REFLECTOR SURFACE MODELLING – A EUROPEAN COLLABORATION

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ABSTRACT

The topic of this paper is the work carried out in Work Package 2.3-2 of the EU network ACE. This work package is concerned with the modelling of the surfaces of modern reflector antennas. In particular the problems associated with homogenisation are described together with an application example. Fast, but approximate, methods are compared to rigorous solutions for realistic strip grid configurations. A new, fast and very efficient interpolation technique for frequency selective surfaces is introduced.

1. INTRODUCTION

This paper describes the work carried out in Work Package 2.3-2 of the EU network ACE, Antenna Centre of Excellence. This work package deals with the modelling of the surfaces of reflector antennas. Reflector antennas may operate over very wide bands typically limited by the feed system. Special surfaces are used for polarization control using gridded surfaces or for frequency diplexing using frequency selective surfaces. It may also be necessary to be able to take into account special surface elements such as CFRP, mesh or paint. Reflector antennas find use in radio-links and as antennas for geostationary satellites – both on ground as terminals and onboard the satellite. Alternatively special surfaces are used as radomes, e.g. to protect antennas under adverse climatic or environmental conditions, on vehicles, trains and aircraft, or onboard satellites.

The list of authors shows the partners involved in this work package. Different topics are investigated by different partners as described in the following sections. It is important to stress, however, that the main purpose of the project is to combine the expertise available internally at each partner into a common and useful knowledge base.

2. HOMOGENISATION

Homogenization is a technique which is usually employed when studying problems where the applied wavelength is much larger than the microstructure. The idea is to replace a heterogeneous structure built up of small details with a fictitious, homogeneous structure, which would produce the same scattering characteristics. Strictly speaking, this can only be done in the limit where the wavelength is infinitely large compared to the microscopic details, but in real engineering problems the homogenisation procedure still produces acceptable results for finite wavelengths. However, it is usually very difficult to deduce the range of validity for the homogenised results. Two separate questions are of particular interest:

1) Under which circumstances is it possible to model a particular structure as a material? For most structures there is in general an infinite number of degrees of freedom for the electromagnetic field, corresponding to the number of modal solutions. By choosing the frequency low enough, the number of modes can be reduced to only correspond to the possible polarizations of the electromagnetic field.

2) Once the structure is modelled as a material, we may ask how strong the dependence on the scale difference between the wavelength and the microscopic structure is. This corresponds to identifying the spatial dispersion, which is given by the dependence of the effective permittivity on ka, where k is the wavenumber of the applied field and a is the typical size of the microstructure.

The main conclusion from the work carried out is that a heterogeneous structure may be modelled as a homogeneous material, even if the applied wavelength is not infinitely large compared to the microscopic scale. A sufficient condition for arbitrary geometries has

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been determined, but a wider range of validity for specific geometries can be anticipated.

2.1. Homogenisation applied to strip grids

The rigorous analysis of periodic strips inside a multilayer structure is performed by expanding the currents on the strips in basis functions, and the amplitudes of the basis functions are determined numerically by the Method of Moments (MoM). The electromagnetic field is in the form of Floquet modes due to the periodicity of the structure. It is sufficient to determine the current on one strip, since the currents on the other strips are identical except for a phase difference.

If the source excites a full spectrum of plane waves, such as a dipole, the Floquet-mode expansion/MoM is a laborious process. A simpler approach is to use approximate boundary conditions. We have used two types of approximate boundary conditions: the asymptotic strip boundary conditions (ASBC), which in the planar case correspond to modelling the strips as a unidirectional conducting screen, and boundary conditions obtained by the homogenisation method (BCHM).

The ASBC are applied to the components of the electromagnetic field that are tangential to the interface which contains the strips. The electric field component parallel to the strips is zero at the strip surface, and the component orthogonal to the strips is continuous across the surface. For the magnetic field it is sufficient to consider the component parallel to the strips, which is continuous across the surface.

The BCHM are obtained by averaging the fields of the fundamental Floquet mode. The zero-order boundary conditions correspond to ASBC, and the first-order boundary conditions include the periodicity, P, and the width, W, of the strips shown in Fig. 1.

As an example, Fig. 2 shows the reflection coefficient for a planar strip grid for different angles of incidence and as a function of the number of strips per wavelength. The polarisation of the incident plane wave is parallel to the strips. The BCHM results are compared to the MoM solution and an almost perfect agreement is obtained.

The BCHM approach has also been applied to strip grids on dielectric cylinders, also shown in Fig. 1, and again very good results are obtained, even for cylinders down to one wavelength in diameter.

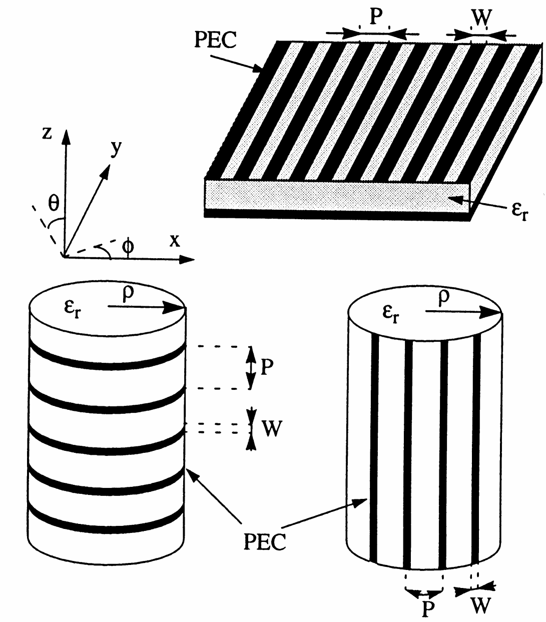

Figure 1. Geometry of strip grids on a planar dielectric slab and on a dielectric cylinder with circular cross-section.

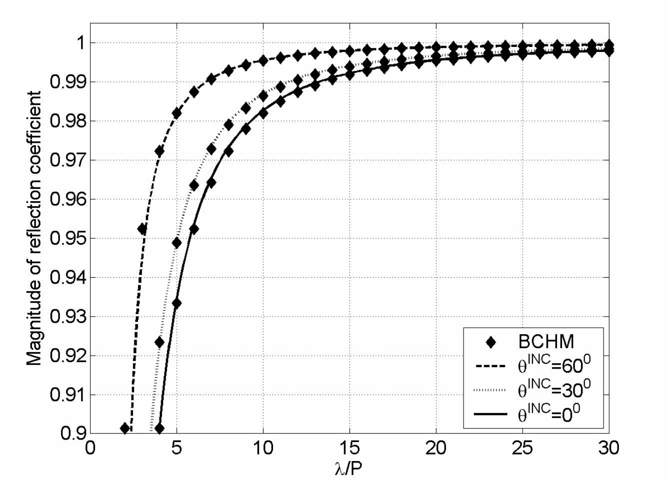

Figure 2. MoM (continuous curves) and BCHM results for the absolute value of the reflection coefficient of a planar strip grid for transverse incidence for W/P = 0.25.

3. FAST METHODS FOR STRIP GRIDS COMPARED TO RIGOROUS SOLUTIONS

A strip grid located on the surface of a reflector antenna is a very popular technology when a good polarisation discrimination is required. For the analysis of such reflectors it is essential that fast and reliable software is available to model the local reflection and transmission properties everywhere on the surface. The present section illustrates the validity of approximate methods for strip grids by comparing them to accurate MoM solutions.

3.1. Rigorous solution for strip grids

Politecnico di Torino has developed the computer program "METallic STrIps Simulator (MESTIS)" and the associated manual [1]. The program is based on a MoM approach and it is possible to model one or more layers of co-planar strip grids and each layer can consist of one, two or three strip grids making arbitrary angles with each other. In addition, it is possible to model dielectric layers around and between the different strip grids. This software package is used to evaluate the faster but more approximate methods.

3.2. Approximate method

The incident plane wave on the strip grid can be written

$$\bar{E}^i = E_\theta^i \hat{\theta}_i + E_\phi^i \hat{\phi}_i \tag{1}$$

and the reflected field becomes

$$\bar{E}^r = E_\theta^r \hat{\theta}_r + E_\phi^r \hat{\phi}_r \quad , \tag{2}$$

where

$$\begin{Bmatrix} E_\theta^r \\ E_\phi^r \end{Bmatrix} = \begin{Bmatrix} R_{\theta\theta} & R_{\theta\phi} \\ R_{\phi\theta} & R_{\phi\phi} \end{Bmatrix} \begin{Bmatrix} E_\theta^i \\ E_\phi^i \end{Bmatrix} \tag{3}$$

and the unit vectors are the usual ones for spherical coordinates. Similar relations can be set up for the transmitted field.

Each strip has a width W and the spacing of the strips is P (the distance from the centre of one strip to the centre of the next). Simple analytical expressions for the reflection and transmission coefficients for strip grids are given by Nakamura and Ando [2]. For a plane wave at normal incidence, $\theta_i = \phi_i = 0$, polarised parallel to the strips the reflection coefficient is

$$\begin{aligned} R_{\theta\theta} &= \frac{1}{1+jt} \\ t &= -\frac{2P}{\lambda} \ln\left(\cos(\frac{\pi}{2}(1-\frac{W}{P})) \right) \end{aligned} \tag{4}$$

and for polarisation orthogonal to the strips one gets

$$\begin{aligned} R_{\phi\phi} &= \frac{jt'}{1+jt'} \\ t' &= -\frac{2P}{\lambda} \ln\left(\sin(\frac{\pi}{2}(1-\frac{W}{P})) \right) \end{aligned} \tag{5}$$

where λ is the wavelength. Expressions (4) and (5) show that if the spacing relative to the wavelength, P/λ, is reduced while the ratio between the width and the spacing, W/P, is kept constant, $R_{\theta\theta} \to 1$ and $R_{\phi\phi} \to 0$.

It is possible to combine the strip grid with other materials, such as a supporting dielectric slab, by cascading the scattering matrix for each of the structural elements. The expressions in [2] have been implemented in the general reflector antenna software package GRASP9 [3].

3.3. Calculated results

This section presents numerical experiments for a single strip grid in free space and a strip grid located on the one side of a dielectric. The reflection and transmission properties are illustrated by just one of the components of the reflection and transmission matrices, namely the magnitude of $R_{\theta\theta}$. The reason is that all the components behave in a similar fashion and it is therefore sufficient to show only one of them.

First, a single strip grid is considered. The parameters are

frequency = 10 GHz (λ = 30 mm)
strip spacing, P = 1.5 mm
strip width, W = 0.1 mm

The results are shown in Fig. 3. The left side of the plot shows the amplitude of $R_{\theta\theta}$ calculated by MESTIS as a function of the angle of incidence (θ, ϕ). θ varies from 0º to 60° and ϕ varies from 0º to 90°. The figure shows that the amplitude is maximum for polarisation in the plane of the strips, $\phi = 0°$, and minimum in the plane orthogonal to the strips, $\phi = 90°$.

The results obtained by GRASP9 for this example are almost identical as identified by the right side of Fig. 3 which shows the difference between $|R_{\theta\theta}|$ obtained by MESTIS and GRASP9. The maximum difference appears at normal incidence and it is around 0.25 per cent. The selected strip dimensions are typical for practical applications and the accuracy obtained with the fast expressions in GRASP9 is acceptable.

In practice the strip grid is often laser etched into a metallic layer deposited on the one side of a dielectric supporting structure. It is therefore of interest to investigate the performance of a strip grid located directly on the one side of a dielectric sheet.

In the next example the strip grid is moved to the surface of a dielectric slab of thickness 3.75 mm, corresponding to $\lambda/8$ (λ is the free space wavelength). The relative permittivity of the dielectric is ε_r = 4. The calculated results are shown in Fig. 4.

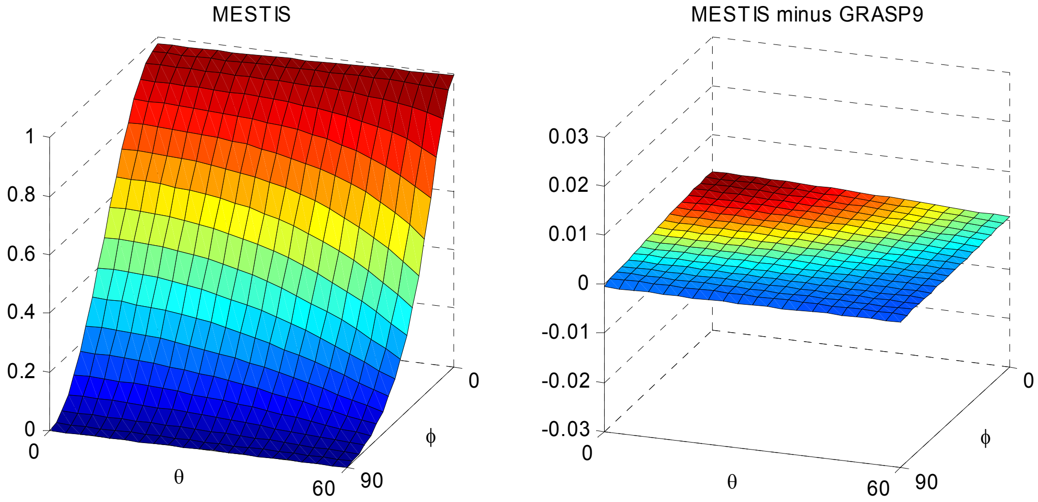

Figure 3. Reflection coefficient for single strip grid in free space, P = 1.5 mm, W = 0.1 mm

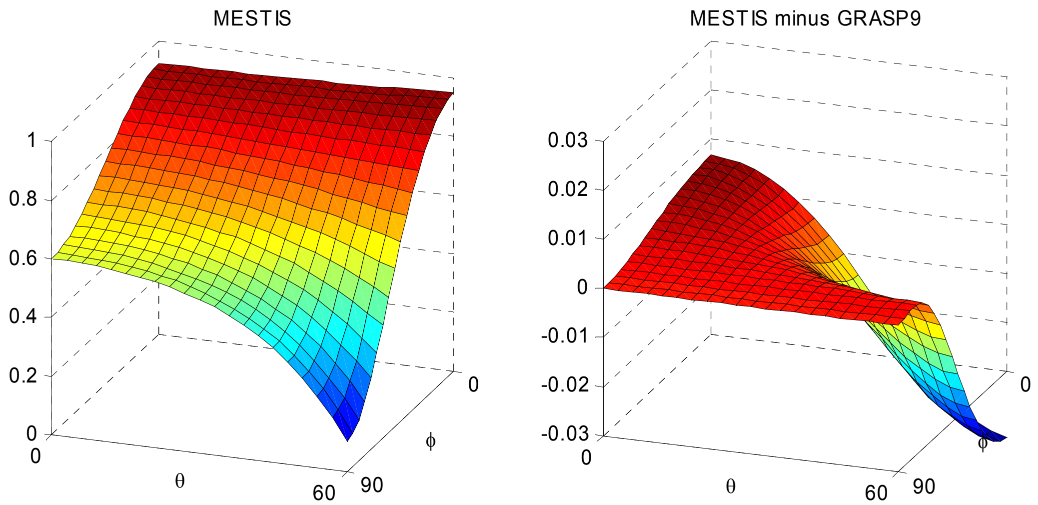

Figure 4. Reflection coefficient for single strip grid located on the top side of a 3.75 mm thick dielectric with ε_r = 4, P = 1.5 mm, W = 0.1 mm.

At normal incidence the agreement between GRASP9 and MESTIS is good, but for increasing angle of incidence and $\phi = 0°$ the difference increases rapidly and for $\theta = 60°$ the error is about 5 per cent which is not acceptable. For $\phi = 90°$ the strip grid is orthogonal to the θ-direction and GRASP9 and MESTIS provide the same result.

Fig. 4 demonstrates that the approximate formulas in GRASP9 give rise to errors when a strip grid is located directly on the surface of a dielectric. We know from previous experience that the simple formulas work well if there is a sufficient distance between the strip grid and the dielectric. It is therefore of interest to find out the lower level of this distance where we still get acceptable results. Reducing the height of the strip grid above the dielectric gradually to zero must necessarily end with the result shown in Fig. 4. Fig. 5 shows the results for a height of 0.3 mm ($\lambda/100$). It is surprising to notice, that the spacing of the strips is five times larger than the distance to the dielectric plate, but still the free space cascading used in GRASP9 works very well. Reducing the distance further the result starts to approach the zero height result in Fig. 4.

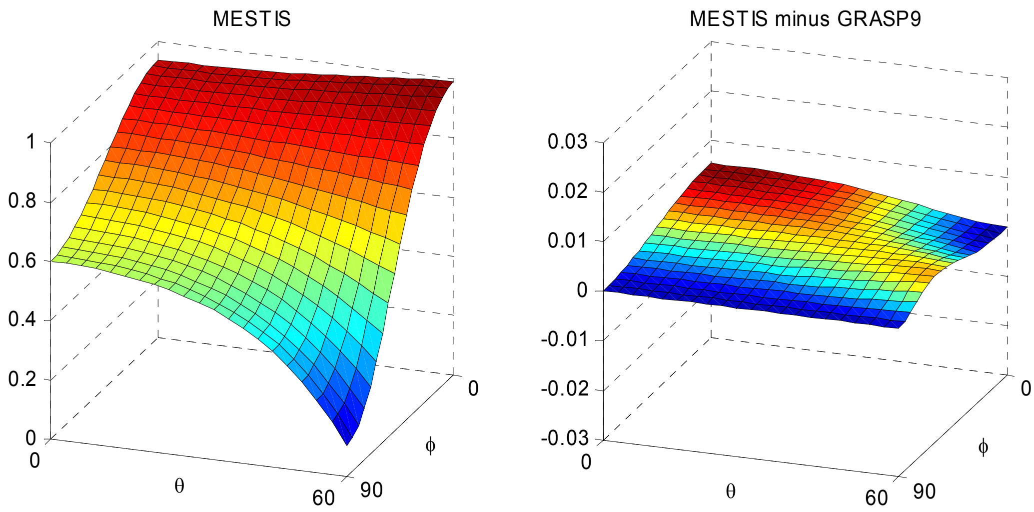

Figure 5. Reflection coefficient for single strip grid with P = 1.5 mm, W = 0.1 mm, located 0.3 mm (λ/100) above a 3.75 mm thick dielectric with ε_r = 4

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The discrepancy between MESTIS and GRASP9 is apparently isolated to an extremely thin layer around the strip grid and it seems likely that the GRASP9 expressions can be improved by simple means taking into account the difference in dielectric constant on the two sides of the grid.

4. FAST INTERPOLATION FOR FREQUENCY SELECTIVE SURFACES

The idea of the work described in this section is to combine the accuracy of a rigorous solution with the speed of a fast interpolation technique. The method being developed is called the Pole-Zero Matching technique, PZM.

Frequency selective surfaces, FSS, are widely used for the realization of polarizers and dichroic reflectors. Due to the large dimensions of these structures, the analysis is usually performed by resorting to high-frequency techniques, such as Physical Optics (PO) or Geometrical Optics (GO), sometimes augmented by diffraction theories (PTD, UTD, ITD). In this framework, it is desirable to have a simple and accurate surface impedance model of periodic surfaces, to be interfaced with existing high-frequency electromagnetic simulation tools.

A method for obtaining the analytical solution of the admittance (scattering) matrix of FSSs is derived. On the basis of a spectral MoM solution, an equivalent network-matrix is defined with the ports corresponding to the accessible TE and TM Floquet Waves of the exact Floquet expansion. The admittance matrix is then characterized by poles and residues associated to the matrix entries for a selected number of values of the incidence angles. The identification of a set of surfaces associated with the poles and residue of the FSS and their regularity allows the interpolations of these surfaces by low-order polynomials. Network theory properties allow the approximation of the entries in terms of summation of rational functions. The consequent closed form expression is applied to evaluate the generalized scattering matrix as a function of the angle and polarization of the incident plane wave.

It is worth remarking that the full-wave analysis for each incident aspect (θ, ϕ) is very efficient, since it implies the inversion of a moderate size MoM matrix. However, obtaining accurate information on the continuous (θ, ϕ) domain requires a large amount of computational time. The main peculiarity of the method presented here is concerned with the possibility of reconstructing an analytical closed form of the generalized scattering matrix in the continuous (θ, ϕ) domain over a large frequency range, starting from the response of the structure at a few samples. This is particularly useful to establish a link between an FSS solver and an HF solver for the analysis of a large FSS curved structure or frequency selective radome without affecting the internal code solver structure. The general process described here can be applied for the synthetic description of different wave phenomena, like those relevant to surface wave propagation and electromagnetic band-gap description, near-field interaction (Green's function) and wave diffraction involving periodic surfaces.

5. CONCLUSIONS

This paper has briefly presented some of the topics that have been studied in Work Package 2.3-2 of ACE. A more detailed description of the work can be found in the report ACE-A2.3D4, which is available at the ACE web site on the internet [4].

6. REFERENCES

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