion process by maximum entropy method is to be solved iteratively, the simplicity of the forward model is a must for a successful imaging method.

IV. FUTURE WORK

As stated in the previous section, the imaging of a flat metal object with known planar incident aperture field consists of the following steps

• The radiated field distribution in the z≥o space is calculated by the radiating aperture field.

- The radiating aperture for the scattered field is obtained, which is the negative tangential part of the radiated field obtained in the previous step; the diffraction effect is neglected.

- The scattered field is calculated.

- The measured scattering field is simulated by adding a random error to the scattering field obtained from the calculation.

- Maximum entropy is used to reconstruct the tangential component on the object surface, thus the shape of the object.

Our future work on the microwave imaging will be set up the experiment system and display the reconstructed metal object image on the computer screen. In the mean time, we will study the effects of a) frequency of the incident wave, b) viewing angle and area, c) size, shape, material and orientation of the object on the quality of the image of the object. The object image obtained from the magnitude and phase of the scattered field and the object image obtained from scattered field magnitude only will also be studied.

We will also work on the image of the metal object covered by dielectric materials. The near field image will be emphasized because of the practical importance and the potential high quality of the image because of the high signal/noise ratio.

ACKNOWLEDGMENT

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